Analytical Hierarchy Process Multi-Metric Objective Function for RPL

Walaa Alayed*†, Lewis Mackenzie* and Dimitrios Pezaros*
*School of Computing Science
University of Glasgow, Glasgow, UK
Email: w.alayed.1@research.gla.ac.uk, lewis.mackenzie@glasgow.ac.uk; dimitrios.pezaros@glasgow.ac.uk
†Princess Nourah bint Abdulrahman University, Riyadh, KSA
Email: wmalayed@pnu.edu.sa

***Abstract*—IPv6 Routing Protocol for Low Power and Lossy Networks (RPL), is based on building an acyclic graph where an Objective Function (OF) is responsible for selecting the preferred parent during Destination Oriented Directed Acyclic Graph (DODAG) construction. In this paper, we propose a new multi-metric OF based on Analytical Hierarchy Processes decision masking algorithm. AHP-OF, combines a set of routing metrics aiming to provide the best routing decision for RPL to satisfy the different application requirements for LLNs such as reliable applications, real time applications and highly available applications. Here we focus on the theoretical aspect of AHP-OF, and finally we evaluate the performance of AHP-OF compared to other OFs using Cooja simulator.**

***Index Terms*—LLN, IPV6 Routing, RPL, Objective Function, OF0, MRHOF,Analytical Hierarchy Processes, AHP, AHP-OF, Routing Metric.**

I. Introduction

Low Power and Lossy Networks (LLN) where nodes with limited power, processing and memory operate at low data rates, play an important role in the implementation of the Internet of Things (IoT). The IPv6 Routing Protocol for LLN (RPL) RFC 6550 [1] was introduced by the Internet Engineering Task Force (IETF) ROLL group to address the requirements of such networks. Node selection and route optimisation within RPL is done by an Objective Function (OF) which defines how the routes are constructed [2].

In this paper, we present a new multi-metric objective function, Analytic Hierarchy Process Objective Function (AHP-OF), inspired by multi-criterion decision making algorithms. AHP-OF combines several routing metrics by using the Analytic Hierarchy Process (AHP) algorithm to provide better neighbour selection compared to existing OFs. The motivation for AHP-OF is to satisfy the various requirements for LLNs such as reliable, real time and highly available applications.

The remainder of this paper is organised as follows. In Section II we give a brief overview of RPL and its objective functions. In Section III we go through some of the literature for RPL OFs. Section IV introduces the AHP-OF, followed by Section V presenting the research methodology and results. Finally, Section VI concludes this paper.

II. Protocol Overview

RPL is based on a directed acyclic graph (DAG) topology. This is a tree-like structure except that here a node can have multiple parents. Within an RPL DAG, all traffic is routed to a single node to form a Destination Oriented Directed Acyclic Graph (DODAG) where no cycles are present [1].

Within a DODAG, there are three types of nodes as shown in Figure 1: first, the *DODAG root* is the node that has the ability to construct a DAG, it is also considered as a sink and/or a gateway to other networks; second, the *routers* which generate, collect, and forward traffic but do not have the ability to construct a DAG; and third, the *leaves* or end nodes which only have the ability to join an existing DAG and generate data traffic but are unable to forward traffic on behalf of other nodes.

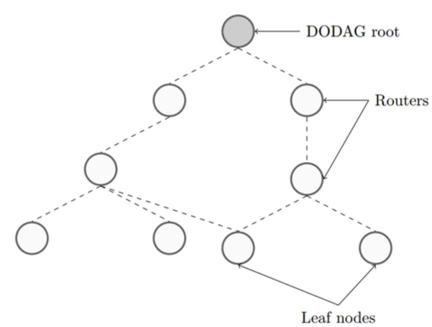

Figure 1: RPL Destination Oriented Directed Acyclic Graph (DODAG)

During DODAG construction, each node selects a set of potential parents on its path towards the DODAG root, with one or more of these considered preferred parents. A preferred parent is selected based on an *Objective Function* (OF) that defines routing metrics or constraints that are translated into ranks used to construct the DODAG. This determines the desirability of a node to be a next hop on the route towards the DODAG root. In other words, a node's rank reflects its position relative to other nodes with respect to the DODAG root. The rank increases as the node moves away from the root and is used to avoid and detect loops.

