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Performance Evaluation of Routing Protocol for Low Power and Lossy Networks (RPL)
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Abstract

This document presents a performance evaluation of the Routing Protocol for Low power and Lossy Networks (RPL) for small outdoor and for a large scale smart meter network. Detailed simulations are carried out to produce several routing performance metrics using a set of real-life scenarios.

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1 Terminology

PDR - Packet Delivery Ratio

Fractional Stretch Factor of link ETX Metric against ideal shortest path - The ETX path stretch is defined as the difference between the number of Expected Transmission (ETX Metric) taken by a packet travelling from source to destination following a route determined by RPL and a route determined by the hypothetical ideal shortest path routing protocol (using link ETX as the metric). The fractional path stretch is the ratio of ETX path stretch to ETX path cost for the shortest path route for that source-destination pair.

Stretch factor for node hop distance against ideal shortest path - The hop stretch is defined as the difference between the number of hop counts taken by a packet traveling from source to destination, following a route determined by RPL and a route determined by a hypothetical ideal shortest path algorithm, both using ETX as the link cost. The fractional stretch factor is computed as the ratio of path stretch to hop count value between a source-destination pair for the hypothetical shortest path route optimizing ETX path cost.

Please refer to additional terminology in [I-D.ietf-roll-terminology].

2 Introduction

Designing routing for low power devices and lossy link networks (LLNs) imposes great challenges, mainly due to low data rates, high probability of packet delivery failure, and strict energy constraint in nodes. The IETF ROLL Working Group took on this task and specified the Routing Protocol for Low power and Lossy Networks (RPL) in [I-D.ietf-roll-rpl].

RPL is designed to meet the core requirements specified in [I-D.ietf-roll-home-routing-reqs],[I-D.ietf-roll-building-routing-reqs],[I-D.ietf-roll-indus-routing-reqs] and [RFC5548].

This document's contribution is to provide a performance evaluation of RPL with respect to several metrics of interest. This is accomplished using real data and topologies in a discrete event simulator developed to reproduce the protocol behavior in detail.

The following metrics are evaluated in this document:

- Path quality metrics;
- Control plane overhead;
- End to End delay between nodes.
- Ability to cope with unstable situations (link churns, node dying);
- Required resource constraints on nodes (routing table size, etc.).

Feedback from the ROLL Working Group are welcome to add new evaluation metrics of potential interest in further revisions of this document.

Although simulation cannot formally prove that a protocol operates properly in all situations, it can give a good level of confidence in protocol behavior in highly stressful conditions, if and only if real life

data are used. Simulation is particularly useful when theoretical model assumptions may not be applicable to such networks and scenarios. In this document, real deployed network data traces have been used to model link behaviors and network topology.

3 Methodology and Simulation Setup

RPL is simulated using OMNET++ [OMNETpp], a well-known discrete event based simulator written in C++ and NED. Castalia-2.2 [Castalia-2.2] has been used as Wireless Sensor Network Simulator framework within OMNET++. The output and events in the simulating are visualized with the help of the Network AniMator or NAM, which is distributed with NS (Network Simulator) [NS-2].

Note that NS or any of its versions are not used in this simulation study. Only the visualization tool was borrowed for verification purposes.

In contrast with theoretical models, which as stated before may have assumptions not applicable to lossy links, real-life data has been used for two aspects of the simulations:

- * Link failure model: Time varying real network traces containing packet delivery probability for each link over all channels for both indoor network deployment.

- * Topology: Gathered from real-life deployment (traces mentioned above) as opposed to random topology simulations.

A 45 node topology, deployed as an outdoor network, shown in Figure 1 and a 2442 node topology, gathered from a deployment of smart meter network, was used in the simulations.

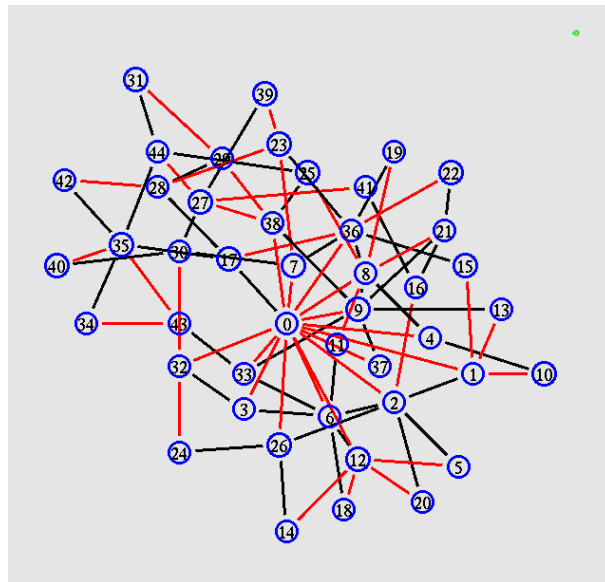


Figure 1: 45 nodes outdoor network topology.

Note that this is just a start to validate the simulation before using large scale networks.

A database of time varying link quality data, gathered from real network deployment, was created. Each link in the topology 'picks up' the same link model from the database corresponding to real model in deployment. Each link has a Packet Delivery Ratio (PDR) that varies with time (in the simulation, a new PDR is read from the database every 10 minutes) according to the gathered data. Packets are dropped randomly from that link with probability $(1 - \text{PDR})$. Each time a packet arrives at the Radio of a node, the module generates a random number by the Mersenne Twister Random number generation method. The random number is compared to the PDR to determine whether the packet should be dropped. Note

that each link uses a different random number generator to maintain true randomness in the simulator, and to avoid correlation between links. Also, the packet drop applies to all kinds of data and control packets (RPL) such as the DIO, DAO, DIS packets defined in [I-D.ietf-roll-rpl]. Figure 2 shows some typical temporal characteristics of some links in the network for the indoor network trace used in the simulations.

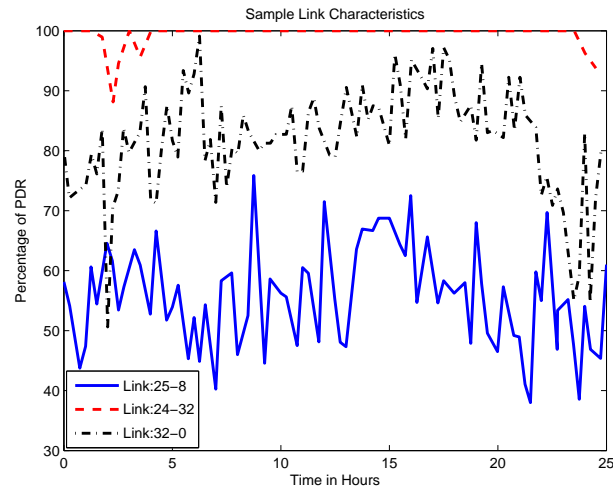


Figure 2: Example of link characteristics.

In the RPL simulator, the LBR first initiates sending out DIO messages, and the DAG is gradually constructed. RPL makes use of trickle timers: L_{min} is initially set to 1 second and $L_{doubling}$ is equal to 16, so that maximum time between two consecutive DIO emissions by a node (under a steady network condition) is 18.2 hours. The trickle time interval for emitting DIO message assumes the initial value of 1 second, and then changes over simulation time as mentioned in [I-D.ietf-roll-rpl].

