A Novel Energy Aware Routing Function for Internet of Things Networks

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Abstract

In recent years, there is a growing interest towards Wireless Sensor Networks (WSN) with the introduction of new application areas such as Industrial Internet, Smart Grid and Smart Cities. With these new application areas, a need has emerged to connect low power devices to Internet and to each other by utilising IPv6 technology. This has created a new networking concept named as Internet of Things (IoT). IoT networks consists of independent devices with globally accessible IPv6 addresses. These devices often connect to Internet via a central entity named as Border Router (BR) which implements a gateway between the low power IPv6 network and the Internet. Many applications in such IoT networks demand very low power operation and in many cases, the nodes in such networks are equipped with small batteries. Hence, keeping such a low power network operational as long as possible using limited energy resources poses a unique challenge for low power wireless networking community. This paper presents a novel energy aware routing algorithm which aims to extend network lifetime by balancing the energy consumption of the nodes within the wireless IoT network.

1. Introduction

Ever increasing need for enabling low power applications ranging from wearables to infrastructure monitoring sensors require energy efficient IoT solutions. Creating an energy efficient IoT network requires sophisticated energy optimisation solutions at different layers of the protocol stack. For example, the energy consumption of a node can be minimised by turning off the radio when the node is not receiving or transmitting information. The latest effort to enable such a duty cycled operation at the MAC layer of the protocol stack has been introduced as an amendment to IEEE 802.15.4[1]. This amendment is named as Time Slotted Channel Hopping (TSCH) mode of IEEE 802.15.4e protocol which enables the radio to use a time slotted access to the wireless communication channel. This in turn can leverage radio duty cycles of less than 1% that can greatly improve the node's energy efficiency and lifetime. While duty cycling of the radio can significantly improve energy efficiency of the node, routing can also play a significant role in optimising the energy consumption of the nodes within the network. For example, a node in a 6LoWPAN [2] network using RPL [3] routing protocol can be selected to be the default router for many nodes which may lead this node to exhaust its energy resources quickly and die. Such a routing approach can significantly reduce the network lifetime where some nodes may run out of energy prematurely due to excessive data traffic running over them. Routing protocols use several routing metrics to optimise different aspects of the network. For instance, RPL routing protocol uses objective functions with a mixture of metrics to optimise the network performance. For example, a network with a high reliability requirement can make use of an objective function based on ETX metric which indicates the reliability of the links between the nodes. But, having such a metric in an energy constrained network might significantly reduce the lifetime of the IoT network.

There are a few studies in the literature addressing energy efficiency aspect of routing objective functions. Takizawa et al. studied a 6LoWPAN WSN smart home application. The porposed smart home is designed with battery-powered and power-supplied nodes. In order to maximize WSN lifetime, they designed an objective function for RPL Routing algorithm in Contiki OS [6] and they compared proposed objective function with MRHOF-based objective method. WSN life- time depends on battery values of battery-powered nodes. So routing algorithm is designed to prioritize the path through AC powered nodes. Thus proposed objective function adds a constant value to MRHOF-ETX based rank calculation if node is battery-powered. If node is AC powered rank is equal to MRHOF-ETX based model. Thereby routing algorithm mainly chooses AC powered nodes and battery-powered nodes are not used for routing traffic of other nodes [4]. However their algorithm doesn't consider battery level of battery-powered nodes. So if a node dies it can cause critical sensor data loss. To prevent this issue, its rank should get higher while its battery level decreases. Moreover the more data hops through network the more it consumes energy from the whole network. So hop count and battery level should be considered while designing an objective function for the routing algorithm. Our proposed objective function calculates rank by making use of battery level, successful packet transmissions and hops count between node and sink to enable a longer network lifetime.

Nayak et al. tried to extend network lifetime by using fuzzy logic controllers. They used fuzzification methods for battery level, Mobility and Centrality information. They assigned fuzzy membership functions name as Less, Medium and High for Remaining battery power; Low, Modarate and frequent for Mobility; Close, Adequate and Far for Centrality. After using a determined rule table and Mamdanis defuzzification method, they achieve approximately 12% extended network lifetime. They estimated link quality by taking account of mobility and distance [5]. Even though this estimation is not completely wrong, it doesn't meet the exact value of successful transmission rate. Here, the proposed algorithm takes not only battery level into account, but also successful packet trans- mission rate by checking received Acknowledgement (ACK) feedback packets. Thus successful transmission rates provide more reliable link quality value to calculate node rank which may have significant impact on the network lifetime.

