Valuation of Routing Approaches for High Dense IoT

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Abstract – The Internet of Things (IoT) presents an enabling technology by which physical objects can communicate over the Internet. Hence these objects can work in favor of humans needs and can prompt the smart environments. Owing to the success in proof-of-concept of IoT and development of low to medium dense networks. The high dense IoT is becoming one of the most important research areas; nevertheless, the stone pillar upon which such network is built, i.e., routing approaches is still questionable. In other words, is it enough for high dense IoT to provide a thin layer above the MAC layer to make packet forwarding or such network require a full routing protocol. Hence two approaches have been emerged “mesh-under” and “routing-over”. This paper presents insightful valuation for these two routing approaches from different perspectives and make use of this valuation to assess the performance of two standards. The results of this paper can help the industrial as well as academia to select the suitable routing protocol and to remediate their shortcomings.

Keywords – Internet of Things, Routing-over Lossy Network Protocol, Meshing-Under, Routing Constraints.

I. INTRODUCTION

The ultimate goal of the Internet of things (IoT) is to enable smart environments by making all things around us more informative and adaptive to our needs [1]. This goal can be achieved by embedding sensors and actuators in most of physical objects surrounding us and connect them to the Internet. Most of these nodes have meagre resources in respect of energy, processing power, storage spaces and communication capabilities. This makes development of communication protocols over them is challenge. Although the IoT has been developed rapidly over low-dense networks [2]. Extension towards high dense requires a lightweight and stable routing protocol to facilitates communication among nodes over multi-hop.

Although many works have been devoted to devise a routing protocol for IoT, most of these protocols follow two approaches: mesh-under or routing-over. Mesh-under defines a simple packet-forwarding mechanism over the Medium Access Control (MAC) layer without needing for a network layer. Conversely, routing-over protocols implement a full function routing protocol within the network layer using the standard Internet Protocol version 6 (IPv6). The key advantages of mesh-under approach is its simplicity which facilitates deployment of high dense IoT networks, however this limits the scalability of networks. The routing-over approach on the other hand burdens resources of IoT nodes with a complete routing protocol. However, routing-over provide benefits in terms of stability. Nevertheless, different IoT requires different applications which in turn makes selection between meshing-under and/or routing-over is a vital research topic.

This paper presented a quantified assessment for both mesh-under and routing protocols from different perspectives using practice standards developed by organization bodies. Namely the IEEE 802.15.5 that was ratified by the Institute of Electrical and Electronics Engineers (IEEE) and Routing Protocol over Lossy networks (RPL) introduced by the Internet Engineering Task Force (IETF). This work is crucial for both industrial and academic disciplines. Industrial specialties require a deep understanding for philosophies under which routing strategies were developed and to utilize such understanding in make a sound decision for the appropriate one. This in turn can reduce the development-to-market cycle without speeding lots of time and efforts in experiencing different routing approaches. From academic outlook, providing insightful evaluation dissimilarities between routing-over and meshing under protocols can help in overcoming their limitations and improving the design criteria. Motived by these benefits several works investigated the performance of routing protocols, for instance [19] provides an analytical model which can be used to expect the probabilities of packet arrival, total number of transmission and delay for meshing under protocols. However, this study uses the fragmentation cost as the main concern and ignored core functions of routing protocols. Form the Implementation points of view; [8, 10] assessed the performance of the RPL under predefined scenarios and ignored the overall functionality. According to our best of knowledge this is the first paper that investigates the need for critical evaluation of both routing-over and meshing-under approaches comprehensively.

The rest of this paper is organized as follows: in section II and III overviews of the mesh-under and the routing-over protocols are presented and exemplified using standards. Section IV summarizes the metrics and constraints that are used to make routing decisions. Section V provides the simulation scenarios and in section VI results and discussion are given. Finally, section VII concludes this work.