A DODAG is constructed by configuring some nodes to be DODAG roots. Nodes advertise their presence by sending link-local multicast DODAG Information Object (DIO) control messages to all RPL nodes. Nodes also listen for DIO messages and based on the rank of their neighbours, they may decide to join the DODAG. Each node that decides to join will provide a routing table among which will be entries having one or more DODAG parents as next-hop defaults.

RPL is a constraint-based routing protocol where nodes or links are either included or excluded based on certain criteria [3]. Metrics are quantitative values that help find the preferred path. A routing metric or constraint can be either additive or multiplicative. They are carried in the DIO message optional field by using the DAG Metric Object Container. According to [4], RPL defines 8 routing metrics and constraints which are associated with either nodes or links.

RPL uses a separate objective function to compute a node's Rank. This value represents the node's distance to the DODAG root. Rank exchanging between the nodes via RPL control messages allows other nodes to avoid loops. Regardless of the objective function used, the Rank always increases further from the DODAG root [2].

Separating objective functions from the core protocol gives RPL flexibility to adapt to different optimisation criteria based on different deployments, applications, and network design requirements [2].

III. Literature review

Objective Function Zero (OF0) is the default objective function for RPL. In OF0, the node's rank is defined as an integer representing the node's distance from the DODAG root. The node's rank increases as it is located further to the DODAG root. OF0 selects the node with the minimum rank as a preferred parent, it can also have a backup feasible successor if one is available. All upward traffic is routed via the preferred parent with no attempt to perform load balancing [2].

The other standardised objective function is the Minimum Rank with Hysteresis Objective Function (MRHOF). This objective function selects a preferred parent based on the minimum metric value, while it uses hysteresis to reduce churn in response to small metric changes [5]. MRHOF only uses additive metrics carried in routing metric container in the DIO control message.

Standardised objective functions support of QoS is limited. For this reason, an Objective Function based on Fuzzy Logic (OF-FL) is proposed in [3]. It specifies a holistic routing metric that effectively combines individual metrics to allow combinations between metrics that are different in nature. It takes into account 4 routing metrics, which are: end-to-end delay, hop count, ETX link quality, and node energy.

In [6], the authors tested both OF0 and the Link Quality Level Objective Function (LLQ OF). LLQ OF is based on the link quality metric, indicated by Received Signal Strength Indicator (RSSI) depending on the distance between communicating nodes. They concluded that OFs determine the network stability as well as the average number of hops and child nodes connected to each router, characterising the RPL overall structure. Hence, using OF0 which tries to minimise the hop count in a battery-powered network can lead to fast energy drain at the nodes closest to the root.

In [7], the authors proposed formulas to quantify primary routing metrics. Furthermore, they investigated combining primary metrics in a lexical or additive manner. A lexical composite routing metric leads to strict performance metric prioritisation, which can be used to ensure application requirements while other performance aspects can be optimised to a certain extent. On the other hand, an additive composite routing metric offers a flexible way of combining metrics based on the metric weight pair.

In [8], the authors proposed a load balanced objective function (LB-OF), which balances the data traffic based on the number of children of each potential parent.

IV. The Analytic Hierarchy Process Objective Function (AHP-OF)

RPL relies on the use of external Objective Functions for selecting the best route, which offers great flexibility in enabling QoS-aware routing and supports various application requirements [3]. Standardised objective functions OF0 and MRHOF are based on single routing metrics: for example, using only the Hop Count metric to construct the DODAG may form the shortest path towards the DOADAG root but it makes an inefficient use of the network resources,ignoring the need for load balancing and not taking the remaining nodes energy into account [3].

