Energy-based Metric for the Routing Protocol in Low-power and Lossy Network

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Abstract: Saving power while ensuring acceptable service levels is a major concern in wireless sensor networks, since nodes are usually deployed and not replaced in case of breakdown. Several efforts have recently led to the standardization of a routing protocol for low power and lossy network. The standard provides various metrics, which can be used to guide the routing. Most protocol implementations use expected transmission count as routing metric, thus focus on the link reliability. To our knowledge, there is no protocol implementation that uses nodes remaining energy for next hop selection. This paper discusses the usage of the latter as a routing metric for the Routing Protocol in Low power and Lossy Networks (RPL). We design an objective function for that metric and compared experiments result with the most popular expected transmission count scheme.

1 INTRODUCTION

Wireless Sensor Networks (WSN) consist of up to hundreds or thousands nodes scattered in an environment of interest, where nodes and their interconnection are constrained. Nodes discover their neighbors, self-organize to build a topology and route sensed data towards a central point: the sink. To deal with challenge presented by low power and lossy networks, the IETF Roll Working Group has recently published several standards related to RPL (Winter, 2012; Vasseur et al., 2012).

RPL organizes network as one or more Directed Acyclic Graph (DAG), each one rooted at a single point : the DAG root. Topology construction begins at this node, which periodically sends a Destination Oriented DAG Information Object (DIO) via link local multicast. DIO carries necessary informations to build the topology, including root unique identifier, routing metrics, originating router's depth called rank, and other network parameters. Nodes in the vicinity receiving DIOs, join the DAG by selecting their parents (one or more) as next hop upwards to the sink. Parent selection process is governed by an Objective Function (OF), which uses routing metrics to select node's preferred parent among neighbors. Different criteria also called routing metrics (Vasseur et al., 2012) are defined to capture node or link characteristics on the path for parent selection. They could be a node attribute: hop count, node residual energy, or a link attribute : throughput, latency, link quality level or expected transmission count (ETX). In this paper, using an online real time battery level estimation model, we design an OF for RPL that used node remaining energy as metric. The proposed OF is compared against the existing that rely on ETX.

The remainder of the document is organised as follows. In the next section we describe energy-based OF characteristics in terms of node battery level estimation, path cost and node rank computation. Section 3 presents some related work on energy aware routing. Implementation parameters, simulations and results are discussed in section 4. Section 5 concludes our work and discusses future directions.

2 ENERGY-BASED OBJECTIVE FUNCTION

2.1 Node' Battery Level Estimation

To predict the lifetime of the node, we use a well-known battery model proposed by (Rakhmatov and Vrudhula, 2003). It uses the current consumption during each node state and its duration to estimate the battery remaining energy. The model is very accurate and cannot be implemented on real sensor nodes

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due to its complex computations and the memory size requirements. (Rahmé and Fourthy, 2010) have approximated the latter by simple computations on low memory to fit into sensor nodes, while maintaining the original model accuracy. Based on these approximations, we implemented this model on real sensor nodes, with the possibility to predict their lifetime online (Nataf and Festor, 2013). Following RPL metrics recommendations(Vasseur et al., 2012), node residual energy is estimated on a scale of 255 (full) to 0 (empty).

2.2 Energy-based Path Cost Computation

Path cost is a scalar value representing link or node characteristics for which it expresses some quality level along end-to-end path. Its calculation depends on the metric chosen by the network operator. After a node has calculated the path cost for all its neighbors and chose the best parent in regard of the relation order for the selected metric, node updates its metric container (by computing its path through that parent) and starts to send its proper DIO. We consider the path cost PW_i from a node i to the sink as the minimum value between the preferred parent path cost and its own energy. At the sink node, this cost is set as the energy value of node. A node selects the neighbor that advertises the greatest path cost value as parent. More formally:

$$PW_i = \min[\max_{j \in N_i}(PW_j), E_i] \quad (1)$$

Where N_i is the set of node i's neighbors toward the sink, and E_i represents the energy of node i. For a given path, the cost value is also the same as the minimum node's energy level encountered on that path, since this energy is critical for the route lifetime. Network topology shown in figure 1 depicts the proposed energy-based path cost. Node 1 is the sink, and is

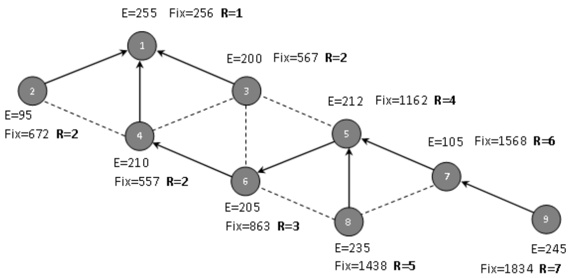


Figure 1: Path cost and DAG Rank calculation.

main powered, other nodes at a given time are supposed to have residual energy as shown. Dashed lines and arrows represent neighbor reachability. Considering the figure, node 6 receives respectively values $PW_3 = 200$, $PW_4 = 210$, $PW_5 = 212$, and $PW_8 = 235$. So node 6 selects 4, as best parent. Similarly, other nodes select their next hop to the sink.