In this paper, we introduce a novel energy aware objective function for RPL protocol with the aim of extending the network lifetime of a wireless IoT network. For this, we used Contiki operating system and its extensive support for IoT pro- tocols. The solution is implemented in Contiki OS and tested using Cooja simulation tool of Contiki OS which enables emulation of a wide variety of embedded hardware as well as implementing algorithms for native computer. Furthermore, we developed a battery model for Contiki OS which enabled us to carry out extensive simulations of the proposed objective function. The paper is organized as follows, firstly we give a brief introduction to RPL routing protocol in Section II. Section III defines the mathematical model of the proposed objective function. Section IV describes the simulation setup and summarizes the main results collected from the Cooja based simulations. Section V includes concluding remarks and future works.

2. IETF RPL Routing Protocol

RPL belongs to the class of gradient routing protocols [7], in which each node is assigned a scalar value called height. Heights are assigned in such a way that they increase with distance to a central node (root, sink). Distance is calculated using a cumulative cost function (objective function) which can be based on hop count, energy consumption, residual node energy, or any combination thereof. The forwarding process selects the next hop as the neighbor with lowest height.

The proposal described in the RPL draft [8] employs a Destination Oriented Directed Acyclic Graph (DODAG) to maintain network state information. A DODAG is a directed graph wherein all edges are oriented in cycle free manner to a sink (root node) node. A path from a node (leaf/forwarder node) oriented towards and terminating at the sink node consists of the edges in the DODAG. Each node in the DODAG is associated with a rank value. The rank of nodes along any path to the DODAG root should be monotonically decreasing in order to avoid any routing loop.

In order to construct a DODAG, the root node will issue a control message called DODAG Information Object (DIO). A DIO message conveys information about the DODAG and includes: a DODAGID used to identify the DODAG as sourced from the DODAG root; rank information used by nodes to determine their positions in the DODAG relative to each other; objective function identified by an Objective Code Point (OCP) that specifies the metrics used within the DODAG and the method for computing DODAG rank. Any other node that receives a DIO message and is willing to join the DODAG should add the DIO sender to its parent list, compute its own rank (associated with the parent node) according to the OCP, and broadcast the DIO message with the updated rank information. The client (child) nodes may receive the DIO message under two circumstances:

- Received as a broadcast from a neighbor as described above;
- A node either on startup or detecting that it has lost connectivity will send out a DODAG Information Solicitation (DIS) message. Neighboring nodes that hear the DIS message will respond to the node who sent the DIS with a DIO message provided they are a part of a DODAG.

After the DODAG is constructed, each child node will be able to forward any upward traffic (destined to the sink node) to its parent as the next-hop node. In order to support the downward traffic from the sink, the child node should issue a control message called Destination Advertisement Object (DAO). While the DAO message passes all the way from the child node to the root (sink) according to the upward path indicated by the DODAG, the intermediate nodes either store routing information for the client or ignore routing information in DAO message and blindly forward DAO message to the root node. The first mode operation, where intermediate nodes store routing information generated from DAO message, is called as Storing Mode and the second mode of operation, where intermediate nodes do not store routing information for the client node, is called as non-storing mode of operation. increase the network lifetime1In this case, the root node appends a source routing header to each packet destined to a node within the network and intermediate nodes make use of this header to forward the packet toward the destination node. In the storing mode, each node queries its routing table for the next-hop of the packet.

In summary, the RPL specification provides the means necessary for any node operating on the same radio channel as the root node, to establish and maintain upward and downward routes in a tree based topology. This is sufficient for the case of a single tree with one root. As described earlier, RPL creates its routing topology based on rank values calculated by objective functions which makes use of several application specific metrics. Thus, if the wireless nodes are severely energy constrained, the objective function shall take this into account when calculating each node's rank. For example, a node with very little energy left will need to increase its rank within the network to encourage its child nodes to find alternative paths. This can increase the network lifetime[1] by balancing the energy usage of the node within the network.

3. System Model

An energy aware objective function for RPL routing protocol can make use of a mixture of metrics to enable a longer network lifetime. In this study, a composite metric, which contains hopcount, remaining energy and ETX[2] metrics, is used for balancing network energy usage and extending network lifetime. Here, the main motivation is that each node has an expected energy efficiency coupled with the ETX. Each node in a network can achieve an relative packet transmission level given in Equation 1.

$$PT_b^i = \frac{R_{en}^i * T_{suc}^i}{T_{tot}^i}, \tag{1}$$

where PT^i_b represents the relative number of packets transmitted successfully using the remaining energy R^i_{en} in the node i. T^i_{suc} and T^i_{tot} values represent the successfully transmitted packets and total transmissions of node i respectively. Equation 1 motivates us to strike a balance between the remaining energy level and the expected transmission count. Hence, when the node calculates its rank value using Equation 2, the battery level and link ETX have an exponential impact on the rank. Furthermore, hopcount value used in Equation 2 makes sure that the energy impact of having multiple transmissions over a longer path is reflected on to the rank calculation function.