Another objective of this study is to give insight to the network administrator on how to tweak the trickle values. These recommendations could then be used in applicability statement documents.

Each node in the network, other than the LBR, also emits DAO messages as specified in [I-D.ietf-roll-rpl], to initially populate the routing tables with the prefixes received from children via the DAO messages to support Point to Point (P2P) and Point to Multipoint traffic (P2MP) in the “down” direction. In this revision of the document, it is assumed that each node is capable of storing route information for other nodes in the network. In further revisions, nodes without storage capability will be added to the network to see the influence of extra states on the nodes and the additional control plane overhead to propagate the route records given by Reverse Route Stacks in the DAO messages.

For nodes implementing RPL, as expected, the routing table memory requirement varies according to the position in the DAG. The worst-case assumption that there is no route summarization in the network is made. Thus a node closer to the DAG will have to store more routing entries. Further revision of this document will explore the influence of performing route summarization along the DAG, which could be performed thanks to a newly defined Objective Function or new address provisioning techniques. It is also assumed that all nodes have equal memory capacity to store the routing states, therefore no source routing is required.

For Simulation of the indoor network, each node sends traffic according to a Constant Bit Rate (CBR) to all other nodes in the network, over the simulation period. To simulate a more realistic scenario, 20%

of the generated packets by each node are destined to the root, and the remaining 80% of the packets are uniformly assigned as destined to nodes other than the root. Therefore the root receives a considerably larger amount of data than other nodes. These values may be revised when studying P2P traffic so as to have a majority of traffic going to all nodes as opposed to the root. In the later part of the simulation, a typical home/building routing scenario was also simulated, and different path quality metrics were computed for that traffic pattern.

The packets are routed through the DAG built by RPL according to the mechanisms specified in [I-D.ietf-roll-rpl].

A number of RPL parameters are studied (such as Packet Rate from each source, Time Period of the LBR emitting new DAG Sequence Number) to observe their effect on the performance metric of interest.

4 Performance Metrics

4.1 Common Assumptions

As the DAO messages help to feed the routing tables in the network, they grow with time and size of the network. Nevertheless, a constraint was not imposed on the size of this table nor on how much information the node can store. Currently, the routing table size is not expressed in terms of Kbyte of memory usage but measured in terms of number of entries for each node. Each entry has the next hop node and path cost associated with the destination node. In further revision of this document, a single full 128-bit address per leaf plus a few bits to store other information and flags will be used.

The link ETX (Expected Transmission Count) metric is used to build the DAG as specified in [I-D.ietf-roll-routing-metrics]. Further revisions of this document will include other metrics and constraints such as the hop count.

4.2 Path Quality

Number of Hops: For each source-destination pair, the average number of hops for both RPL and shortest path routing is computed. Shortest path routing refers to a hypothetical ideal routing protocol that would always provide the shortest path in term of Total path cost ETX (or whichever metric is used) in the network. The Cumulative Distribution Function (CDF) of hop distance for all paths ($n*(n-1)$ in an n -node network) in the network with respect to the number of hops is plotted in Figure 3 for both RPL and shortest path routing. One can observe that the CDF corresponding to 4 hops is around 55% for RPL and 90% for shortest path routing. In other words, for the given topology, 90% of paths have a path length of 4 hops or less with an ideal shortest path routing methodology, whereas in RPL Point-to-Point (P2P) routing, 90% of the paths will have a length of no more than 5 hops. This result indicates that despite having a non-optimized P2P routing scheme, the path quality of RPL is not much worse than an optimized one. Another reason for this may relate to the fact that, the sink is at the center of the network, thus routing through the sink is often close to an optimal (shortest path) routing. This result may be different in a topology where the sink is located at one end of the network.

Path Cost ETX: The path cost ETX of the path is computed for each source-destination pair. Figure 4 shows the CDF of the total number of ETX to deliver a packet from a source to any destination

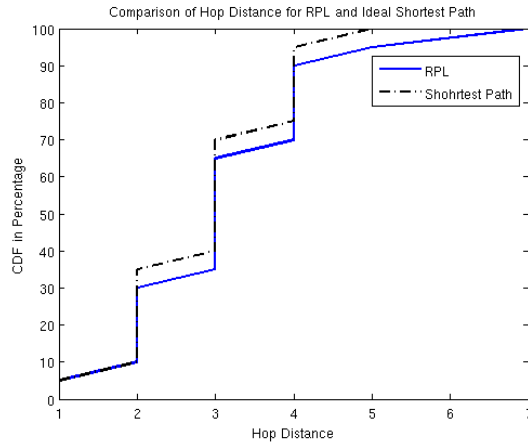


Figure 3: CDF: hop distance versus number of hops.

node with respect to total ETX of the path from each source to each destination in the network, for both RPL and shortest path routing. Here also one observes that the total path cost ETX along the path from all source to all destination is close to that of a shortest path routing for the network in the simulation.

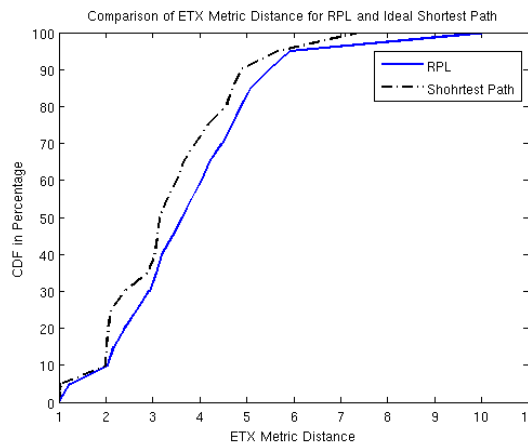


Figure 4: CDF: Total ETX along path versus ETX value.

Path Stretch: In this simulation, the path stretch is also calculated for each packet that traversed the network. The path stretch is determined as the difference between the number of hops taken by a packet while following a route built via RPL and the number of hops taken by shortest path routing (using link ETX as the metric). Once again, the CDF of path stretch is plotted against the value of path stretch for different packets in Figures 5 and 6 for hop count stretch and ETX metric stretch respectively.

4.3 Routing Table Size

The objective of this metric is to observe the distribution of the number of entries per node. Figure 7 shows the CDF of the required number of routing table entries for all nodes. One can see, that 90% of the nodes need to store less than 10 entries in their routing cache.

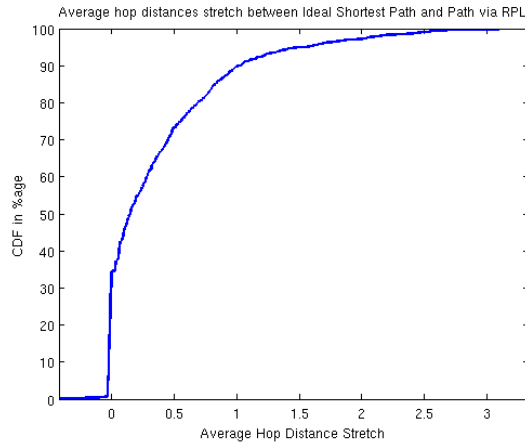


Figure 5: CDF: Hop count stretch versus hop count of a packet.