2.3 Energy-based DAG Rank

To avoid cycle in the network, every node uses a scalar value: the rank, to record its relative position to other nodes with regard to DODAG root. Rank value must monotonically decrease as we move upwards to the sink, but it does not necessarily change as fast as some link or node metrics would. For this reason, rank value is thought as a fixed-point number where the position of the radix point between the integer part and the fractional part is determined by the `MinHopRankIncr` parameter. When rank is compared for parent relationships or loop detection purpose, only the integer part is used, but OF computes entire fixed-point value (16-bit). Once a node (say N) has chosen its preferred parent (P), node computes its own rank from preferred parent's rank as defined in (2) where $step = MAX_{energy} - Node_{energy}$.

$$\begin{aligned} &Rank(N) = Rank(P) + Rank_{incr} \\ &\text{with } Rank_{incr} = step + MinHopRankIncr \end{aligned} \quad (2)$$

This formula ensures the monotonicity property of the rank which increases by at least one point (`MinHopRankIncr`) between node and its preferred parent, when child node has a full battery level. The increment is even greater as node consumes its battery, because of penalty of step which feeds the fractional part of fix-point rank value. By cumulative effect of penalties in the node's parentage, node's rank can grow to more than one point as shown in figure 1 (rank increase between node 5 and 7). Root rank is set to the same value as `MinHopRankIncr` (256 in this example).

3 RELATED WORK

Among techniques used to maximize the network lifetime, energy aware routing protocols appear to be suitable for multi-hop wireless sensor networks, since they explicitly take into account node residual energy for route establishment. EESP (Shivaprakasha and Kulkarni, 2011) follows shortest path algorithm by combining distance and node residual energy as cost. Similarly, (Mohajerzadeh and Yaghmaee, 2009) proposed an algorithm which considers both energy and delay metric to find an optimal path. (Chiang et al., 2007) proposed Minimum Hop (MH) routing protocol which organize routing topology based on nodes hop counts and battery power levels. For a given node, neighbors are classified into three categories: *parent*, *sibling* and *child node*, on the basis of their vicinity in hop count to the sink, respectively one less, same, and one more than that of the sending node. MH first tries to reach sink by path through a parent node, which guarantee a min hop path. In case of more than one parent, the protocol uses the one with the highest energy level. If there is no parent node available, the sender forwards data through the sibling node with the highest energy level. MH uses a local (parent or sibling) energy view of the sender for next hop selection, and does not always reflect the real energy distribution of node in the path. On contrary, (El-Semary and Azim, 2010) proposed the path energy weight protocol that improve MH by using an energy-weighted function, to indicate how balanced is the energy among all nodes along a given path. This path weight takes into account all nodes energy along the path, although greatly disadvantaging lower energy nodes. In our approach only the lowest node energy constrained the path. All previous protocols improve the average energy consumption in the network compared to a solely hop count-based protocol. Their major difference is that, they use the later as main criterion for next hop selection, node's energy level is usually used to break the tie. We do present another scheme, namely one that favors node energy on a routing standard for WSN, while using the rank notion to avoid routing loops.

4 SIMULATIONS AND RESULTS

4.1 Environment Setup

Experiments were carried out using Cooja simulator (Osterlind and Dunkels, 2006). Network topology is a $300 \times 300m^2$ 2D-grid of 20 sensors, the sink is located at the upper left corner. Each sensor node acts in a $120m$ maximum transmission range with $140m$ interference range, and periodically sends data to the sink using UDP as the transport layer with a Tx/Rx success ratio of 80%. The layer 2 medium access control is ContikiMAC (Dunkels, 2011) that provides power efficiency by the node keeping their radios turned off for roughly 99% of the time. All nodes have full battery charge at the beginning of the simulations, with an initial power level set to $880mAh$. The hardware characteristics for the simulation computer are 3.2Ghz Dual Core Intel XEON processor board, with 8GiB Memory size, on Ubuntu 11.10 operating system.

