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MAC-aware Routing Metrics for Low Power and Lossy Networks

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Abstract—In this paper, routing metrics for low power and lossy networks are designed and evaluated. The cross-layer interactions between routing and medium access control (MAC) are explored, by considering the specifications of IETF RPL over the IEEE 802.15.4 MAC. In particular, the experimental study of a reliability metric that extends the expected transmission count (ETX) to include the effects of the level of contention and the parameters at MAC layer is presented. Moreover, a novel metric that guarantees load balancing and increased network lifetime by fulfilling reliability constraints is introduced. The aforementioned metrics are compared to a routing approach based on back-pressure mechanism.

I. INTRODUCTION

Low power and lossy networks (LLNs) are composed by many wirelessly interconnected devices with limited power, memory, and processing resources. The IEEE 802.15.4 [1] standard defines flexible physical and MAC layers for low data rate and low power applications. According to recent surveys, the standard represents more than 50% of building and industrial automation market. Meanwhile, routing protocols are still being under standardization. The Internet Engineering Task Force (IETF) is currently working towards the specification of a reference standard for LLNs, the IETF routing protocol for low power and lossy networks (RPL) [2]. RPL is designed to be compatible with many existing MAC protocols, particularly the IEEE 802.15.4 MAC.

The current routing metrics such as ETX [3] or back-pressure routing [4] are designed independently of the MAC layer. However, in many applications, it is inefficient to design MAC and routing protocols separately. In the network, the decision over different routing paths depends on the performance indicators (successful packet reception probability, or reliability, delay, and energy consumption), which are influenced by the MAC parameters. On the other side, routing determines the distribution of the traffic load in the network that affects the reliability, the delay and the energy consumption. In the following, we give more details about the required cross-layer interactions and we propose and validate two routing metrics that guide the interactions between MAC and routing, without requiring modifications of the standards.

II. MAC-AWARE ROUTING METRICS

In this section, we present two metrics that are based on the link performance at the MAC layer. Moreover, they are simple and easy-to-implement in practice using mechanisms defined in standards. Considering a node V_i (as depicted in the example topology in Fig. 1), we denote by R -metric: $R(i) =$

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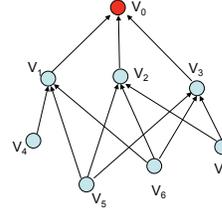


Fig. 1. Routing graph example for a topology with single root node V_0 . $R_{i,0}$, where $R_{i,0}$ is the end-to-end reliability between node V_i and the sink node V_0 . Node i forwards its packets by selecting a parent V_j that

$$\underset{j \in \Gamma_i}{\text{maximize}} \quad R_{i,j} \cdot R(j).$$

The set of candidate receivers Γ_i is composed by the set of nodes that can guarantee a progress towards the destination V_0 , according to RPL specifications. An analytical model based on Markov chain analysis to derive analytically the reliability $R(i)$ is presented in [5]. For a given forwarded traffic Q_i , the reliability is a function of the backoff and retransmission parameters at MAC layer. The forwarded traffic Q_i includes the traffic λ_i generated by the node, and the traffic originated by children nodes. Moreover, the reliability is a function of the busy channel probability α_i , which is not known *a priori*. However, α_i can be estimated at node V_i during the channel access procedure, using a sliding window.

ETX, the default reliability metric in RPL, is an additive metric over a path. It estimates the expected number of retransmissions needed to reach a destination. R -metric extends ETX, by considering also packet losses due to the MAC contention. In fact, R -metric is based on the probability that a packet is successfully transmitted over each link of a path, within a maximum number of backoffs and retransmissions at the MAC layer. This estimation of this probability is faster than the ETX estimation, which is performed over a certain number of received ACKs. We illustrate the difference between the two metrics through a simple numerical example.

In Fig. 1, node V_7 can use two paths to the destination, one path through V_2 and the other through V_3 . Assume that the path through V_2 has $ETX_{7,2} = 2$ and $ETX_{2,0} = 2.25$, which determines a total expected number of retransmissions $ETX_{7,0} = 4.25$ to the destination. The second path has $ETX_{7,3} = 1$ and $ETX_{3,0} = 3$, which makes a total $ETX_{7,0} = 4$. In absence of a retry limit at MAC layer, the second path through V_3 has the minimum ETX value and gives the highest end-to-end delivery ratio. However, if we set a maximum number of retransmissions $n = 3$, the link $(3,0)$ will have a high dropping probability at MAC layer, since the expected number of retransmissions approaches the maximum number of allowed retransmissions per packet. The path through V_2 guarantees a better end-to-end reliability.