A. The Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a multicriteria decision making algorithm where ratio scales are driven from paired comparisons of options or criteria. It was developed by Saaty in 1971-1975 [9]. AHP reduces complex decisions to many pairwise comparisons and then synthesise the results.

The three principles for solving a problem using AHP are [9]:

1) **Decomposition:** the problem is structured to levels where the elements in a level are independent from those in succeeding levels.
2) **Comparative judgements:** pairwise comparisons of the relative importance of elements in a given level are constructed with respect to a shared criterion or property in the level above.
3) **Synthesising the priorities:** priorities are synthesised to give a composite or global priority of an element, which in turn is used to weight the local priorities of the elements compared to each other using it as the criterion.

B. DIO Packet format

In existing single-metric objective functions, only one routing metric/criteria is carried within the DIO control packet, because the latter has a single metric container field. By adding extra metric container fields to the DIO packet as in Figure 2, carrying multi-routing metric/criteria and applying multi-metric objective functions can be realised.

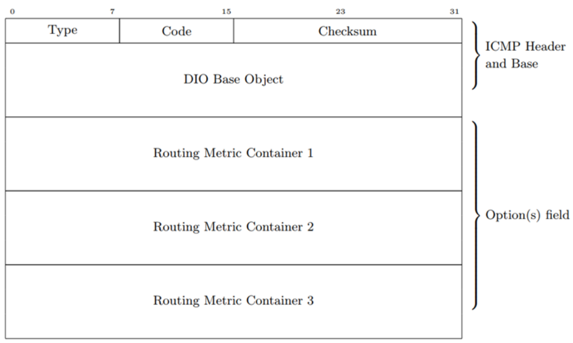

Figure 2: RPL DIO Control message with 3 routing metrics/constrains container

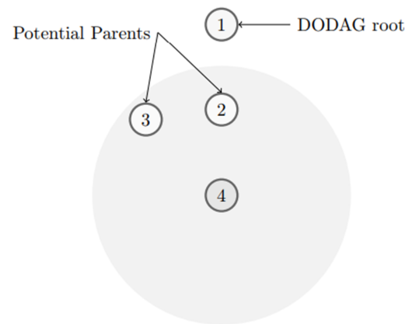

Figure 3: AHP-OF

C. Metrics Selection

Based on route properties the following will be the selected metrics/constraint to apply AHP-OF:

- **The Expected Transmission Count (ETX):** this metric is an indicator for the link quality between a node and its neighbour by measuring the number of transmissions needed to deliver a packet successfully. The higher the ETX value, the lower the link quality [4]. By using ETX, we can assure high reliability and low link latency.
- **Hop Count** (HP) indicates the number of traversed nodes along the path. With the combination with ETX, this can assure low end-to-end latency.
- **Node Energy** (NE) indicates the remaining battery level in nodes. By avoiding routing through nodes with low node energy, this can increase the network life time and hence achieving high availability.

D. AHP-OF functionality

Objective functions are responsible for assigning a node's Rank which is used by RPL to construct the DODAG. In general, each node should compute its own rank and then share it with its neighbours via a DIO message. To have a loop free DODAG, a parent node's rank should be lower than the rank of its child nodes. This can be achieved if the objective function works in an additive manner. So, whenever a node receives a DIO message from its potential parents which includes their rank, the node's own rank is computed as the preferred parent's rank added to the node's interpretation of its routing metrics.

Assuming that during the DODAG construction there is (Node 4), with 2 potential parents, (Node 2 and Node 3), within the node's range, as shown in Figure 3. Node 4 will receive a DIO message carrying the rank and 3 routing metrics from each of the potential parents. To select the preferred parent, Node 4 will run the AHP-OF to choose the preferred parent. AHP-OF would work as follows.

