Performance Evaluation of RPL Metrics in Environments with Strained Transmission Ranges

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***Abstract* – An examination of existing studies in the area of Routing Protocol for Low-Power and Lossy Networks (RPL) implementation in wireless sensor networks (WSNs) reveals a consistent approach taken of optimal node distribution. This in order to best evaluate networking metrics such as Packet Delivery Ratio (PDR), latency and energy consumption. The tests detailed in this paper differ from previous work, in that there is no concerted effort to ensure the appropriate density of the network topologies. The intention being to 'strain' the limits of the transmission ranges. Using the Cooja simulator, we take the approach of utilising nodes in less-than perfect, real-world scenarios. In this way the main factor at play is the ability to retain nodes as part of the Destination Oriented Directed Acyclic Graph (DODAG) build in environments with 'strained' transmission ranges. In this regard we compare Objective Function Zero (OF0) Hop-count with The Minimum Rank with Hysteresis Objective Function (MRHOF) Energy and expected transmission count (ETX) metrics. In utilising the energy metric, a novel approach, we prove that it is ineffective in this scenario. Resultantly, the ETX metric outperforms Hop-count, producing results that improve over time, adjusting to 'strained' environments to include more motes in the DODAG build as time passes. In conclusion, we propose future work to develop an extension to Cooja to utilise the ETX metric with an Energy constraint. This in order to better evaluate the use of node energy levels as part of a DODAG build in 'strained' WSN implementations in the future.**

***Keywords* – RPL, Cooja, OF0, MRHOF, ETX, Energy, Hop-count, Strained.**

I. Introduction

There can be little doubt that the world has moved into a new phase of internet technology. Now moving away from a rigid network infrastructure, towards a fully connected internet of smaller, smart devices known as the Internet of Things (IoT). Many examples can already be found such as mobile applications to control your heating at home [1]. The focus of this paper is the Low-Power and Lossy Network (LLN), in this case a WSN, where tiny, low-power devices, or sensors, are networked together, be that on the public or private internet. These networks are becoming widely used in industry such as oil and gas [2] or even in the exploration of other worlds [3].

At the Link-layer these devices can be connected in many ways with IEEE802.15.4 [4] the wireless standard for delivery of Link Layer frames across LLNs such as WSNs [5].

The need for a routing protocol to be used in these networks resulted in the establishment by the Internet Engineering Task Force (IETF) of the Routing Over Low power and Lossy networks (ROLL) working group [6]. This working group subsequently developed and standardised RPL [7]. RPL is a flexible and adaptive protocol, specifically designed with the propensity for link losses in WSNs in mind. These link losses are expected in WSNs with the potential for environmental factors coming into play, which could cause interference and therefore extreme link-instability, resulting in high levels of packet loss. In this case different principles must apply. RPL cannot overreact to packet loss by immediately recalculating routes, due to the limited power and data transfer rates available [8]. In terms of traffic flow, RPL supports multipoint-to-point (MP2P), important where many leaf nodes collect data, such as in a WSN. Also supported are point-to-multipoint (P2MP), and point-to-point (P2P) [7].

In regard to the establishment of the best route to a destination in RPL, RFC 6550 [7] specifies building a DODAG. A DODAG is a logical topology placed over a physical network of which there can be several and of which a node can be a member of multiple occurrences. An example of how multiple DODAGs are created can be seen in Figure 1. The characteristics of a DODAG will reflect Quality of Service (QoS) or constrained-based routing requirements in such that each DODAG 'instance' has a particular role to provide regarding routing across the physical network. A DODAG is built according to an OF [9], can utilise several different metrics and constraints and plays a significant role in the building of a DODAG instance.

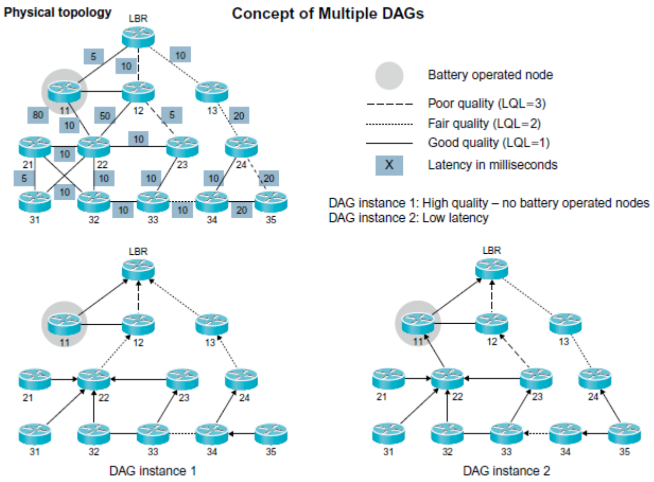

Figure 1. Example of multiple DODAG instances [8]

The aforementioned OFs, and the metrics and constraints utilised therein, are of greatest interest in this particular study. While an OF can be sole driver in DODAG construction, such as in “RFC6552: Objective Function Zero” for RPL [9], generally the OF uses metrics and constraints to build the DODAG and the routes within. This is the case with MRHOF [10], with RPL utilising constraint-based routing, such as energy and CPU levels or remaining memory capacity [8]. As such an OF may include or exclude routes depending on these requirements. In the case of RPL the use of constraints and metrics is combined into a routing object. For example the routing object could specify a constraint such that the OF should prune any paths with nodes below a certain memory capacity or could specify a metric such as hop-count. Within this study, both OFs currently standardised for use with RPL shall be utilised.

OF0 [9] is a default OF for RPL which does not, in fact, use a metric. Instead OF0 uses Rank to decide upon the preferred next hop. OF0 also utilises a ‘feasible successor’ in the event of the preferred successor not being available. In most installations of RPL this will produce similar results as if the ‘Hop-count’ metric was being used. Therefore it is recommended that actual dynamic metrics such as Link Quality Level Reliability or ETX are used [9].