II. INTRODUCTION TO MESH-UNDER PROTOCOLS

The mesh under protocol approach provides a thin layer over the MAC protocol without need to ratify a complete routing-over IoT nodes. One of the famous example for this approach is IEEE 802.15.5 [2] which was specified by the same working group who specified the physical and MAC protocols of IEEE 802.15.4 to enable a low-power node to communicate beyond its transmission range without squandering its resources. In the IEEE 8.2.15.5...
based networks, physical topology is mapped to a tree where each tree has a single root called Mesh Coordinator (MC). A node wishes to join a network should elect another node that had jointed the network and that has the shortest metric to the MC. Thereafter, a child-parent relationship is formed between these two devices; such relationships constitute the tree links. Another sort of links dubbed mesh links are defined between a node and its children/sibling. The said protocol relies on the MC to assign address to the entire network based hierarchal delegation procedures. This results in being all nodes under a common parent to have consecutive addresses which eliminates the need to use address resolution protocol as the case in IPv6 based protocols. This addressing scheme has another advantage that is reduction of routing table size; as a node can compare its own address with the destination to the next hop without need to maintain an individual entity for each destination.

A node operating IEEE 802.15.5 maintains states of all links between it and its neighbors located 1 within hops where 1 is a global factor set by the MC. A node uses this information to work out the connectivity matrix which enables it to map the physical topology into logical representation. The standard defined two mechanisms to enable a node to update its information about link states: Hello packets and Up-Down flag. The Hello packets are exchanged periodically over mesh and tree links with the aim to ascertain lost links. The Up-Down flag, on the other hand, is used to detect topology inconsistency; a node whenever constructs a new packet sets this flag to UP if the packet is destined towards MC and DOWN otherwise. Hence all intermediate nodes that received a packet checks the value of this flag, if an incongruity is found then a mismatching message is flooding over the network to remediate the inconsistence topology. An additional to the aforementioned, IEEE 802.15.5 defines a mechanism by that allows a node whenever wants to leave the network to inform others about its desire. Hence other nodes can update their information accordingly without needing for any additional overheads.

With respect to energy saving techniques, this standard offers two energy saving modes: ASES which stands for Asynchronous Energy Saving and SES that is shorthand for Synchronous Energy Saving. The former technique allows a node to sleep without pre-arrangement with other nodes which may result in reducing throughput of the network. Conversely, the SES technique requires all nodes to sleep and wakeup simultaneously.

III. Introduction to Routing-over Protocols

The routing-over approaches defines a complete routing protocol by which different IoT nodes can communication using IPv6. The Routing Protocol for Lossy networks (RPL) was one of the earliest protocol that designed especially for low-rate and lossy networks such as IoT. The RPL defined the fundamental procedures that underpin routing scheme and left other specifications e.g., addresses allocation, rout selection and power-optimization techniques to be adjusted according to application needs. Due to that, the RPL becomes highly parametrical protocol and there is a need a fine tuning.

The RPL employs the Destination Oriented Directed Acyclic Graph (DODAG) to form logical map of a network; a node can have multiple parents, children, and siblings but there is no way to return to the same node through the DODAG lines. Comparing to the IEEE 802.15.5 tree structure; the DODOAG can increase the stability of network by provide path redundancy to the root [8]. A network can run several RPL instance each of which can be optimized to different object function, e.g., reducing latency, avoiding high losses rate links. Moreover, multiple roots can be found within the same instance. A node can participate in different RPL instance and play different roles: router or host albeit it cannot join different roots within the same instance [9].

The RPL uses the rank in the same manner the tree level is used in IEEE 802.15.5 except that the rank is derived from the metrics which vary according to the OF whereas the tree level depends always on the hop count.

The RPL uses DODAG Information Object (DIO) signaling message to construct DODAG diagram. When the root establishes a RPL instance, it selects the OF and sends a DIO message. Upon arriving this DIO to other nodes; they compute their ranks using the specific OF and broadcast their DIOs to enable other nodes to join the RPL network. Interestingly, Rank is changed monotonically which enable other nodes to rectify any inconsistence rank received from other nodes by sending their rank in DIOs [10]. Hence employing DIO control message ensures the routes to the root called Multi-Point-to-point routing (MP2P) are always existence and optimal.