1) **Pairwise comparisons**
Assuming the performance requirements of an indoor WSN are reliability, low end-to-end latency, and a fair power consumption the routing metrics, can be ordered on relative importance as ETX, Node energy, Hop Count.
To give weight to each routing metric, a pairwise comparison is performed between the metrics based on the AHP scale in Table I. Results of the routing metric comparison are shown in Table II. The preference value of comparing a metric to itself is always 1. If the preference value of comparing ETX to Energy is 7, then the preference value of comparing Energy to ETX is 1/7.
For each routing metric AHP-OF will perform a pairwise comparison between the nodes based on the AHP scale shown in Table I. Results of the nodes comparison for ETX, Energy and Hop metrics are shown respectively in Tables IIIa, ,IIIb, and IIIc.

Table I: AHP Scale

Intensity of Importance	Numerical Value
Equal importance	1
Moderate importance	3
Essential or strong importance	5
Very strong importance	7
Extreme importance	9

Table II: AHP Criteria comparison

Criteria	ETX	Energy	Hop Count
ETX	1	7	3
Energy	1/7	1	1/5
Hop Count	1/3	5	1
Total	1 10/12	13	1 1/5

2) **Synthesising**
After carrying out the pairwise comparisons between the metrics and the nodes for each metric, results are synthesised as follows.

a) Sum the values in each column, as in Table II.
b) Divide each value in each column by the corresponding column total, as shown in Table IV.

Table III: Node AHP comparison. (a) ETX. (b) Energy. (c) Hop count.

(a)

Potential Parent	Node 2	Node 3
Node 2	1	5
Node 3	1/5	1
Total	1 8/15	9

(b)

Potential Parent	Node 2	Node 3
Node 2	1	5
Node 3	1/5	1
Total	1 12/35	6 1/3

(c)

Potential Parent	Node 2	Node 3
Node 2	1	3
Node 3	1/3	1
Total	1 10/21	13

c) Average the values in each row to provide a preference vector for the metrics, as shown in Table IV.

Table IV: AHP Criteria Synthesising

Criteria	ETX	Energy	Hop Count	Average (Preference Vector) ω
ETX	21/31	7/13	5/7	0.64339
Energy	3/31	1/13	1/21	0.07377
Hop Count	7/31	5/13	5/213	0.28284
Total	1	1	1	

3) **Compute an overall score for each decision alternative**

Assume that the potential parent's Rank is $PRank$, the Node ETX is $nETX$, Node Energy is $nEnergy$ and Node Hop Count is $nHOP$. from the Table IV Preference Vector, if the ETX Weight is $wETX$, Energy Weight is $wEnergy$ and Hop Count Weight is $wHOP$ then the node's overall score will be computed as follows:

$$\begin{aligned} NodeScore = PRank &+ nETX \times wETX \\ &+ nEnergy \times wEnergy \\ &+ nHOP \times wHOP \end{aligned} \tag{1}$$

4) **Rank the decision alternatives**
Based on the results of applying Equation 1, the minimum $NodeScore$ is assigned as the node's Rank and the potential parent associated with that will be the preferred parent.

V. Research Methodology

We chose to work on Cooja because of the RPL support, which is on the RFC 6550 [1] standard. In other tools this has not been officially implemented or added yet. In addition, compared to other tools, Cooja's features seem to be ahead in terms of supporting industrial WSN platforms and friendly GUI.

A. The simulation scenario

We used Cooja [10] as a simulation tool to build a network model, assumed to be installed in an indoors area of approximately (30x30 m^2). The network is constructed using wireless sensor Tmote Sky nodes. The nodes are assumed to be static wireless sensor motes that generate packets randomly with an average interval of 1 $packet/min$ where the transmission range is 10 m and the interference range up to 13 m.

For an hour of simulation time, we tested the performance of the RPL protocol in terms of node's average power consumption, packet loss ratio, average end-to-end latency and control packet ratio, for different objective functions.

B. Performance Metrics

The node-level performance metrics we measured are as follows:

- Power consumed by each node
- Average packet end-to-end latency, taken over received packets
- The number of packets sent by the node that failed to reach their destination (packet loss).