MRHOF [10] again seeks to reduce the distance to a destination. However, unlike OF0, MRHOF utilises metrics in this regard. The OF itself is not an algorithm. In the case of MRHOF it determines the shortest path using the metrics, and/or constraints, carried within the metric container advertised in the Directed Acyclic Graph (DAG) container option in DODAG Information Object (DIO) messages [7]. If no metric is advertised in the DIO messages then MRHOF will default to the ETX metric [10]. However, MRHOF can use any of the metrics defined in RFC6551 [11] such as Hop Count, Link Latency, ETX, Node Energy or Throughput.

Recent studies aimed at evaluating the performance of RPL, with regard to the different OFs and metrics therein, have tended to focus on performance based on PDR, energy consumption and latency. Simulations are generally designed to organise the nodes within a WSN in the most effective way with regard to transmission ranges. This study, however, aims to take a completely different approach, in that the network topologies utilised within the simulations performed as part of this study have been designed in that the nodes are located at distances aimed to ‘strain’ their transmission ranges. The performance of the network in relation to RPL metrics is based on the ability to maintain nodes as part of the network after a set period of time. This is seen as of great importance given the ‘real-world’ implementations of WSNs and the possibility of inhospitable environments.

The remainder of this paper is divided into 4 sections. Section II summarises existing studies, highlighting the use of various simulation tools in the study of RPL. The different approaches taken to the testing of the performance of RPL are also examined, leading to the novel approach taken within this study. Section III details fully the approach taken to testing, graphically demonstrating both the network topologies utilised as well as all results in regard to the effect of different metrics on the percentage of nodes able to participate in the DODAG build. Section IV examines all results and what can be concluded from them and finally we outline the future work and the conclusion in Section V.

II. Related Work

There have been a variety of studies into the performance of RPL, as well as different ways of implementing the protocol and novel approaches to utilising RPL for future developments. The implementation of a “cross-layering design approach” [12], using a simulated implementation of RPL on the Contiki OS [13], is achieved by an exploration of the area each node inhabits in order to manage their neighbour tables. Also employed is link estimation [12]. This results in considerably better delivery rates and highlights the need for novel approaches to routing in the IoT in general.
With regard to energy-saving, this is the one area affected by all others. Poor data delivery, as previously commented on, will result in heavy energy consumption. The non-avoidance of loops is another area of concern as this can also lead directly to high energy consumption when not implemented correctly. *Karkazis et al* [14] use simulation to test the effects of combining primary and composite routing metrics, and propose a set of complex formulae to implement this. The result is a successful convergence to optimal loop-free paths within an LLN using the RPL protocol [14].

A fairly early thesis detailing an implementation of RPL in a WSN, and examining the Hop Count Object and Node Energy Object metrics [15], utilised the OMNeT++ simulation model [16]. OMNeT++ is not a simulator in the traditional sense but more a modular platform on which simulations can be built. Based around scripts written in C++, it is extremely flexible and particularly suitable for simulating mobile protocols such as Destination-sequenced Distance Vector (DSDV) [17] and Ad Hoc On-Demand Distance Vector (AODV) [18]. Several simulation models are available for OMNeT++ with Castalia [19] and MiXiM [20] particularly useful with regard to WSNs. However, this is generally in the use of routing-under at the MAC layer. To simulate routing of RPL, a network layer routing protocol, in OMNeT++ requires customisation of the code in order to replicate the way RPL behaves. The MiXiM module is utilised in [15] to demonstrate how the use of the hop count metric in RPL shall cause a faster depletion of energy within nodes than when using the node energy metric. To achieve this a considerable amount of programming is produced to replicate the RPL code. OMNeT++ is also utilised in [21]. The approach taken in this publication is to attempt improvements to RPL by implementing multipath routing in the form of three different schemes, each based on RPL. Those being Energy Load Balancing (ELB), Fast Local Repair (FLR) and a combination of both (ELB-FLR). What is explored in this paper is the consideration of a node of the same rank in the event of a parent node going down, or a “sibling” in the case of FLR. This can subsequently result in more efficient redundancy as it opens up a far greater choice of alternative routes than would previously have been available. In the case of ELB residual energy of nodes is used in calculating their rank as well as in routing. This means that the energy level is then an integral part of the decision making process when it comes to assigning parents, as higher residual energy will contribute to a lower rank. The ELB-FLR approach seeks to combine these two methods to result in a proposed new protocol, with high levels of redundancy and the always important issue of energy levels also accounted for [21]. In the case of simulation, the OMNeT++ simulator has a new IPv6 communication stack implemented utilising User Datagram Protocol (UDP) at the Transport layer, RPL and IPv6 over Low power Wireless Personal Area Networks (6LoWPAN) at the Network layer and non-beacon mode Carrier Sense Multiple Access (CSMA) at the Data-link layer with ContikiMAC [21]. ContikiMAC is implemented in the Contiki OS [13].

This leads to what has in recent studies become a widely used simulation software in the area of replicating the use of RPL, that being the Cooja simulator used within Instant Contiki 2.7 [13]. In regard to other simulation software available to replicate the behaviour of RPL, generally these were developed for other protocols and have required to be amended, sometimes unsatisfactorily, in order to produce results for RPL simulation. The attraction of the Cooja simulator is that the ContikiRPL model is seen as "the first real-world implementation of RPL" [22]. The ContikiRPL open-source code used in Cooja is the real code which is simulated on real nodes, thus providing a realistic and accurate simulation model which far exceeds the performance of other simulation software [23].