$$Rank_i = (101 - R_l) * (101 - ETX_l) + hopcount * 250. \tag{2}$$

$$ETX_l = \prod_{r \epsilon R} (ETX_r). \tag{3}$$

In Equation 2 ETX_l represents the composite link ETX from source to destination which is given in Equation 3. The composite energy level of the link is given as R_l and represents the minimum energy level along a routing path. When a node i uses Equation 2 to calculate its relative rank in the network, the first part of the equation makes sure that its rank value exponentially increases with composite link energy and link ETX metrics. The second part of the equation, as mentioned before, makes sure that node i factors in its hop distance from the root node in the rank calculation which also prevents routing loops within the topology. The constant values in Equation 2 are calculated empirically by running several simulations belonging to different wireless communication topologies.

The remaining energy, ETX and hopcount metrics are forwarded to the nodes within the network via DIO packets. Each metric is processed at intermediate nodes and rank values are calculated according to the received composite metrics. For example, battery energy level is assigned to each node randomly depending on its ID. Hence, if the node is assigned a random energy level, this energy level is used for all the simulations to enable a meaningful comparison.

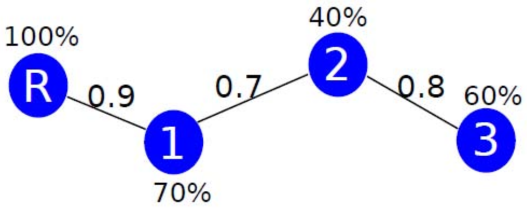

Fig. 1. An example routing path

Nodes in the network only forward minimum energy level in the DIO messages along the path from the root to themselves. This stems from the fact that any routing path is as strong as its weakest link which is the node with the least energy level. For example, in Fig. 1 there is a routing path established from node 3 to the root node R. The percentage value beside the nodes represents the remaining energies of the nodes. When the node 3 forwards a DIO it puts a battery level value of 40% to the DIO message representing the minimum battery level along the routing path. Hence, when another node wants to join this routing path, it should calculate its rank according to the energy level indicated in the DIO message sent by node 3.

The composite link ETX represents the probability of the success of the entire link and given a in Equation 3. For example, if we want to calculate the composite link ETX of the routing path given in Fig. 1, we need to multiply all the link success probabilities along to route to find the composite link ETX. In this example, the composite link success probability is found to be 0; 504 which means that on average a packet from node 3 to node R needs to be transmitted twice along the route to reach the destination node. This will have a negative impact in terms of energy consumption hence the rank calculation function should take this metric into account as given in Equation 2.

Using the equations introduced here, we implemented an objective function for RPL routing protocol in Contiki OS. To test the performance of the proposed objective function, we also implemented a battery model which takes the energy consumption values of the parts of the emulated embedded hardware in to account. Each mode in the network is assumed

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[1] Here, the network lifetime is defined as the instance when the first node in the network runs out of energy.

[2] ETX metric represents the expected number of transmissions for a node to reach its next-hopneighbor.

to have the same battery (i.e. 3V 3000 mAh battery) apart from the root node which is assumed to be mains powered. The nodes start with a random energy level and this level is saved for each node so that the comparisons between different objective functions are meaningful. The next section details our finding on the lifetime of a wireless network consisting of 30 nodes emulated in Cooja tool of Contiki OS.

4. Simulation Results

Fig. 2 gives the simulated network setup where the sink (Root) node (Node ID 1) is located at the center of the network and 30 nodes are uniformly distributed around this sink node. The node at the edge of the network reaches the sink node via multi-hop links established by RPL routing protocol of Contiki OS. The furthest away node from the sink node can be reached via four hops that is the maximum hopcount for the simulated network. The sink node is assumed to be mains powered and assumed to have a battery level of 100% all the time. Nodes at the network start with a random battery level ranging from 60% to 100%. Nodes communicates with each other over a lossy medium where link success is moddelled using a probabilistic model where the success probability of the link changes with distance upto a certain propagation limit. For example, when the link success probability is set to 70% the nodes are able to successfully communicate with each other 70% of the time when placed at the propagation limit set by linear path loss model given in [9]. If they are placed side-by-side, the nodes are able to communicate with each other with 100% link reliability.