4.2 Results

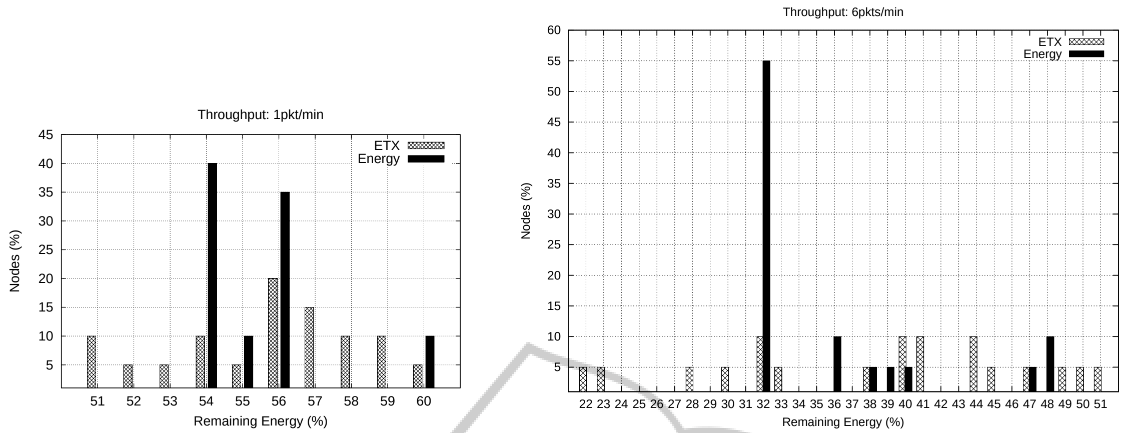
Simulations were performed for one month network activities (corresponding to 13 real days on our simulation computer). We define the network lifetime as the date on which the first node has completely exhausted its battery (Dietrich and Dressler, 2009). The energy aware RPL implementation was compared against the ETX implementation. For both, the sink collects data generated at various throughput expressed as the number of application packets per minute (*pkts/min*), each having 87 bytes of size. Then, we evaluate energy depletion and packet delivery ratio for both scenarios, one at $1pkt/min$, the other at $6pkts/min$.

4.2.1 Remaining Power Distribution

Energy aware routing aims to use nodes with higher remaining power level, thus these nodes drain their battery more quickly and further become less attractive to relay data. The network should be reorganized to find more interesting nodes for routing and so on, thereby a balancing on all nodes battery levels should occur. This can be seen in figure 2 which presents the proportion of nodes in the network with the corresponding percentage of remaining energy at the end of the simulation. In figure 2a at $1pkt/min$, 85% of nodes have the power level between the range 54% to 56%, whereas the ETX-based routing spread the energy distribution unequally among the nodes. At a higher rate ($6pkts/min$) in figure 2b, this observation is much more pronounced, since the traffic flow is more important and nodes exhaust their battery much faster. At the same time, in both illustrations the ETX-based scheme presents much less-power nodes (around 20%) than the energy aware scheme, the latter delaying the first nodes that will completely exhaust their battery and the possibility to create network holes. This is an important point, because the network integrity can be affected when some nodes are stopped. We estimated by a linear regression when first nodes drain completely their energy. Computations indicate a network lifetime of 35 days for ETX-based RPL, while 40 days for energy aware scheme, thus the increase in network lifetime is around 14%.

4.2.2 Transmission Accuracy

We also evaluated the accuracy of routing to collect the application data. The table 1 highlights the total number of received packets at the sink for both rates. ETX-based routing promotes routes with higher packets delivery ratio, while energy aware routing don't care on that. It is therefore not surprising that



(a) (b)

Figure 2: Nodes Remaining Power Distribution.

the number of received packets with ETX is slightly greater than energy aware scheme as outlined by the table, but this delivery ratio difference between these two schemes is minimal (only around 3%).

Table 1: Transmission Accuracy.

Throughput	Sent Pkt	Received (ETX)	Received (Energy)
6 pkts/min	4488635	4390282 (97.80%)	4251962 (94.72%)
1 pkt/min	748105	735680 (98.34%)	722394 (96.56%)

5 CONCLUSIONS AND FUTURE WORKS

In this paper, we presented an instantiation and implementation of the routing protocol for low power and lossy network that uses the node's remaining energy as the main routing metric. The implementation makes use of a well-known battery theoretical model from which we estimate at runtime the node battery lifetime for routing. Experiments reveal that, compared to the popular RPL ETX-based scheme, the proposed implementation increase the network lifetime and distributes energy evenly among nodes without an appreciable lack of the transmission accuracy.

Our future works aims to combinate these both metrics (energy and ETX), in accordance with (Zahariadis and Trakadas, 2012). We expect to leverage the strengths of each, and obtain a better compromise. Furthermore we seek to provide additional decision criteria in order to better guide the routing decisions in WSN.

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