According to [23], one of the earlier studies to utilise ContikiRPL in the Cooja simulator, this study differed from others at the time in that it focused more on the actual construction of the network rather than individual variables. In this regard the ability to simulate large networks was of high importance. An evaluation of ContikiRPL found that general implementation was less complex. Also it was proven that a battery lifetime of several years was possible, as well as a high PDR [23]. By the standard of more recent studies the results of this particular study are not hugely revealing, in that they prove that power consumption of a DODAG increases in relation to the number of nodes and that a node consumes more energy depending on its position within the DODAG, regarding the number of neighbours it has. Thus the more routing the node must perform the more energy it consumes. It was also shown how the Average Hop Distance, Convergence Time and the size of each node's routing table could be directly related to the size of the network and the position of the DODAG root. With regard to Objective Function the study demonstrated that OF0, which builds a DODAG based on Rank, merely reducing the number of hops, is more effective with regard to hop-count reduction and power consumption than MRHOF. With MRHOF using the ETX metric in DODAG construction. However, with OF0 not considering network throughput, the possibility is raised of further OFs [23]. Studies of the performance of RPL have become more complex since this study took place in 2012, however, it demonstrates the constraints which were in place before the advent of ContikiRPL.

Where many implementations of RPL shall be within stationary WSNs there must also be regard paid to mobile implementations. The authors of [24] examine a topology where mobile sink nodes are utilised within an otherwise stationary WSN. The simulations within this paper demonstrated how power consumption increased greatly when the sink was mobile, and that performance factors such as latency and PDR were also greatly affected. The conclusion being that RPL is currently suitable for fixed node WSNs but that further investigation must take place with regard to mobility [24]. This paper utilises Cooja to demonstrate the differences in latency, PDR and Average Power Consumption (APC) depending on whether the sink is fixed or mobile and then on the particular mobility model, with the sink moving both in straight lines and in a circular fashion around the other nodes. Within the Cooja simulation the Unit Disk Graph Model (UDGM) was deployed. Simulations were performed for 10 and 15 minute timeframes and showed how power consumption was greater in tests using a mobile sink. What was also demonstrated was how PDR was significantly higher in a fixed node network overall but that latency had interesting results. In a network simulation where the sink node moved around the fixed nodes in a circle, latency was noticeably worse than a fixed network. However, in a simulation where the mobile node moved in a straight line through the fixed nodes the latency was shown to be much better than a fixed network.

One of the first studies to investigate the impact of the two Objective Functions, in combination with particular topologies and Packet Reception Ratio (RX), was [25]. This study demonstrated that performance can be optimised depending on the topology used, in this case random or grid, and that MRHOF can provide slightly better results in regard to PDR and energy consumption [25]. However, there is clearly room for further study with regard to different topologies and the various metrics and constraints used with MRHOF. Some of the ideas within this paper are built upon in the testing performed as part of this study.

Bringing research completely up to date, [22] demonstrates how Cooja is now seen as the logical choice for the simulation of RPL networks. This study proposes a proactive version of RPL, namely Pro-RPL, based on a "suffering index" [22] which is defined by RPL nodes' tendency to fail. With the aim being to predict the likelihood of failure, and therefore circumnavigate the issues that then follow. Among those being the buffering of data within a node until a link is re-established and the change of parentage within the DODAG. The operation of pro-RPL is thus; utilising information from DIO messages (used by RPL to build upward routes from leaf nodes to sink nodes) received from neighbouring nodes, the suffering index of each node's parent is calculated "based on the path cost from the parent to the root, the parent's neighbouring index, energy consumption and its number of alternative parents" [22]. This study is typical of many current studies to be found with regard to RPL and how to improve routing within WSNs. More novel approaches are now being taken in an attempt to address many of the inherent problems with RPL, and routing in WSNs in general. This would certainly appear to indicate the recent standardisation of RPL by the IETF should be seen as a baseline to build from, rather than a defined end-point in the development of this area [7].

Summary

The diversity of studies into the performance of RPL makes a direct comparison across all papers problematic. However, several observations can be made. Firstly in regard to the use of a particular simulator, in using the actual code utilised in real nodes, Cooja would appear to be the most realistic choice currently available. In terms of the performance of metrics, whilst both OF0 and MRHOF have both been utilised, only the ETX metric is used with MRHOF in any of the studies summarised. Finally, when measuring the performance of RPL it is clear that no consideration is given to the physical layout of the network other than all nodes should be well within range. This in order to measure metrics such as PDR, Latency and Energy Consumption. As such this led to the conclusion that a gap exists in research where the effect on a network where transmission ranges between nodes are 'strained' is examined. It was concluded that this study should utilise the Energy metric in Cooja, as well as hop-count and ETX. Finally, the performance metric should be that of the ability to retain nodes as part of the DODAG build.

III. Performance Evaluation

A. Introduction

Testing as part of this study is implemented using the Cooja simulator within Instant Contiki 2.7, not to be confused with the Contiki OS which is an actual operating system for use within real Wireless Sensors. As such, although the tests in this study are performed on simulation software, the nodes, or motes as referred to within Cooja, used in each simulation are compiled with the actual firmware used in physical versions of said motes [13]. Resultantly, each mote should behave as if in a real implementation of a WSN. Secondly, the performance of each mote is within the physical parameters of that mote type. In the case of the testing to be performed as part of this document, the most simple of the motes available for use within Cooja shall be used, that being the Tmote Sky sensor [26]. The Sky mote has integrated sensors as well as radio, antenna, microcontroller and programming capabilities. From the point of view of testing within this document one of the most important features is "Integrated onboard antenna with 50m range indoors / 125m range outdoors" [26].

In order to avoid ambiguity the term 'mote' is used throughout this section and on all graphs as opposed to 'node'. This is merely to replicate the language used within the Cooja simulator.