For low power applications, the reliability can be just set in terms of minimum requirement, and the objective is mainly the improvement of the network lifetime. We propose a metric, called Q -metric, that determines the traffic that must be handled by a specific node providing in this way a balanced traffic distribution in the network. Node V_i selects the forwarding parent by solving the following optimization problem,

$$\begin{aligned} & \underset{j \in \Gamma_i}{\text{minimize}} && P_t Q_j + P_r (Q_j - \lambda_j) && \text{(II.1)} \\ & \text{subject to} && R_{i,j} \cdot R(j) \geq R_{\min}, \end{aligned}$$

where P_t is the transmission power consumption, P_r is the reception power consumption, and R_{\min} is the required reliability by the application. The cost function in Eq. (II.1) is the sum of the cost for transmitting the total traffic Q_j and cost for receiving traffic generated by children nodes ($Q_j - \lambda_j$). The metric provides load balancing by selecting the lightest parent, in terms of traffic load. As far as the implementation of this metric is concerned, node V_i needs only local information about its own forwarded traffic Q_i , and the generated and forwarded traffic from each candidate destination, which is available through the exchange of the control DIO messages in RPL.

The back-pressure algorithm [4] uses a weighted ETX cost, which includes the queue differential between transmitter and receiver. However, the back-pressure metric is not able to capture the contention level when the traffic load is low (which is the case in most WSN applications in real life). Q -metric is able to directly measure the contention level without measuring the node queues. In the next section, we present the effectiveness of the proposed metrics in comparison to the back-pressure routing.

III. EXPERIMENTAL EVALUATION

We present experimental results related to the performance of IETF RPL, the contention-based IEEE 802.15.4 MAC and the proposed enhancements. As a benchmark, we evaluate the performance of our metrics against the back-pressure algorithm proposed in [4].

The IEEE 802.15.4 protocol is implemented on a test-bed using the TelosB platform. We assume the topology in Fig. 1, where each node generates the same traffic with rate $\lambda = 5$ pkt/s, except V_2 that generates traffic with rate $\lambda_2 = 20$ pkt/s (dominant node). We chose the unslotted MAC modality since it is one of the recommended in the IETF RPL standard. However, the methodology that we have proposed above can be applied to any randomized MAC, compatible with IETF RPL.

In Fig. 2(a), we present the end-to-end reliability of each node. R -metric guarantees high reliability for the dominant node V_2 which forwards most of the traffic in the network. However, the reliability of V_4 is compromised. When using the R -metric, nodes V_4 – V_7 tend to forward their traffic through the dominant node V_2 , thus reducing the level of contention at the MAC layer. When using the Q -metric, nodes V_4 to V_7 tend to distribute the traffic uniformly in the set of candidate receivers V_1 to V_3 thus increasing the level of contention. The average end-to-end reliability of the network is higher for the R -metric. However, by reducing the level of contention at the

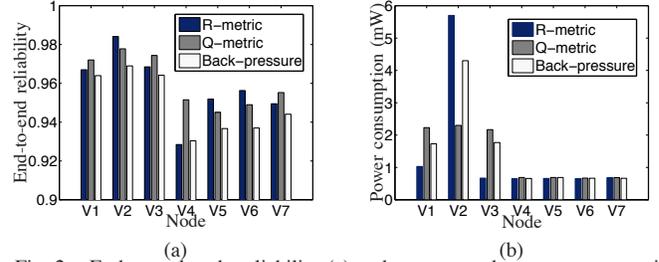


Fig. 2. End-to-end node reliability (a) and average node power consumption (b) for the multi-hop topology in Fig. 1, by fixing $\lambda_i = 5$ pkt/s for $i \neq 2$ and $\lambda_2 = 20$ pkt/s.

dominant nodes, the R -metric increases the level of contention for the communication paths that do not include the dominant nodes. Therefore, end-to-end reliability in the path that includes V_4 and V_1 is affected significantly by the dominant node V_2 . Q -metric guarantees a minimum reliability of 95% among all nodes and outperforms the back-pressure metric. The frequent parent switching in the back-pressure routing causes an increase of the traffic due to high DIO message transmissions that affect the reliability. We conclude that Q -metric is preferable if a guaranteed reliability is required for all paths in the network (which is desired by many control applications).

In Fig. 2(b), we present the average power consumption of each node. The calculation of the power consumption considers packet transmission and reception, idle-listening, and carrier sensing for each node. By choosing the dominant node V_2 as forwarder, the R -metric determines an unbalanced energy consumption. Node V_2 has a power consumption up to 6 mW, while the rest of the network operates between 0.5 mW and 1 mW. With the Q -metric, the power consumption is more balanced among nodes and the maximum consumption, which is crucial for the network lifetime, decreases of at least a factor 2 compared to the R -metric. The back-pressure routing present a reduction of the maximum energy consumption when compared to the R -metric. However, the dominant node V_2 consumes 70% more power compared to the Q -metric.

IV. CONCLUSIONS

We presented and evaluated two routing metrics that take into account the dynamic behavior of the MAC and routing layers in LLNs. We directly compared their performance to existing routing metrics. The inclusion of such an experimental study in the current standardization process could be very beneficial in the direction of improving the performance of LLNs under realistic conditions.

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