For the point-to-point routing, the RPL exploits reactive distance vector to make its nodes update their routing table upon request using data packets [3]. To build the routing table, the RPL uses a especial control message dubbed Destination Advertisement Object (DAO) to allow each node to inform its parent about selected address. A parent whenever receives such message, it can maintain the address in its routing table or forward the message upwards to the root. Hence, RPL offers two operational modes storing and non-storing, in the former, as its name indicate, each node stores full information about other devices whereas in the latter mode, the root acts as the main controller and other devices behaves like dummy terminals. A sound decision regarding the operation model should be made otherwise the performance of network can be degraded significantly. For instance, if a non-storing mode is used over a high traffic network then a considerable delay can result as a node must send all received packets to the root to forward them downwards. On the other hand, employing a storing mode over a lossy network can result in black holes in networks due to depletion of IoT batteries fast. A tradeoff between minimizing routing table and reducing packet delivery delay is highly required, otherwise the point-to-point routing can be very poor [11]. Additional, a node can use some signaling messages such as Measurement Object (MO) to measure link quality [12] or Route Discovery...
From a perspective of loop detection, the RPL employs strict operation to ensure that a node cannot increase its rank beyond any of its parent ranks and allow a node when it wishes to leave the network to poison its rank by broadcast a DIO message with INFINITE_RANK based on this message, other nodes run local repair to rectify their depended ranks [14]. RPL provides also a global repair which is used when a global change has occurred to the network, e.g., new OF is used.

Fig.1 shows conceptual protocol stack for both RPL and IEEE 802.15.5, as shown in this figure the MESH layer is added above the MAC layer in IEEE 802.15.5. Conversely, in the RPL multiple layers are need: IPv6 core protocol to enable a node to be use the IPv6 addressing scheme, 6LoWPAN [15] to enable a node to fragment and compress the long IPv6 header into 2 bytes and does fragment when required. The ICMPv6 is used to carry the RPL control packets.

The simplest metric used in most of existing routing protocols is the hop count; however, it may not maximize the throughput of network [5] because it ignores the state of wireless links and nodes.

### B. Expected Transmission Count (EXT)

The EXT was presented in [6, 8] to enable 802.11 nodes to measure the link quality and the responsibility of nodes. A node computes the ratio between the received and expected number of probes packets over specific time in forward $R_f$ and reversed $R_r$ directions. Probes packets are broadcasted periodically containing a list of number of probes which have been received to a node by others during predetermined time. The EXT for $(h)$ hops is the summation of all individual EXT and given as:

$$
EXT = \sum_{i=0}^{h} \frac{1}{(1-R_f)(1-R_r)}
$$

The EXT as defined above can be inappropriate for IEEE 802.15.4 networks: firstly, periodically broadcasting can shorten the life of networks; secondly, the CSMA-CA of IEEE 802.15.4 depends on “delay-sense” sequence while the CSM-CA in 802.11 depends on “sense-delay” then probes experience more delay then scheduled; especially if the inactive periods are taken in account; hence inaccurate EXT values are highly expect. Thirdly, as probes are almost smaller than other packets, the Frame Error Rate of them cannot be generalized to other packets i.e., the control and data packets have higher losses than calculated by EXT. Here we propose to calculate the EXT on the actual packets during the whole active period, this way; we can obtained more accurate EXT values, reduce the overhead in a network and achieve more stability.

### C. Links Color Attribute

It is another concept in routing metrics which has been used on IS-IS routing protocol and supported by the RPL [7, 8]. The idea is to color links between nodes according to different criteria e.g., capacity, traffic pattern, channel losses. These coding are left for implementers and are not specified in the standard. Accordingly, we defined 8 states of links varies from stable “always connected links” to mobile unstable “mobile” links.

### V. SIMULATION SCENARIOS

The NS3 simulator has been used to as a simulator platform in this study, for the physical layer, it is assumed an ideal channel model and IEEE 802.15.4 with CSMA-CA is used as to manage access to the shared channels. The data rate of network is adjusted as 250kps using 2.4 GHz band. Packets are generated using Poisson distribution with mean ($\lambda$) set based on offered load (G) while length of Data frames follow a uniform distribution between the minimum and maximum transmission unit. 100 IoT nodes have been scattered spontaneously over a small volume of 2x2x2 m$^3$ to represent a high dense network. The transmission and reception powers are taken from real nodes and other parameters which have not been summarized here are varied according to the situation under consideration.

The following parameters are used to assess network readings: the total energy consumed by the root ($E_{root}$) average Energy ($E$) of other nodes; average end to end...
VI. RESULTS AND DISCUSSION

Although IEEE 802.15.5 and the RPL standards differ in many aspects e.g., the routing concepts, layer architecture; they share a common goal which is to build a free loop logical map in which nodes can use a combination of metrics and constraints to configure themselves. This section compares these standards from different perspectives related to self-organization.