Testing within this document shall build on previous studies with the primary focus on the two OFs, OF0 and MRHOF. Within Contiki the use of OF0 effectively results in the use of Hop-count as a metric. In the case of MRHOF the ETX metric and another metric where the remaining Energy level of nodes is used are available in Cooja and both shall be utilised. As previously stated, this study approaches testing from a different angle from other studies. In this regard, the novel approach shall be taken of utilising 'strained' transmission ranges within topologies. This is with the intention of analysing the best performing OFs and metrics therein. From the analysis of the data recorded, the positives and negatives of each OF shall be discussed, as well as conclusions drawn as to potential future developments.

B. Testing Outline

As has been clearly illustrated, RPL has been tested in various scenarios. The approach taken in the testing within this document was to utilise all metrics available in relation to building a DODAG. In this regard both OFs have been used – OF0 [9] and MRHOF[10]. A particular OF utilises the metric advertised in DIO messages, with OF0 using rank which essentially results in the use of Hop-count and MRHOF defaulting to ETX. For the purpose of this testing the use of OF0 shall be referred to as using Hop-count. The use of MRHOF raises the possibility of utilising other metrics which may be within the Metric Container of a DIO. The Cooja simulator in the Instant Contiki OS [13] facilitates the use of the Energy metric when building a DODAG instance, taking into account the energy level of motes. Therefore, this allows the use of three different metrics with the possibility to compare the results across these.

Within the parameters of each metric the tests in this section utilise two different network layouts. Those being a tree formation with a sink mote at the top and a circular formation with the sink mote in the middle. These topologies are utilised with both 25 motes and 50 motes, with the location of the motes aimed at testing the ability of RPL to build a DODAG under certain conditions. More specifically, that the range between motes shall be random and often not ideal, in order to attempt to replicate possible issues in a physical environment. Previous testing has tended to control density of networks in order to keep control of scenarios and thus more easily compare results in regard to power consumption, PDR and latency. The testing performed as part of this dissertation deliberatively takes the approach of utilising less than perfect scenarios in order to 'strain' the networks in regard to transmission range. Therefore, with this in mind, the main factor examined within testing is of the number of motes lost in regard to taking any part in the DODAG build. To this end we examine the effect of each metric, to determine the significant factors in affecting the ability to build and maintain a DODAG instance in these circumstances. In particular this allows the comparison of the performance of the Energy metric to Hop-count and ETX, a relatively novel approach.

Each scenario is run over 10 and 20 minutes to examine the effect of each metric as time passes. Finally, each scenario is run with two different transmission ranges. Firstly a transmission range of 70m and an interference range of 90m, secondly a transmission range of 50m and an interference range of 100m.
In addition to these parameters more specific observations will be made regarding power levels of particular nodes and what can be observed from the particular scenario.

C. Test Parameters

The parameters for testing are shown in Table 1. Four tests are performed, with each test utilising a particular topology and number of motes. These topologies using the aforementioned transmission and interference range combinations, all of which is illustrated in Table 1. Tests 1 and 2 comprise of 1 sink and 24 senders, whereas Tests 3 and 4 comprise of 1 sink and 49 senders, with all tests performed over 10 and 20 minutes. All topologies are designed with the intention of 'straining' these transmission ranges in that communication between motes should not be optimal. The main difference in the topologies is that in Tests 1 and 3 a tree topology is utilised, whereas in Tests 2 and 4 a circular topology is in use.
The 10m grid demonstrates the distance between motes of between 30m and 50m, as can be observed in Figures 2-9.

Test Parameters	Values		
Objective Functions	OF0	MRHOF	
Metrics	Hop-count	ETX	Energy
TX Range/INT Range	70m/90m, 50m/100m		
Topologies	Tree (Sparse), Circle (Sparse)		
Simulation Times	10 minutes, 20 minutes		
Number of Nodes	25, 50		
Mote Type	Tmote Sky		
Wireless Channel Model	UDGM		