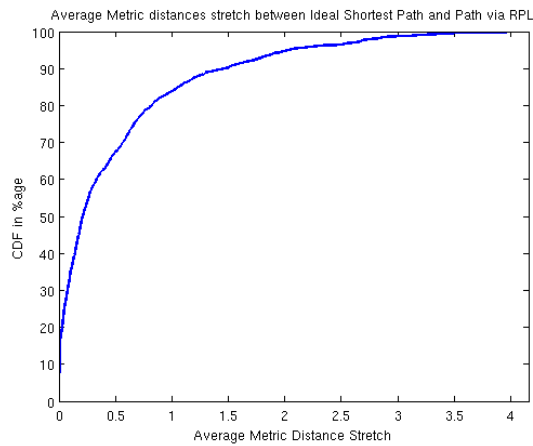


Figure 6: CDF: ETX metric stretch versus ETX value.

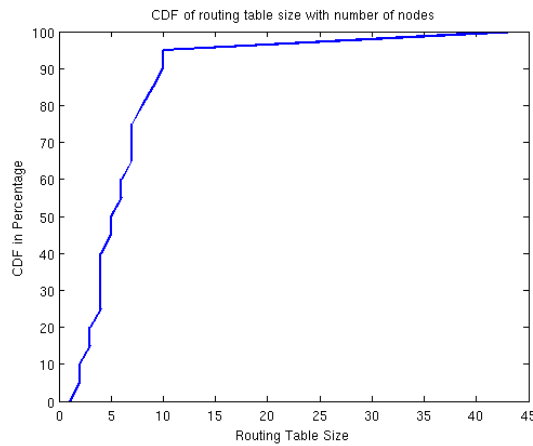


Figure 7: CDF of routing table size with respect to number of nodes.

4.4 Delay bound for P2P Routing

For delay sensitive applications, such as home and building routing, etc., it is also important to limit the end-to-end delay. Figure 8 shows the upper bound and distributions of delay in P2P routing between any two given nodes when RPL is employed for different hop counts between source and destination. Here, the hop count refers to the hop distance when RPL is employed and not shortest path distance between two nodes. Each packet has a length of 127 bytes, with a 240 kbps radio, which makes the transmission time to be approximately 4 ms.

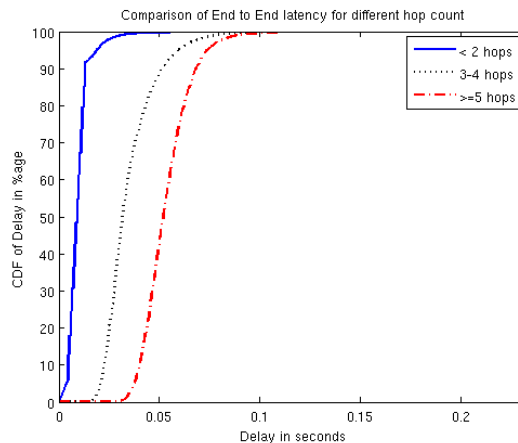


Figure 8: Comparison of packet latency for different hop count in RPL.

4.5 Control Packet Overhead

The control plane overhead is an important routing metric in LLNs. It is imperative to bound the control plane overhead. One of the distinctive characteristics of RPL is that it makes use of trickle timers so as to reduce the number of control plane packets by eliminating redundant messages. The aim of this metric is thus to analyse the control plane overhead in stable condition (no network element failure overhead) and in the presence of failures.

Data and control plane traffic comparison for each node: Figure 9 shows the comparison of the amount of data packets transmitted (including forwarded) and control packets (DIO and DAO messages) transmitted for each node when minimizing ETX is used by the OCP along the DAG. Here one can observe that considerable amount of traffic is routed through the sink itself. This result also reinforces the fact that the amount of control traffic in the protocol is negligible. As expected, the nodes closer to sink and that act as forwarders handle much more data packet transmission than other nodes. The leaf nodes have comparable amount of data and control packet transmission, as they do not take part in routing data.

Data and Control Packet Transmission with Respect to Time: In Figures 10, 11 and 12, the amount of data and control packets transmitted for node 12 (low rank in DAG, closer to the root), node 43 (in the middle) and node 31 (leaf node) are shown, respectively. These values stand for number of packets transmitted for each 10 minute intervals, to help understand what is the density of data and control packet exchange in the network. One can observe that nodes closer to the sink have larger amount of data, and the amount of control traffic is negligible in comparison to the data traffic. Also, the variation in data traffic is much larger for a node closer to the sink, because the destination of the packets varies over time,

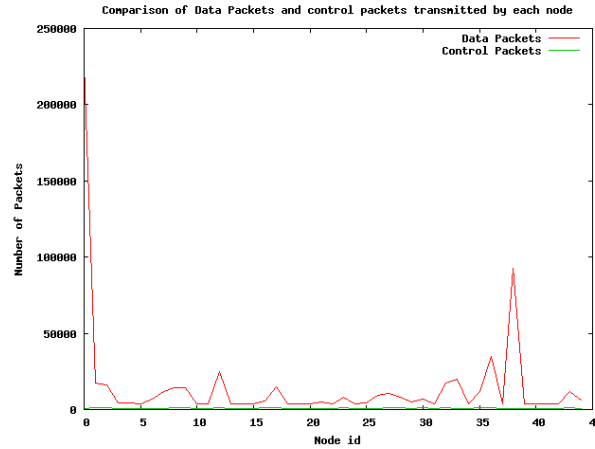


Figure 9: Amount of data and control packets transmitted for each node when minimizing ETX is used OCP along the DAG.

and 20% of the packets are destined to sink only. For the nodes that are further away from the sink, the variation in data traffic becomes smaller, and the amount of data traffic is also smaller.

The control traffic exhibits a wave-like pattern. The amount of control packets for each node drops quickly as the DAG stabilizes due to the effect of trickle timer. However, as a new DAG Sequence is advertised, the trickle timers are reset and the nodes start emitting DIO frequently again to stabilize the DAG. In a node closer to sink, the amount of data packets is much larger than that of control packets, and somewhat oscillatory around a mean value. The amount of control packets exhibits a 'saw-tooth' behavior, mainly because the ETX link metric was used, and because when the PDR changes, the ETX path cost for a child node to its parent changes, which results in changing the DAG rank of the child. This event resets the trickle timer and triggers the emission of new DIO. Therefore, one can observe that the number of control packets attains a high value for one interval, and the amount comes down to lower values for subsequent intervals. Also, for leaf nodes the amount of control packets are more than data packets, as leaf nodes are more prone to face changes in their DAG rank as opposed to nodes closer to sink when the link PDR in the topology changes dynamically.