C. Results

Here we evaluate the performance of the new multi-metric OF MRHOF-AHP compared to the standardised single metric objective functions.

In Figure 4a we can see that most nodes have power consumption less than 100 mW. However, for OF0 this can rise to 180 mW and up to 200 mW in MRHOF-ETX. The same behaviour is observed for the other performance metrics as well, as in Figure 4b and Figure 4c. In MRHOF-AHP most node performance metric values almost never exceed the middle of the spectrum; the other OFs, however, have some nodes with high values implying heavy loading relative to the rest of nodes within the DODAG.

From Figure 4 we can say that MRHOF-AHP balances the load in an attempt to avoid the high spikes in certain nodes.

VI. Conclusion

In this paper, we presented a new objective function Analytical Hierarchy Processes OF (AHP-OF) to improve the DODAG construction and hence the performance in RPL, by taking into account a number of metrics. Based on our experiment using Cooja simulator, on a node level AHP-OF balances the load between the nodes within the DODAG. For future work, we will compare AHP-OF to other multi-metric OFs and study the performance of AHP-OF were the nodes are mobile.

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Table V: Node's metrics AHP Synthesis. (a) ETX. (b) Energy. (c) Hop count.

(a)

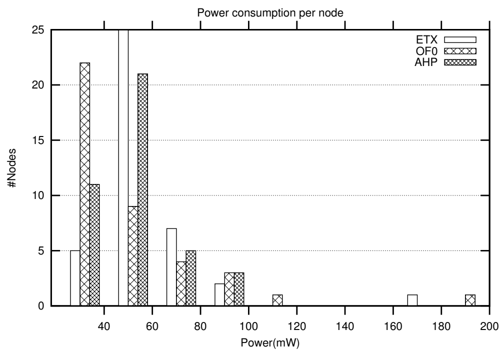
Potential Parent	Node 2	Node 3	Average
Node 2	15/23	5/9	0.63335
Node 3	3/23	1/9	0.10616
Total	1	1	

(b)

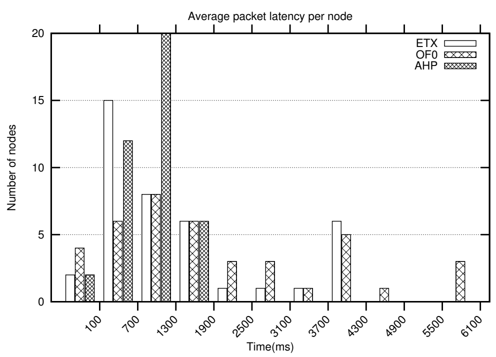
Potential Parent	Node 2	Node 3	Average
Node 2	35/47	15/19	0.72351
Node 3	7/47	3/19	0.19319
Total	1	1	

(c)

Potential Parent	Node 2	Node 3	Average
Node 2	21/31	5/7	0.64339
Node 3	7/31	5/21	0.28284
Total	1	1	



(a)



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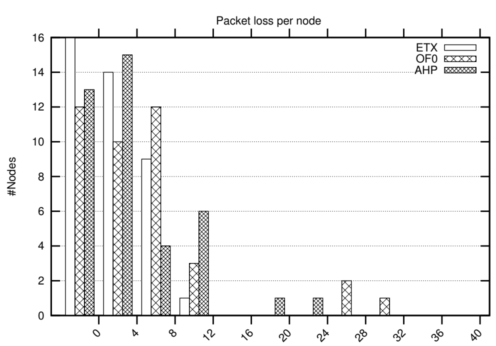

(c)

Figure 4: Node level performance. Here is a single case, where the network size is 40 nodes in addition to the sink. The Y axis represents the number of nodes within the network, while the X axis represents the measured performance metric (a) Node's power consumption. (b) Node's average end-to-end latency. (c) Node's packet loss.

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