Table 1. Test Parameters

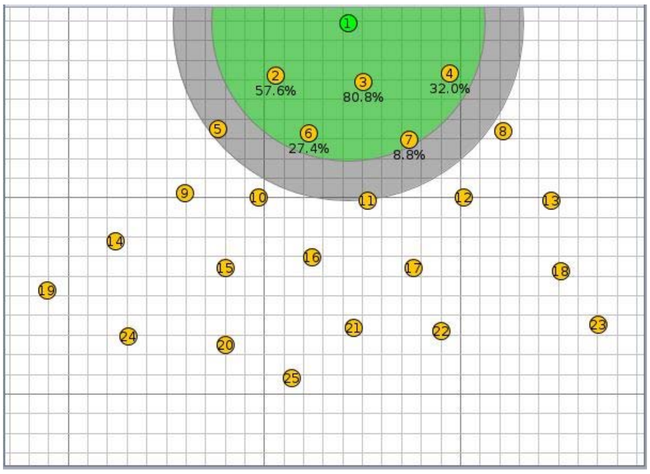

Figure 2. Test 1 with 70m, 90m Transmission, Interference Ranges

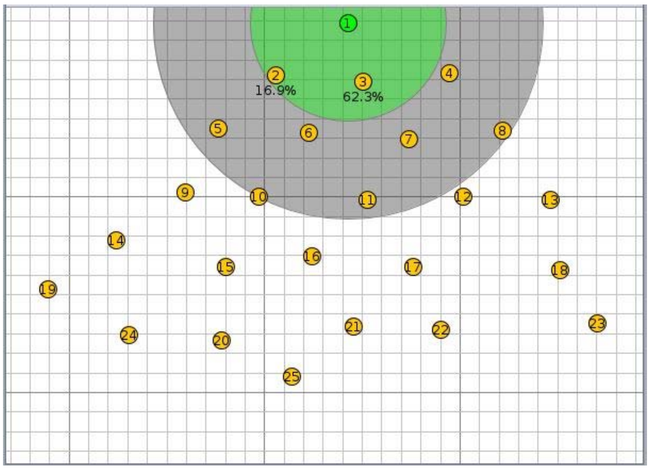

Figure 3. Test 1 with 50m, 100m Transmission, Interference Ranges

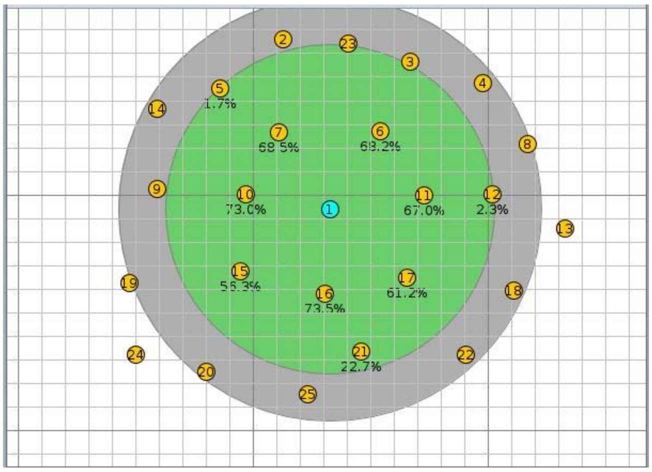

Figure 4. Test 2 with 70m, 90m Transmission, Interference Ranges

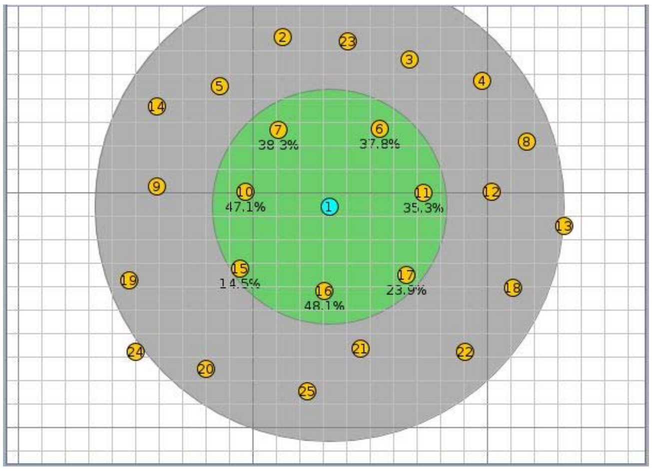

Figure 5. Test 2 with 50m, 100m Transmission, Interference Ranges

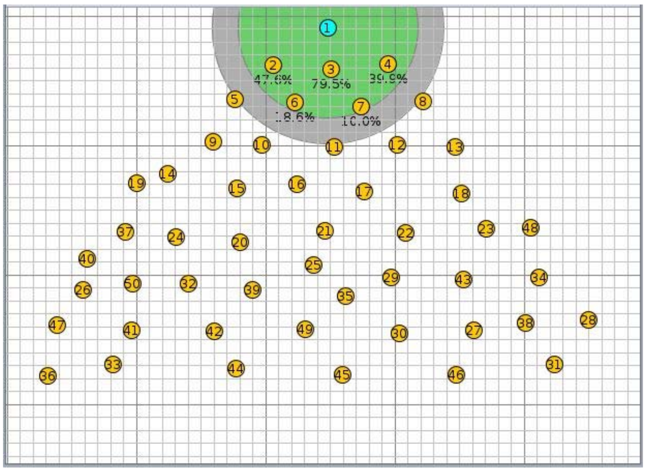

Figure 6. Test 3 with 70m, 90m Transmission, Interference Ranges

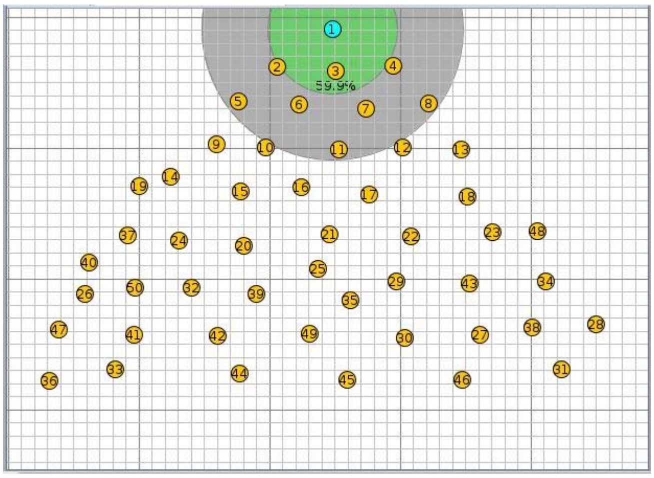

Figure 7. Test 3 with 50m, 100m Transmission, Interference Ranges

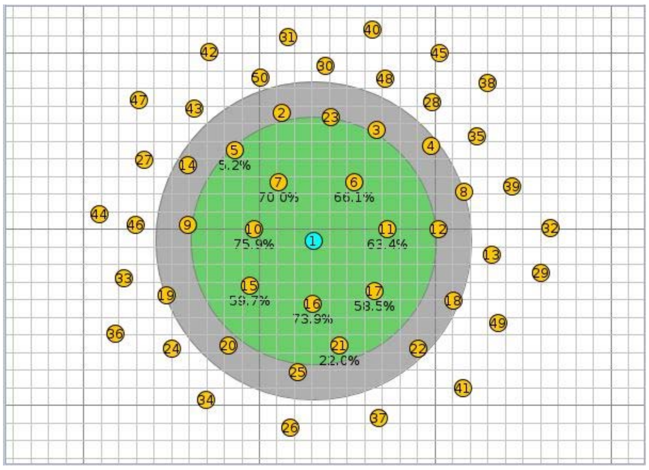

Figure 8. Test 4 with 70m, 90m Transmission, Interference Ranges

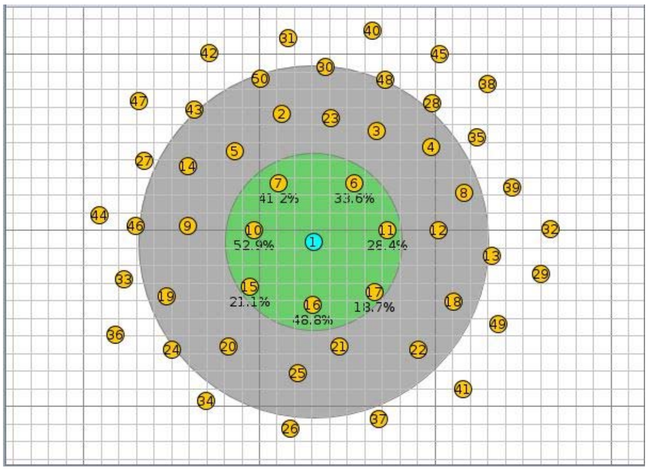

Figure 9. Test 4 with 50m, 100m Transmission, Interference Ranges

D. Results

Test 1

The results in relation to Mote Loss are compared across the four different test runs as part of Test 1. The results can be observed in Figure 10. What is immediately clear is that the change to a transmission/interference range of 50m/100m from 70m/90m has a major effect on the ability of RPL to build and maintain a DODAG instance. What this demonstrates is that when motes are only within the interference range of each other it causes great difficulty in exchanging messages to a degree that a DODAG can be maintained. In regard to the different metrics in use it can be observed that the Energy metric loses the greatest number of motes in all scenarios, losing over 70% of motes in the 50m/100m scenario over 20 minutes. What can be observed regarding the Hop-count and ETX metrics is that both perform better over greater periods of time, with mote loss decreasing in the 20 minute scenarios. Even for the more challenging 50m/100m scenario, by the time the scenario has been running for 20 minutes, RPL using MRHOF with the ETX metric has 76% of the motes making up the DODAG.