4.6 Loss of connectivity

Upon link failures, a node may lose his parents: preferred and backup (if any) and its sibling (if any). In this case, if a packet has to be sent and the routing table does not contain an entry for the corresponding destination the packet is dropped. RPL proposes two mechanisms for DAG repairs, known as Global Repair and Local Repair. In this version of the document, simulation results are presented to evaluate the amount of time packets are lost because of loss of connectivity for two cases: *a*) when only Global Repair mechanism is implemented (i.e. of periodic emission of new DAG Sequence number by the DODAG root), and *b*) when poisoning the sub-DAG is used in case of unreachability of any parent or sibling node to forward data along with Global Repair mechanism. The idea is to tune the frequency at which new DAG Sequence Numbers are generated by the DAG root that are used for Global Repair, and also to observe the effect of the same when local repair is used in conjunction. It is expected that a higher frequency will lead to shorter duration of connectivity loss at a price of a higher rate of control packet in the network. For local repair, the simulation results show the trade-off in amount of time that a node may remain without service

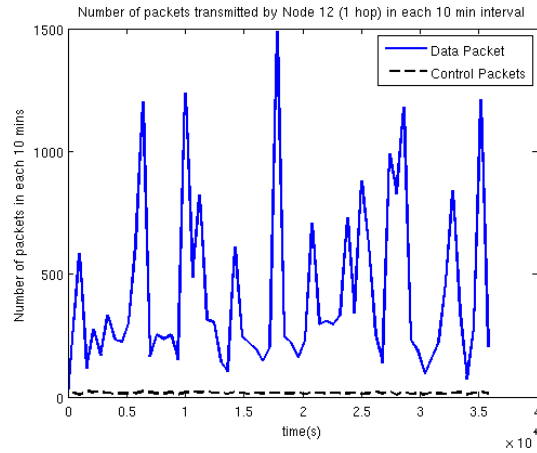


Figure 10: Amount of data and control packets transmitted for node 12.

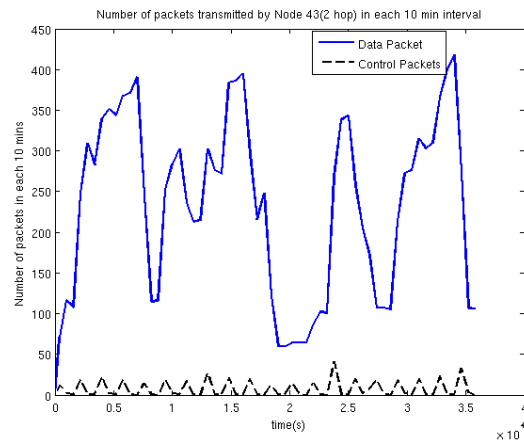


Figure 11: Amount of data and control packets transmitted for node 43.

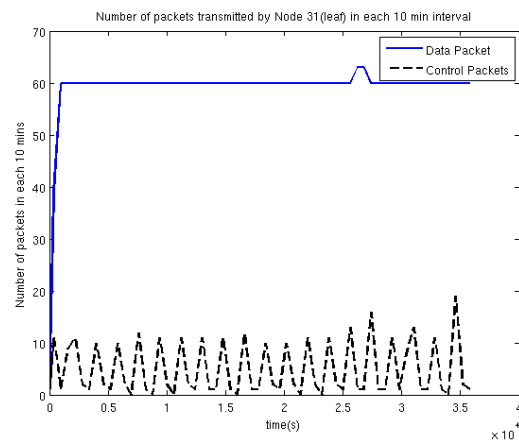


Figure 12: Amount of data and control packets transmitted for node 31.

and total number of control packets for extra bit of signalling.

Figure 13 shows the CDF of time spent by any node without service, when the packet rate from the sources is a packet each 10 seconds, and new DAG Sequence Number is issued every 10 minutes. This plot reflects the property of Global Repair without any local repair scheme. When all the parents (and siblings) are temporarily unreachable from a node, the time before it hears a DIO from another node is recorded, which gives the time without service. In some cases, this value might go up to the DAG Repair Timer value, because until a DIO is heard, there is a lack of connectivity.

The effect of the DAG Repair Timer on time without any service is plotted in Figure 14, where the source rate is 20 seconds/packet and in Figure 15, where the source sends a packet every 10 seconds.

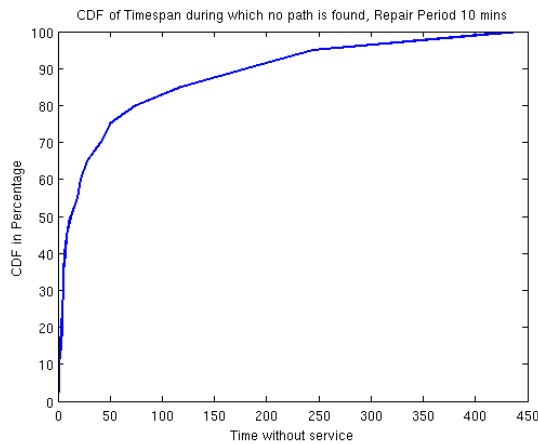


Figure 13: CDF: Loss of connectivity.

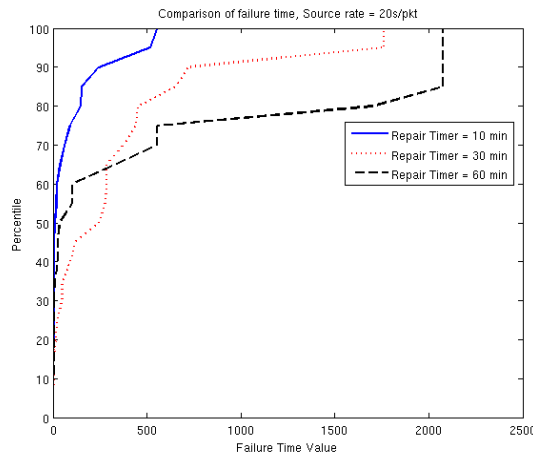


Figure 14: CDF: Loss of connectivity for different global repair period, packet rate 20/s.

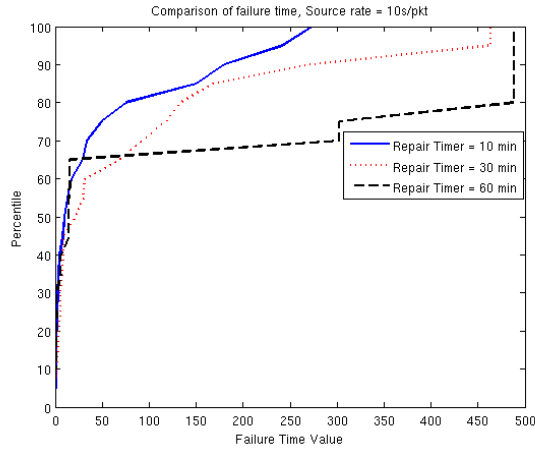


Figure 15: CDF: Loss of connectivity for different global repair period, packet rate 10/s.

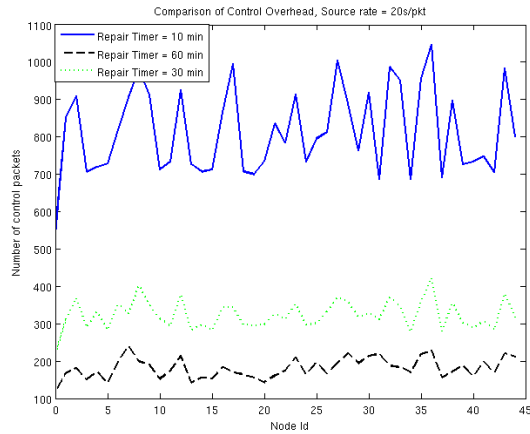


Figure 16: Amount of control traffic for different global repair timer period.