D. Logical Formation

To compare the time required to build the logical mapping over both IEEE 802.15.5 and RPL, different number of nodes are scattered randomly and a node uses 3 dBm to transmit a packet. For the RPL, the 6LoWPAN is used as the LLC layer and addresses are assignment using two methods: stateless when each node select its own 16 bits address randomly then the Duplication Address Detection (DAD) is used as specified in the standard; and state full with solely DCHP server running on the root and the MAC association control frames are used to assign the address. Employing these schemes ensures a fair comparison between two protocols. The parent is selected based on the minimum number of hop-counts while LQI is used to discernment between offers received from different nodes. No data packet are sent during this period as specified in [15]. Table I compare the time required by each protocol to build the logical mapping.

<table>
<thead>
<tr>
<th>Node number</th>
<th>IEEE 802.15.5</th>
<th>RPL-Stateless</th>
<th>RPL-statefull</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5000</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>20</td>
<td>10000</td>
<td>180</td>
<td>250</td>
</tr>
<tr>
<td>50</td>
<td>15000</td>
<td>470</td>
<td>600</td>
</tr>
<tr>
<td>100</td>
<td>60000</td>
<td>3000</td>
<td>4000</td>
</tr>
</tbody>
</table>

It can be seen from these results that RPL stateless mode takes the mimin delay to form the logci map, following by the state full and finally IEEE 802.15.5 produces the highest delay. The explanation can be given by considering that fact that RPL maps network as a DAG which can have one or more root, and allow a node to have to multiple parents, children, siblings which facilities using the Equal Cost Multiple Path (ECMP) to balance the load between them. On the other hand, IEEE 802.15.5 uses strict tree level to identify the location of a node with respect to the mesh coordinator which has tree level equals 0; the tree level is an integer number which is limited to 255; i.e. an IEEE 802.15.5 tree cannot be exceeded beyond this limit and the addressing, consequently, multi-hop forwarding algorithm can fail if nodes cannot be allocated within this limit. The RPL uses an intelligent rank scheme computed according to metrics in use; As a result, an RPL node can select the best path according to the required conditions per packet.

E. Multi hop Forwarding Algorithm

Fig.3 show the overhead due to control packets used to form logic topology of the network vs number of nodes within the network.

As illustrated above, the control packet needed in IEEE 802.15.5 is more than in RPL. This can be attributed to that 4 message per node in the IEEE 802.15.5 are required (MAC association request, MAC association response, MESH children report number, and MESH address assignment). On the other hand, these messages are reduced to 2 in the RPL: for stateless address and for state-full (MAC association request and MAC association response) the length of all of them are nearly same. When data packets are sent over the same networks, more control packets are propagated through the network to maintain the topology. Fig.2. shows the CDF of maintained control packets for different node numbers.

The main reason behind the characteristic shown in Fig.4 is that although the Hello and DIO control messages used by IEEE 802.15.5 RPL protocol respectively to update the routing information. The frequencies of their sending are different. Hellos are sent at constant period while DIOs are send according to the trick algorithm [10,11] which control the generation of DIO according the stability of network; i.e. time between two consequent DIOs can be increased exponentially if the network is stable. All other control frames in both standards are adhered to the same timing policy. In terms of routing
protocol overhead that added to data packet. The MESH header adds 18 bytes overhead to each data packets (2 bytes for frame control, 2-8 bytes for the originator address and 2-8 bytes for final destination address) in additional to one byte for up down flag which used to detect the loop. The RPL on the other hand, does not add any header above data packets. the 6LoWPAN take this responsibility and adds the compression header (2 bytes) and mesh header (1 byte for dispatch and hop count, 2-8 bytes for the originator address, and 2-8 bytes for the final destination address).

F. Operation Modes

The RPL supports mainly two operation modes: storing mode, in which a node has to keep information about others in its routing table; nodes in this mode can/cannot support the multicast. Since a node does not store a routing table in non-storing mode, all data packets are unicasted to the root which sent them back to the destination; when a root wishes to communicate with other node it construct a packet with source route header as specified in [17] the RPL also supports a network that does not need any downward route as the case when nodes sense data and send them to the root. In the IEEE 802.15.5 all nodes have to store the Link State Table. To assess this index, the size of routing table under the above scenario is measured in bytes and shown in Fig.5.