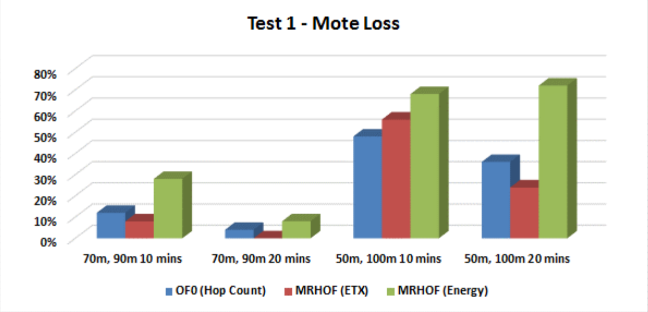

Figure 10. Test 1 Mote Loss

Test 2

The results in relation to Mote Loss are compared across the four different test runs as part of Test 2. The results can be observed in Figure 11. What should be considered firstly is that the scale of this graph is far smaller than in Test 1, with no scenario suffering mote loss above 30% for any of the metrics used. Again the change to a transmission/interference range of 50m/100m from 70m/90m has an effect on the ability of RPL to build and maintain a DODAG instance, but not to the extent of the tree topology utilised in Test 1. This demonstrates the greater variety of routes available to the sink mote in this topology, even when the transmission range is reduced. In regard to the different metrics in use, the only relevance is in regard to the 50m/100m scenario as there is no loss of motes whatsoever at the end of both runs of the 70m/90m scenario. In regard to the 50m/100m scenario again it is the Energy metric which performs worst, although to a lesser degree than in Test 1. Again both ETX and Hop-count perform well the longer the scenario runs for. Hop-count in particular has no loss of motes at all after 20 minutes.

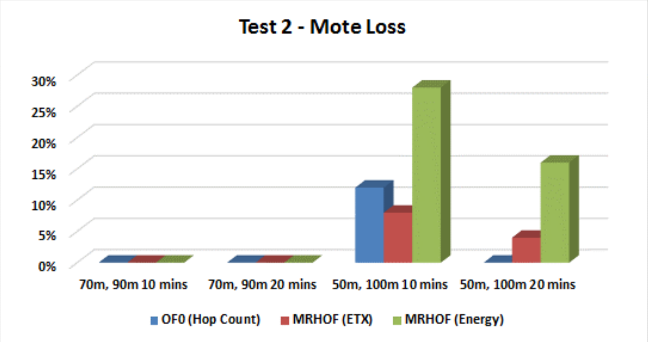

Figure 11. Test 2 Mote Loss

Test 3

The results in relation to Mote Loss are compared across the four different test runs as part of Test 3. The results can be observed in Figure 12. What can be immediately observed regarding the topology is that the 50m/100m suffers catastrophic mote loss irrespective of the timeframe, to the point where it can be concluded that this scenario is not viable. This scenario would have to be improved with regard to mote density regardless of which metric is utilised. Alternatively, the 70m/90m scenario performs slightly better initially, although the Energy metric again suffers from major loss of motes. As the time progresses from 10 minutes to 20 minutes the Energy metric does improve slightly but the ETX metric improves greatly.