Figure 16 shows the effect of DAG global repair Ttimer period on control traffic. As expected, as the frequency at which new DAGSequenceNumber are generated increases, the amount of control traffic also decreases because the trickle interval gets larger for each node, which is pretty intuitive. However this smaller amount of control traffic comes at a price of increased time for loss of connectivity.

The effect of the DAG repair timer on time without service, when local repair is present, is plotted in 17, where the source rate is 20 seconds/packet. A comparison of the CDF of loss of connectivity for global repair mechanism and global + local repair mechanism is shown in Figures 18 and 19 (semilog plots), where the source generates a packet every 10 seconds and 20 seconds respectively. In the plots, one can observe that using the method of poisoning the sub-DAG greatly reduces the time without connectivity.

A comparison between the amount of control overhead used for global repair only and global plus local Repair mechanism is shown in Figure 20, which highlights the improved performance of RPL in terms of convergence time at very little extra overhead.

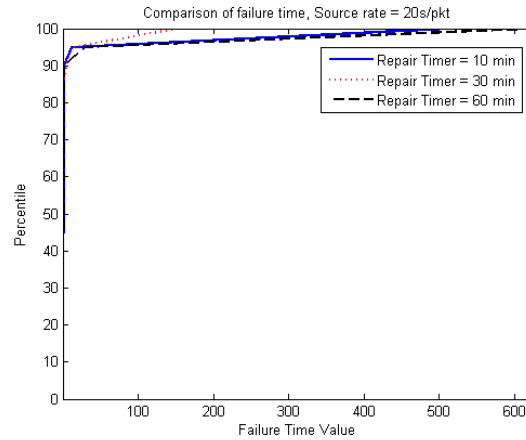


Figure 17: CDF: Loss of connectivity for different global repair period with poisoning, packet rate 20/s.

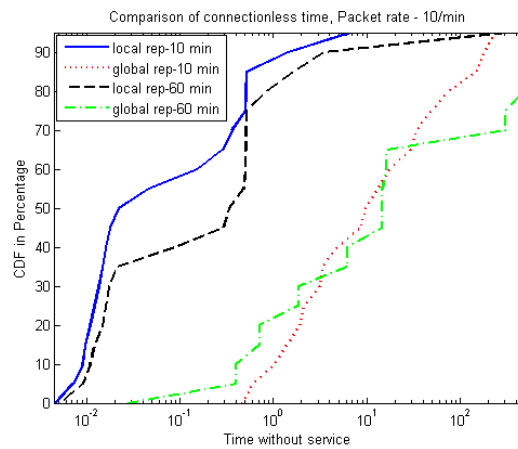


Figure 18: CDF: Comparing loss of connectivity for global repair and poisoning, packet rate 10/s.

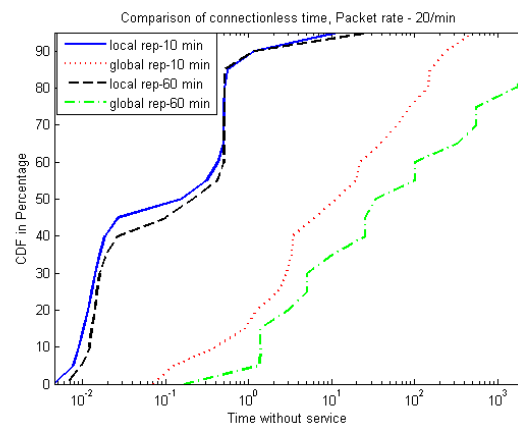


Figure 19: CDF: Comparing loss of connectivity for global repair and poisoning, packet rate 20/s.

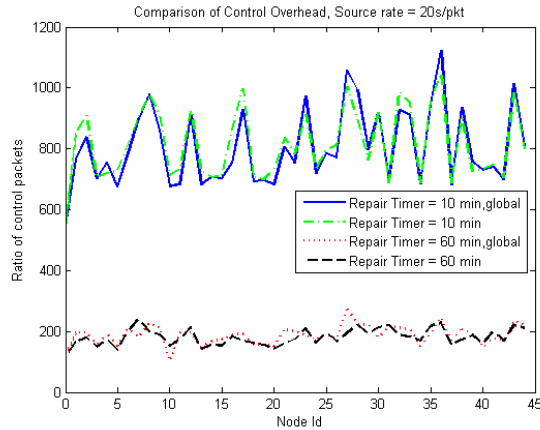


Figure 20: Number of control packets for different DAG Seq Number period, for both global repair and poisoning.

5 RPL in a building routing scenario

Unlike the previous traffic pattern, where a majority of the total traffic generated by any node is destined to the root, this section considers a different traffic pattern, which is more prominent in home or building routing scenario. A node sends 60% of its total generated traffic to its physically 1-hop distant nodes, 20% of traffic to its 2-hop distant nodes. The rest of the traffic is once again distributed among all other nodes in the network. The CDF of average hop distance path stretch in terms of hop distance, ETX path cost and delay for P2P routing for all pair of nodes is calculated. The delay bound is more important in this scenario, as the applications in home and building routing has typically low delay tolerance.

5.1 Path Quality

Figure 21 shows the CDF of number of hops for both RPL and ideal shortest path routing for the traffic scenario described above. Figure 22 shows CDF of the expected number of transmission count for each packet to reach destination. Figures 23 and 24 show CDF of the stretch factor for these two metrics.

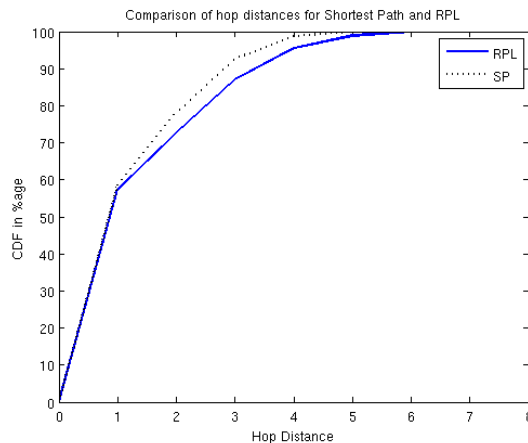


Figure 21: Comparison of end-to-end hop distance for RPL and ideal shortest path in home routing.

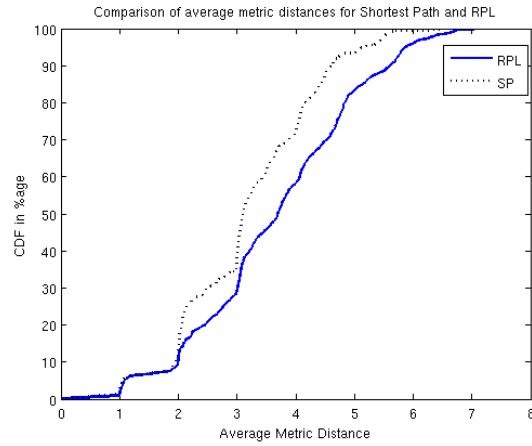


Figure 22: Comparison of link ETX metric for RPL and ideal shortest path in home routing.