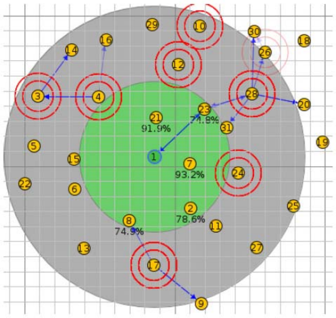


Fig.2. Simulated 31 node uniform network

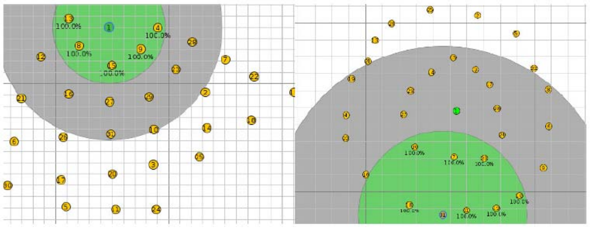
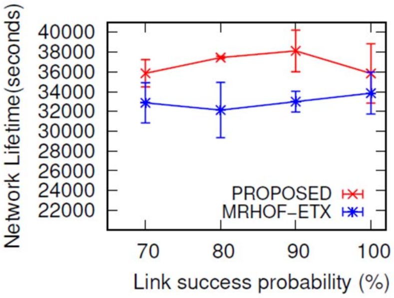


Fig.3. Two 31 networks with different hop distances

The simulations are carried out for different link success probabilities ranging from 70% to 100% with 10% step increments. At each link success level, the performance of the proposed routing objective function is compared with Contiki OS MRHOF objective function using ETX link metric where ETX link metric represents nodes expected transmission count to its parent. The simulations are repeated for 5 times using different random seeds at each link success probability level and averaged. The simulations are run until any one of the node in the network runs out of energy. The result in Fig. 4 and Fig. 5 represents the averaged performance results for the simulated networks highlighting the overall impact of link success probabilities on the performance of the tested objective functions.

The result in Fig. 4 indicates that it is possible to balance the network energy usage and extend network lifetime by as much as 30% when the proposed objective function is used. The results also indicate that the performance of the proposed routing objective function is better when the network has unreliable connections. This finding is significant since it shows that in a real life deployment, our proposed objective function can significantly improve network lifetime by not only optimising energy usage, but also making used of the most suitable link with the best route link success probability. Although the performance results here indicate a significant improvement, it is of interest to couple this work with transmit power control to further improve energy efficiency of the network and achieve a longer network lifetime as compared to the state of the art.



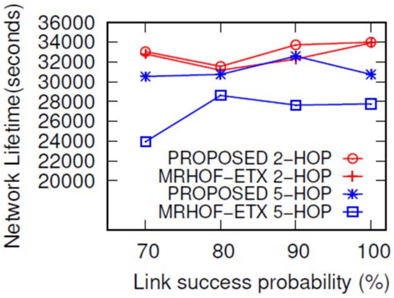


Fig.5. Impact of hop distance on the network lifetime

The result in Fig. 5 represents the performance of the proposed objective function for different hop distances for two different network setups given in Fig. 3. For the first network setup, the maximum hop distance is arranged to be 2 hops. For the second network setup, the nodes are arranged to have a maximum hop distance of 5-hops from the sink node to show the impact of the hop distance on the proposed objective function. As it can be seen from the results, the network lifetime for the two tested objective functions show a similar performance for the two hop scenario as expected. This result indicates that most of the nodes in the network only use their energy resources to transmit their own data. Hence, the energy consumption of the network is somewhat balanced resulting in a similar lifetime performance for the two objective functions. On the other hand, when the maximum hop distance of the network is 5-hop, the proposed objective function outperforms the ETX based objective function by up to 30% highlighting the importance of balancing energy consumption of the network in a multi-hop RPL network. This performance improvement of the proposed routing objective function is expected to increase with the increasing hop-count.

5. Conclusions and Future Work

In this paper, a novel energy aware routing objective function is proposed, implemented and tested for RPL routing protocol. The performance of the solution is compared with the state of the art RPL objective function implemented in Contiki OS. The results indicate a network lifetime improvement of around 30% for a uniform network topology. This improvement is achieved when the network has unreliable links which is the case for most of the low power and lossy wireless networks. Furthermore, analysis also indicated that the proposed objective function performs better with the increasing hop count as compared to the ETX based objective function of RPL routing protocol. While the proposed solution can have significant improvements in terms of network lifetime, it is also of interest to couple this solution with transmit power control to further improve the energy efficiency of the network. Future work will look into a cross layer solution to integrate a transmit power control mechanism to the objective function. Following this step the solution will be integrated to state of the art IETF 6TiSCH protocol.

6. Acknowledgement

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