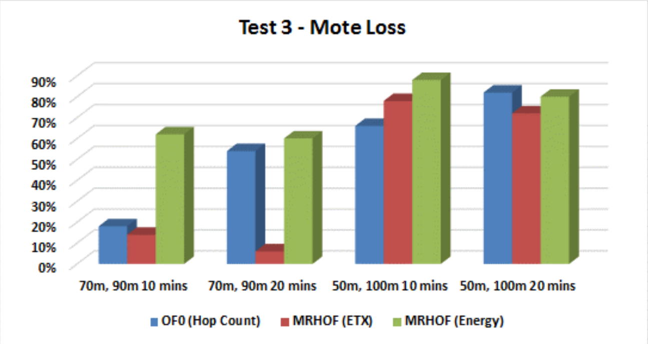

Figure 12. Test 3 Mote Loss

Test 4
The results in relation to Mote Loss are compared across the four different test runs as part of Test 4. The results can be observed in Figure 13. It could be argued that this scenario demonstrates most effectively the difference in performance with regard to mote loss across the three different metrics used. Again the poor performance of the Energy metric is clear, even in the almost ideal 70m/90m scenario where ETX and Hop-count lose very few motes by the end of the 20 minute test. Moving to the 50m/100m scenario there is a catastrophic loss of motes when utilising the Energy metric. However, whereas the Hop-count metric still endures losses of 32% reducing to 24%, the ETX metric sees losses move from 14% to only 6% in a less than ideal network scenario.

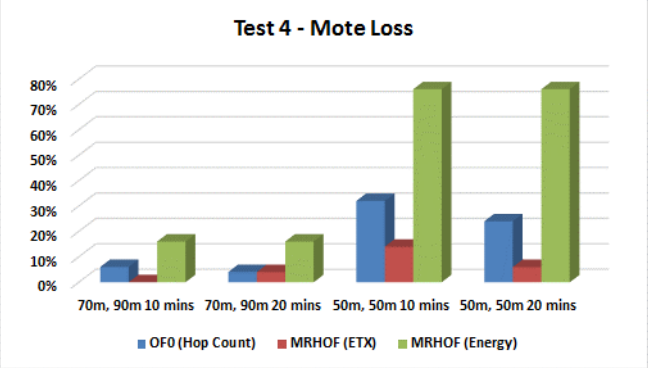

Figure 13. Test 4 Mote Loss

IV. Final Evaluation

The topologies utilised within this study have been designed with the aim of 'straining' the transmission ranges of motes. In this regard the ability to maintain motes within a DODAG under these conditions is of greatest interest. Therein, we evaluate the performance of the use of Energy as a metric as part of MRHOF, in comparison to the use of the more commonly used ETX within MRHOF and Hop-count as part of OF0. The effectiveness and particular requirements of each topology are also be examined. Observing the performance of the Energy metric across all tests it is immediately apparent, that in terms of maintaining motes within a DODAG, it is far less effective than Hop-count or ETX. When considered logically this should not be surprising. The motes utilised within the networks are battery-powered and as time passes the power levels decrease. If the sole metric used to determine the best path to the sink mote is one which utilises the remaining energy levels within motes then issues would appear unavoidable. The 1-hop motes, and any other which may be the parent mote in a bottleneck situation, will obviously use more energy than others due to the higher levels of processing involved. This is an obvious issue when considering energy levels in order to establish parentage, and therefore establish the optimum path to the sink mote. In this regard it can be concluded that the Energy metric is not effective when used alone. Some results would render the network virtually useless and it is clear that this only worsens over time.

Contrastingly, the other metric utilised by MRHOF, that of ETX, performs very well in regard to sustaining motes within a network of strained transmission ranges. This is particularly true versus the use of OF0 and Hop-count over longer periods. This again would seem logical in this scenario given that the ETX metric seeks to avoid the lowest quality links in the network [11], rather than taking a blunt-force approach of merely utilising the shortest path to the sink mote. In conclusion, in a topology where the transmission ranges of motes are strained, a metric of the remaining energy levels of motes is ineffective on its own. Over a longer period of time it would appear any network utilising this metric in these conditions would eventually be rendered useless. Of interest going forward would be to comprise testing where Energy and ETX are used together. It may be that this could be best achieved by utilising Energy as a constraint rather than a metric. Greater depth of investigation is required in this area as the Cooja simulator would appear to provide a more simplistic use of metrics than that described in "RFC 6719: The Minimum Rank with Hysteresis Objective Function" [10] and "RFC6551: Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks" [11]. Cooja also does not provide a facility to utilise constraints within MRHOF as a matter of course, therefore some manipulation of code would be required. This would also be the case in regard to combining the Energy and ETX metrics.

With regard to the topological layout of the tests within this paper, it can be concluded that a circular layout results in better performance in regard to maintaining the number of motes. It is clear that a tree layout puts considerably greater strain on first-hop motes and can also cause other bottlenecks within the network. In conclusion, node density is extremely important in a tree formation and should be given careful consideration as part of the initial design.

V. Conclusion

This series of tests differ from previous work in this area in two regards. Firstly, there is no concerted effort to ensure the appropriate density of the network topologies, with the intention of straining the limits of the transmission ranges. Secondly, the use of an Energy metric with MRHOF to bring a comparison with OF0 and MRHOF using ETX.

When considering a sparse, strained network topology it can be concluded that the optimum metric for use with RPL, in terms of maintaining the maximum number of motes, is the MRHOF with ETX. In regard to the Energy metric it can be concluded that it is highly ineffective in this environment. It may be that there are benefits to be gleaned from using this metric in a more controlled environment. *Alwassi, Qasem, Yassein and Al-dubai* [25] aim to determine the optimal RX when using OF0 and MRHOF with ETX. It could be of interest to repeat these tests with the Energy metric to determine any possible benefit.