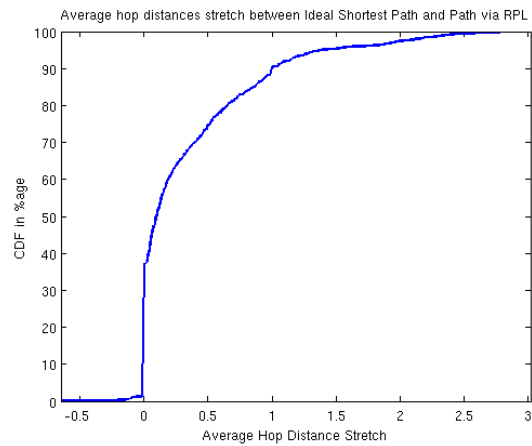


Figure 23: Stretch factor for node hop distance with ideal shortest path.

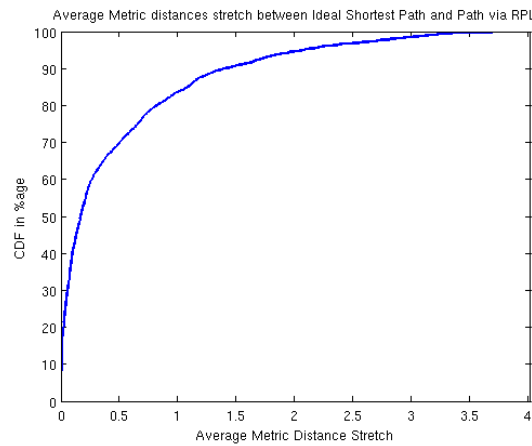


Figure 24: Stretch Factor of link ETX Metric with ideal shortest path.

5.2 Delay

To get an idea of maximum observable delay in the mentioned traffic pattern, the delay for different number of hops to the destination for RPL is considered. Figure 25 shows how the end-to-end packet latency is distributed for different packets with different hop counts in the network.

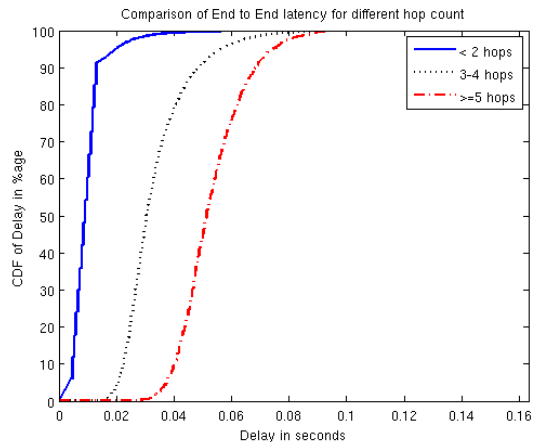


Figure 25: Comparison of packet latency for different hop count in RPL.

6 RPL in a Large Scale Network

In this section we focus on analyzing how RPL operates in a large network by focusing on a few metrics: the latency and path cost stretch for performance and the amount of control packets for scalability. RPL is simulated in a 2442 node smart meter network to observe the effect of these metrics as the network size grows larger. We also use the corresponding gathered link traces to simulate the packet drop pattern in the network. To simulate a more realistic scenario for a smart meter network, 100% of the generated packets by each node are destined to the root, and no traffic is generated for nodes other than the root.

6.1 Path Quality

To investigate whether RPL scales well with the size of the network, the Cumulative Distribution Function (CDF) of ETX path cost in the large scale smart meter network is compared to an ideal hypothetical shortest path routing protocol which minimizes the total ETX count over the path (Figure 26). In this simulation, the path stretch is also calculated for each packet that traversed the network. The path stretch is determined as the difference between the number of Expected Transmission (ETX Metric) taken by a packet while following a route built via RPL and the same metric taken by shortest path routing (by using link ETX as the metric). Here, the CDF of fractional path stretch, which is determined as the path stretch value over the path cost of an ideal shortest path, is plotted in Figure 27. The same fractional path stretch value for hop distance is shown in Figure 28.

6.2 Delay

Figure 29 shows how the end-to-end packet latency distributed for different packets with different hop counts in the network.

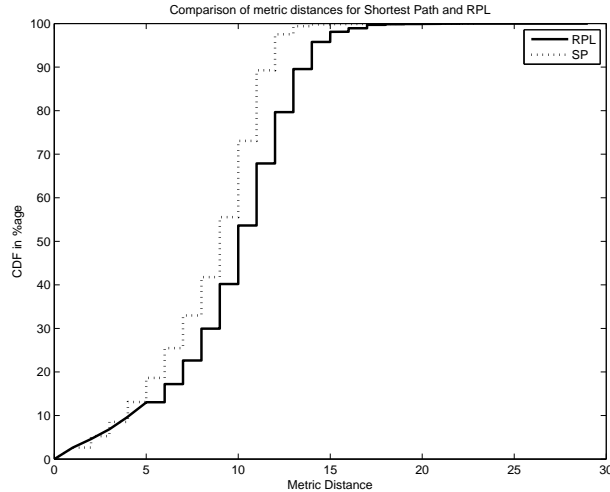


Figure 26: CDF of Total ETX Path cost vs ETX value

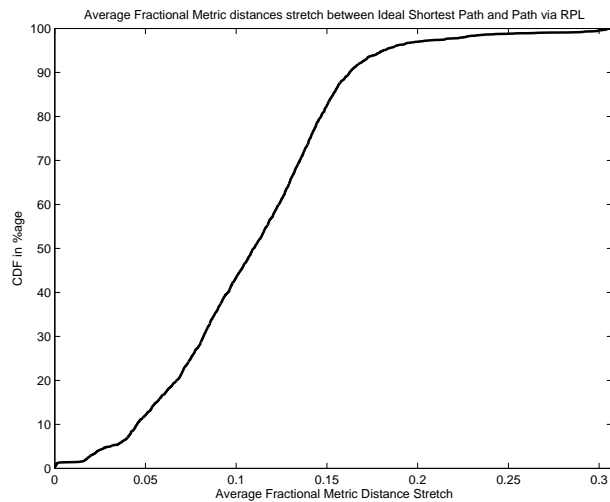


Figure 27: CDF of Fractional stretch in ETX Path cost

6.3 Control Packet Overhead

Figure 30 shows the comparison of the amount of data packets transmitted (including forwarded) and control packets (DIO and DAO messages) transmitted for each node when minimizing ETX is used as the link metric to optimize the DAG. Here one can observe that in spite of the large scale of the network, the amount of control traffic in the protocol is really negligible in comparison to data packet transmission. Also, as expected, we can observe from Figures 31, 32, 33 that the nodes closer to sink and that act as routers have much more data packet transmission than other nodes. The leaf nodes have comparable amount of data and control packet transmission, as they do not take part in routing the data. As seen before, the data traffic for a child node has much less variation than the nodes which are closer to the sink. This variation decreases with increase in DAG depth.