G. Multiple Instances

The RPL enables a network to build multiple instances each one of them are optimized to different Object Function, e.g., minimize packet latency, avoiding the low power nodes; within each instance, more than one (root) can coexist this can prolong the life time of nodes and avoid the single point of failure. The IEEE 802.15.5 on the other hand supports a single MC only and limits the communications to those nodes within the same LoWPAN; in other words, a node can communicate with other node that have been assigned an address with the same MC.

H. Loop Detection and Repairing

In the RPL, rank is used as an indicator for the loop; a node must compute its rank based on rank of its parent as well as the DEFAULT-MIN_HOP-RANK_INCREASE parameter which vary according to the OF in use. A node uses the DAG Information Object (DIO) control frame to broadcast its rank. If there is inconsistent between its rank and others, the DIO message can be unicasted from them to assist it to rectify this inconsistent. Whenever a node wants to disjoin the network; it broadcasts a DIO packet with INFINITE_RANK, then other nodes run the local repair to correct its entity in their routing table. If there is a major change that affects the whole network e.g. new node is added by root, the global repairing is run by the nodes to reform the DAG. To assess performance of network under this circumstance, a new simulation session was set and different types of nodes were lost their connectivity to other nodes at different times where nodes are arranged in linear topology with one root located at the middle of them; link color attribute and the EXT is used as the metric, data packets are arranged to ensure that a failure node continuously receives packets form upper lower nodes.

We start by the root node (MC in the IEEE 802.15.5). In the IEEE 802.15.5 if the MC is die before completing the address assignment, then no addresses will be assigned and the communications in network is limited to single hop only; conversely if the MC die after that, the meshing function can be run normally without any problem; however, new nodes cannot join the network unless the parent has spare address to assign it to a new node. In the RPL non-storing mode a loss of root means a loss for the routing function at all; since all packets have to forward up to it then down to the destination. In storing mode, if the root dies then the multi-hop function can run normally.

When a router node dies; the number of control packets increases with the location of router and the number of another node that use it to route their packet. It is expected that when a node with the second rank (tree level=2 in IEEE 802.15.5) dies the number of signaling messages dwarfs their peers if fourth rank dies. However, the total time required to reform the logical map “coverage time” and number of packet lost due the host unreachability are more crucial factors to evaluation protocols.
setting the routing parameters in the network as they are imposed by the root and spread over the whole network without any negotiation.

1. Energy Saving Modes

The RPL and 6LoWPAN have not specifies any energy saving modes. To investigate how the energy saving mode affect forming self-origination network, we construct 49 nodes in a grid topology where the distance between each node and other is 20 meters vertically and horizontally, the transmission range is set at 47 meters, then a packet can be received by 8 nodes on average; In ASES a node can enter sleeping modes once it has no packet to be sent to others during its remaining active period. The Wakeup Notification (WN), Extending Requests (EREQ) and Extending Replay (ERER) control messages are employed as specified.

In the IEEE 802.15.5 both modes consumed approximate same energy, the reason behind this is that while the ASES mode saves some energy the number of alteration in construction of logical mapping consumes this energy. In the RPL, the ASES gives better reading than the case with SES since the construction of DAG is stable than the root.

VII. Conclusion

This paper has introduced a fare comparison between two different routing approaches used in IoT network; namely routing-over and mesh-under. The results demonstrate that although meshing under is very simple and adaptive protocol which make it suitable for low-traffic and stable network. The results also show that, the routing-over network is sophisticated and highly parametric protocol that can employs over more complicated networks operating under lossy link. However, this in turn requires designers to set the routing parameters previously which reduce design to market cycle and reduces the portability of protocols.

REFERENCES


AUTHOR’S PROFILE

Mohammed Baz received the Ph.D. degrees from the University of York, in 2015 in the field of applications of statistical inference on designing communication protocols for low-power wireless networks. Mohammed is the author of a number of published papers in recognized conferences and has acted as a reviewer for a number of IEEE journals including IEEE Transaction on Vehicular Technology, IEEE Access journal, and IEEE Wireless Communications Letters. Now, Dr. Baz works for Computer Engineering Department in College of Computers and Information Technology in Taif University and has been a member of multiple committees related to academic fields as well as participant in research projects. Moreover, he has taught several courses and supervised several capstone projects.