In regard to the Cooja simulator it is clear that there is an issue when considering the ability to properly utilise MRHOF in particular. Currently only the ETX and Energy metrics are available, however, there is also currently no framework to utilise the use of constraints. In regard to this study in particular, in order to fully test a WSN layout within a 'strained' environment, the use of the ETX metric with an Energy constraint is required. This study proposes an extension to the current Cooja code in order to build upon the studies within this paper.

References

[1] "Hive." [Online]. Available: https://www.hivehome.com/. [Accessed: 22-Mar-2016].

[2] CENSIS, "Low cost self-learning wireless gas sensors for building, healthcare and oil and gas applications." [Online]. Available: http://censis.org.uk/censis_projects/gss_gcu/. [Accessed: 03-Mar-2016].

[3] NASA, "NREN (NASA Research and Engineering Network)," 2006. [Online]. Available: http://www.nren.nasa.gov/adhoc.html. [Accessed: 03-Mar-2016].

[4] "IEEE 802.15.4," 2016. [Online]. Available: http://www.ieee802.org/15/pub/TG4.html. [Accessed: 22-Mar-2016].

[5] G. Montenegro, N. Kushalnagar, J. Hui, and D. Culler, "RFC4944: Transmission of IPv6 Packets over IEEE 802.15.4 Networks," 2007.

[6] IETF, "Routing Over Low power and Lossy networks (roll) -." [Online]. Available: http://datatracker.ietf.org/wg/roll/charter/. [Accessed: 16-Oct-2015].

[7] T. Winter, P. Thubert, A. Brandt, J. Hui, R. Kelsey, P. Levis, K. Pister, R. Struik, J. Vasseur, and R. Alexander, "RFC6550: RPL: IPv6 Routing Protocol for Low-Power and Lossy Networks," 2012.

[8] J.-P. Vasseur and A. Dunkels, "RPL Routing in Smart Object Networks," in *Interconnecting Smart Objects with IP*, 2010, pp. 111–116.

[9] P. Thubert, "RFC6552: Objective Function Zero for RPL," 2012.

[10] O. Gnawali and P. Levis, "RFC 6719: The Minimum Rank with Hysteresis Objective Function," 2012.

[11] M. Kim, D. Barthel, J. Vasseur, and et al, "RFC6551: Routing Metrics Used for Path Calculation in Low-Power and Lossy Networks," 2012.

[12] E. Ancillotti, R. Bruno, and M. Conti, "Reliable Data Delivery With the IETF Routing Protocol for Low-Power and Lossy Networks," *IEEE Trans. Ind. Informatics*, vol. 10, no. 3, pp. 1864–1877, 2014.

[13] Contiki, "Contiki: The Open Source Operating System for the Internet of Things," 2015. [Online]. Available: http://www.contiki-os.org/. [Accessed: 09-Nov-2015].

[14] P. Karkazis, P. Trakadas, H. C. Leligou, L. Sarakis, I. Papaefstathiou, and T. Zahariadis, "Evaluating routing metric composition approaches for QoS differentiation in low power and lossy networks," *Wirel. Networks*, vol. 19, no. 6, pp. 1269–1284, 2013.

[15] S. Hammerseth, "Implementing RPL in a mobile and fixed wireless sensor network with OMNeT++.," pp. 1–101, 2012.

[16] "OMNeT++ Discrete Event Simulator," 2015. [Online]. Available: https://omnetpp.org/. [Accessed: 09-Jan-2016].

[17] G. He, "Destination-sequenced distance vector (DSDV) protocol," *Netw. Lab. Helsinki Univ. Technol.*, pp. 1–9, 2002.

[18] C. Perkings, E. Belding-Royer, and S. Das, "Ad hoc On-Demand Distance Vector (AODV) Routing," *IETF RFC 3561*, pp. 1–37, 2003.

[19] Castalia, "Castalia - Wireless Sensor Network Simulator." [Online]. Available: https://castalia.forge.nicta.com.au/index.php/en/. [Accessed: 16-Jan-2016].

[20] "MiXiM," *Sourceforge.net*. [Online]. Available: http://mixim.sourceforge.net/. [Accessed: 18-Jan-2016].

[21] Q. Le, T. Ngo-Quynh, and T. Magedanz, "RPL-based multipath Routing Protocols for Internet of Things on Wireless Sensor Networks," in *2014 International Conference on Advanced Technologies for Communications (ATC 2014)*, 2014, pp. 424–429.

[22] N. Khelifi, S. Oteafy, H. Hassanein, and H. Youssef, "Proactive maintenance in RPL for 6LowPAN Proactive Maintenance in RPL for 6LowPAN," in *Wireless Communications and Mobile Computing Conference (IWCMC*, 2015, no. 2015 International, pp. 993–999.

[23] O. Gaddour, A. Koubaa, S. Chaudhry, M. Tezeghdanti, R. Chaari, and M. Abid, "Simulation and performance evaluation of DAG construction with RPL," in *3rd International Conference on Communications and Networking, ComNet 2012*, 2012.

[24] I. Wadhaj, I. Kristof, I. Romdhani, and A. Al-dubai, "Performance Evaluation of the RPL Protocol in Fixed and Mobile Sink Low-Power and Lossy-Networks," in *14th IEEE International Conference on Ubiquitous Computing and Communications*, 2015.

[25] H. Altwassi, M. Qasem, M. B. Yassein, and A. Al-dubai, "Performance Evaluation of RPL Objective Functions," in *IEEE International Conference on Ubiquitous Computing and Communications*, 2015, no. October.

[26] Moteiv Corporation, "Moteiv: tmote sky low power wireless sensor module," *Tmote Sky Data Sheet*, 2006. [Online]. Available: http://www.eecs.harvard.edu/~konrad/projects/shimmer/references/tmote-sky-datasheet.pdf. [Accessed: 13-Feb-2016].