In Figure 34, the effect of global repair period timer on control packet overhead is shown.

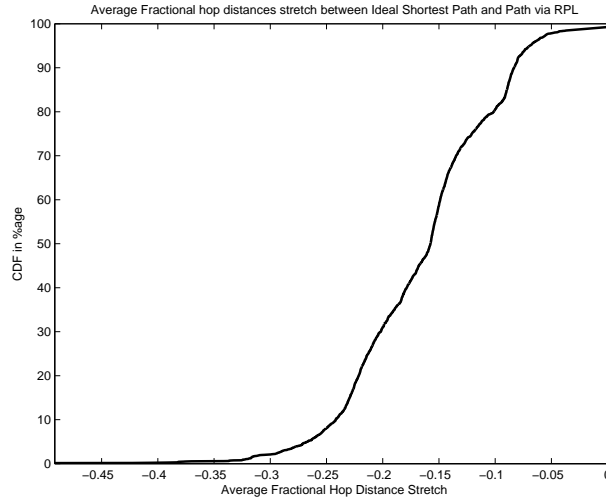


Figure 28: CDF of Fractional stretch in Hop count

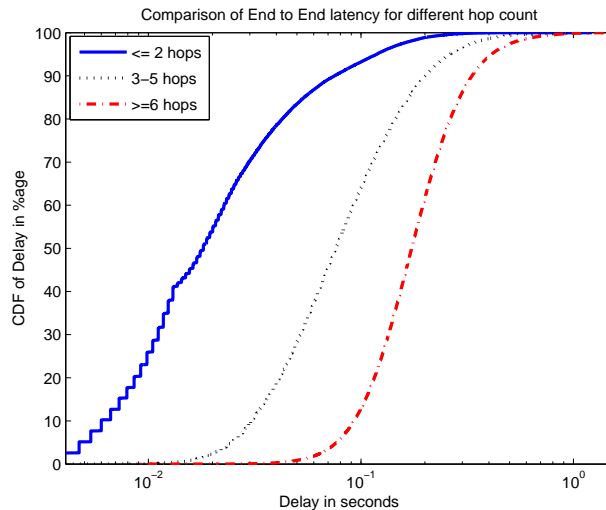


Figure 29: End to End packet delivery latency for different hop count

7 Scaling Property and Routing Stability

An important metric of interest in low power devices is the maximum load experienced by any sensor node CPU in terms of number of control packets transmitted by the node. Also, to get an idea of scaling property of the network, it is also crucial to analyze the amount of packets handled by the nodes for different sizes of network. In this simulation, at any given interval, the node with maximum control overhead load is identified. In this draft, the amount of maximum control overhead processed by that node is plotted against time for three different network under study. The first one is Network ‘A’, which has 45 nodes and is shown in figure 1 in section 3 ; Network ‘B’, which is another deployed outdoor network with 86 nodes; and finally, Network ‘C’, which is the large deployed smart meter network being considered in this draft. In figure 35, the comparison of maximum control load is demonstrated for different network scale.

For a network built with low power devices with lossy links, it is important that the routing information is not flooded to the entire network, and that the routing structure is kept as stable as possible. Any change in routing information, specially parent-child relationship, would reset the timer to emit new DIOs, and

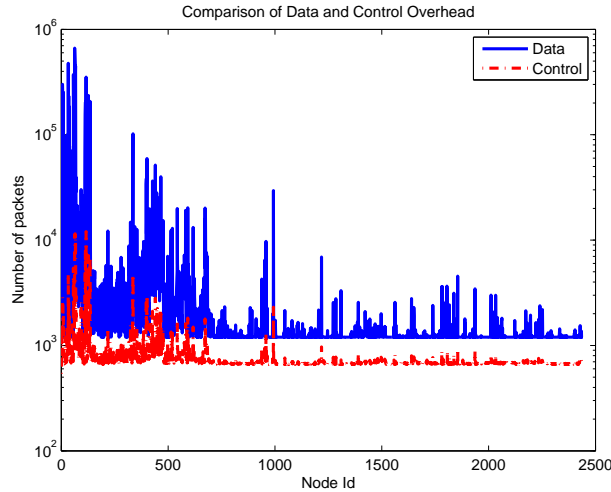


Figure 30: Data and Control Packet comparison

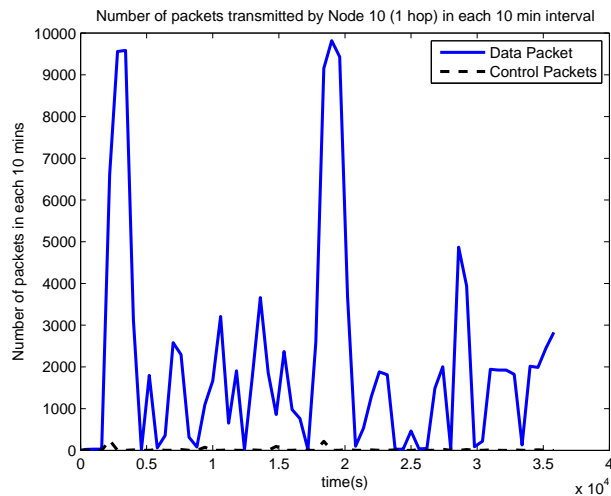


Figure 31: Data and Control Packet over time for Node 1

hence, change the node’s path metric to reach the root. This change will trigger a large number of control information broadcasts in the sub-DAG, and would multiply its way to the leaves of the network. Therefore, it is important to consider the correct moment for triggering new DIO control packets, and accordingly define a threshold to control when it should be inevitable to release new RA-DIOs with reset timers.

In this study, the effect of the tolerance value before emitting new RA-DIO with new metric value to root is analyzed to help answer the question, “ How much change should the protocol ignore?”. Four cases are considered in this study to compare the path stretch factor and change in routing path.

- No change in DAG depth of a node is ignored.
- The implementation ignores 10% of change, so that if the change in depth due to DIO reception from a parent is less than 10%, the node will not advertise the new metric to the root,
- The implementation ignores 20% change in the DAG depth of a node before deciding to advertise a new depth.

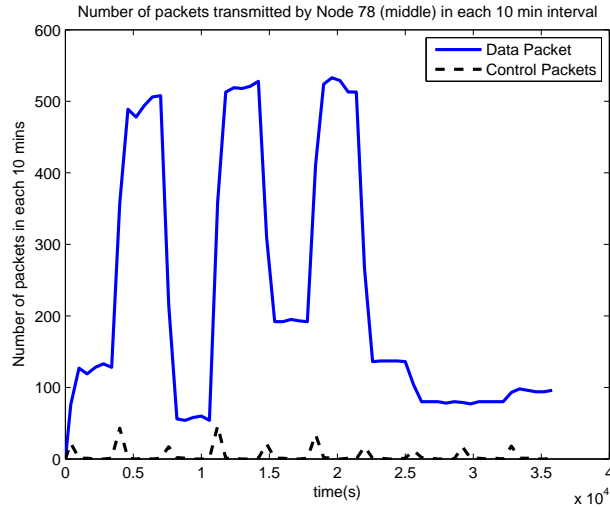


Figure 32: Data and Control Packet over time for Node 78

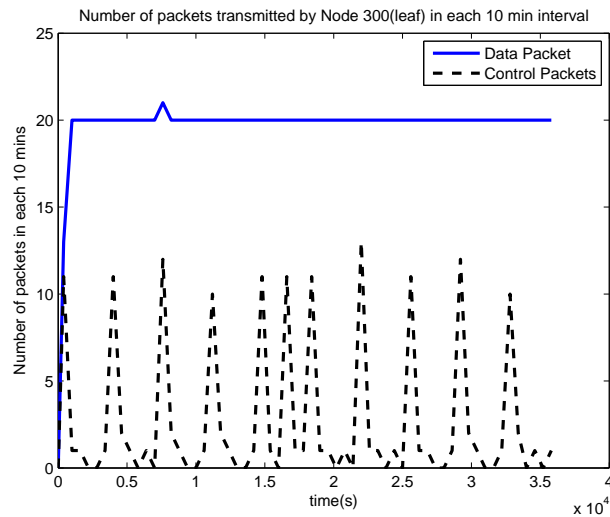


Figure 33: Data and Control Packet over time for Node 300

- The implementation ignores 30% change in the DAG depth of a node before deciding to advertise a new depth.

This decision does affect the optimum path quality to the root. As observed in Figure 36, for 0% tolerance, 95% of paths used have a stretch factor less than 5%. Similarly, for 10% and 20% tolerance level, 95% of paths will have a 15% and 20% fractional path stretch. However, the increased routing stability and decreased control overhead is the profit we gain from the 10% extra increase in path length or ETX, whichever is used as the metric to optimize DAG.

As the abovementioned threshold also affects the path taken by a packet, this study also demonstrate the effect of the threshold on number of times P2P paths are changed between source and destination pair. For Network ‘A’ shown and discussed in figure 1 in section 3 and the large Smart meter network, the CDF of path change is plotted against fraction of path change for different threshold of emitting a new DIO when the metric cost to LBR changes. For figure 37 and figure 38, we plot the fraction of times a path was changed (for each source destination pair) in X axis. If there have been X packets transferred from

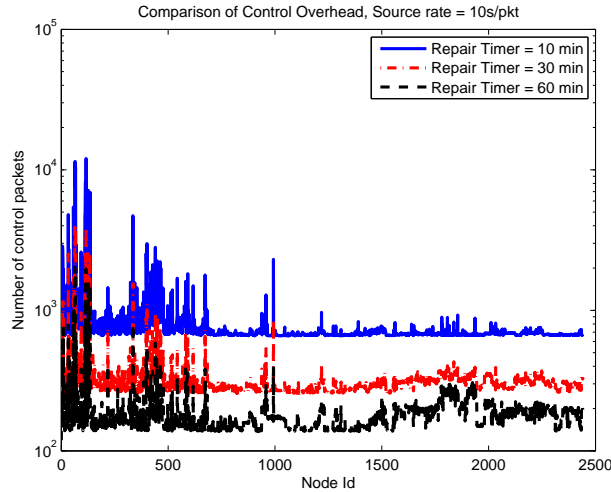


Figure 34: Amount of control packet for different global repair timer period

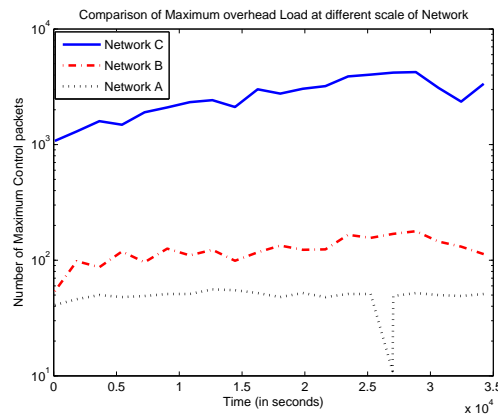


Figure 35: Scaling property of maximum control packets processed by any node over time.

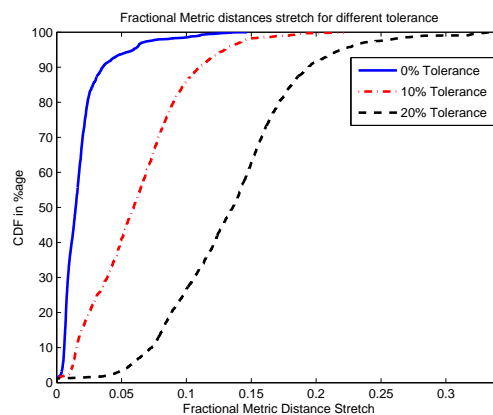


Figure 36: Fractional stretch factor for different tolerance level

source A, to destination B, and out of X times, Y times the path between this source Destination pair is changed , then x axis indicates $Y/X * 100\%$. In vertical Axis , CDF is plotted.

This draft also compares the CDF of fraction of path change for three different networks; Network ‘A’

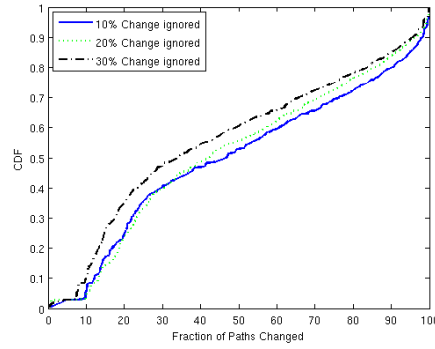


Figure 37: Distribution of Fraction of Path change, Network 'A'

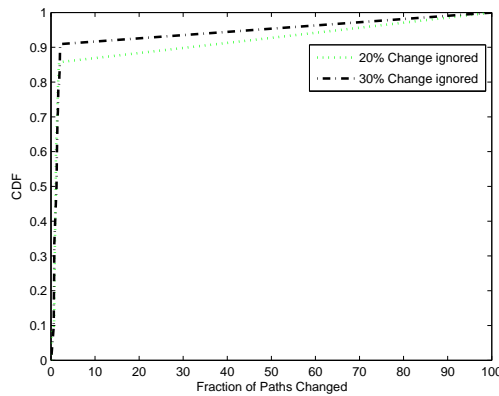


Figure 38: Distribution of Fraction of Path change, Large Network 'C'

with 45 nodes, Network 'B' with 86 nodes, and the smart meter network with 2442 nodes as Network 'C'. Figure 39 demonstrates how the three networks exhibit change of P2P routing path when 30% change in metric cost to the root is ignored before shifting to a new parent.

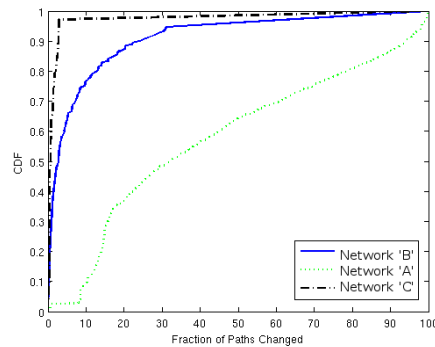


Figure 39: Comparison of Distribution of Fraction of Path change

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