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Reliable link quality estimation in low-power wireless networks and its impact on tree-routing



Nouha Baccour^{a,d,*}, Anis Koubâa^{b,d}, Habib Youssef^c, Mário Alves^d

^a Department of Computer Science, National Engineering School of Sfax, Tunisia

^b Prince Sultan University, Saudi Arabia

^c Higher Institute of Computer and Communication Techniques, Tunisia

^d CISTER/INESC-TEC, ISEP, Polytechnic Institute of Porto, Porto, Portugal

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ABSTRACT

Radio link quality estimation is essential for protocols and mechanisms such as routing, mobility management and localization, particularly for low-power wireless networks such as wireless sensor networks. Commodity Link Quality Estimators (LQEs), e.g. PRR, RNP, ETX, four-bit and RSSI, can only provide a partial characterization of links as they ignore several link properties such as channel quality and stability. In this paper, we propose F-LQE (Fuzzy Link Quality Estimator, a holistic metric that estimates link quality on the basis of four link quality properties—packet delivery, asymmetry, stability, and channel quality—that are expressed and combined using Fuzzy Logic. We demonstrate through an extensive experimental analysis that F-LQE is more reliable than existing estimators (e.g., PRR, WMEWMA, ETX, RNP, and four-bit) as it provides a finer grain link classification. It is also more stable as it has lower coefficient of variation of link estimates. Importantly, we evaluate the impact of F-LQE on the performance of tree routing, specifically the CTP (Collection Tree Protocol). For this purpose, we adapted F-LQE to build a new routing metric for CTP, which we dubbed as F-LQE/RM. Extensive experimental results obtained with state-of-the-art widely used test-beds show that F-LQE/RM improves significantly CTP routing performance over four-bit (the default LQE of CTP) and ETX (another popular LQE). F-LQE/RM improves the end-to-end packet delivery by up to 16%, reduces the number of packet retransmissions by up to 32%, reduces the Hop count by up to 4%, and improves the topology stability by up to 47%.

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1. Introduction

Typically, radio transceivers used in Wireless Sensor Networks (WSNs) are low-cost and low-power, due to scalability and lifetime requirements. This fact makes radiated signals very prone to noise, interference, and multi-path distortion. Furthermore, these radio transceivers rely on antennas with non-ideal radiation patterns leading to

anisotropic connectivity. Consequently, radio links in WSNs are extremely unreliable and often unpredictable. They experience quality fluctuation over time [1,2] and space [3,4], and their connectivity is typically asymmetric [3,5]. The unreliability of WSN links greatly affects the network performance. This raised the need for link quality estimation as a fundamental building block for the design of network protocols and mechanisms, including medium-access control (MAC), routing, mobility management, localization, and topology control.

Link quality estimation enables network protocols to mitigate and to overcome link unreliability. For instance, link quality estimation is instrumental for routing protocols

* Corresponding authors at: CISTER/INESC-TEC, ISEP, Polytechnic Institute of Porto, Porto, Portugal.

E-mail addresses: nabr@isep.ipp.pt (N. Baccour), aska@isep.ipp.pt (A. Koubâa), habib.youssef@fsm.rnu.tn (H. Youssef), mjf@isep.ipp.pt (M. Alves).

to maintain correct network operation [6–13]. Delivering data over high quality links (i) improves the network delivery by limiting packet loss and (ii) maximizes its lifetime by minimizing the number of retransmissions, and avoiding route reselection triggered by link failures.

Basically, link quality estimation consists of evaluating a metric, a mathematical expression, within an estimation window w (e.g., at each w seconds, or based on w received/sent packets). We refer to this metric as Link Quality Estimator (LQE). Existing LQEs can be classified as either hardware-based or software-based. Hardware-based LQEs such as the Received Signal Strength Indicator (RSSI) are directly read from the radio transceiver, i.e., they do not require any additional computation. Software-based LQEs are derived based on collected packet statistics e.g., packet sequence number. Some of them either count or approximate the packet reception ratio or the average number of packet transmissions/ retransmissions, and some others provide a score that identify the link state.

Existing LQEs (hardware or software) are not sufficiently accurate because they assess some link properties and ignore others, which provide a partial characterization of the link [14,15]. For example, the Packet Reception Ratio (PRR) can only capture link delivery property. It ignores other important properties that impact the link quality, such as asymmetry or stability. A link may have a good PRR and thus appears as a “good quality link”, whereas the link involves several MAC retransmissions due to its high asymmetry (some acknowledgements are not delivered). Hence, the link state characterized on the basis of PRR alone can be misleading. A link that has a good delivery but has also high asymmetry is not a good quality link. Therefore, the main question investigated in this paper is the following:

Is it possible to design an LQE that provides a holistic characterization of low-power links, by combining several aspects/properties that impact overall link quality (e.g., asymmetry, stability, channel quality), so that to improve the performance of higher layer mechanisms/protocols such as routing?

We believe that such holistic link quality estimation can be achieved through a composite LQE that combines several link metrics. Each metric captures a particular link property. However, four main challenges should be addressed:

- The first challenge is **which link properties to consider** and what metrics to use for their assessment. A vast array of research works tackled the empirical characterization of low-power links through real-world measurements with different platforms, under different experimental conditions, assumptions, and scenarios (e.g., [1,2,4,16–20]). Therefore, there is the need to thoroughly analyze their outcomes, and identify the most relevant key observations. Such observations would be helpful to determine the most important properties that impact the quality of low-power links.
- The second challenge is **how to combine selected metrics**, given that they do not have necessarily the same nature. This challenge should be carefully addressed as a LQE can involve appropriate link metrics but the resulting link quality estimate may not be effective due to the inadequacy of the

combination technique. For example, Rondinone et al. [21] suggest combining PRR and RSSI metrics through the multiplication of PRR by the normalized average RSSI. Another alternative would be a combination through a weighted sum.

- The third challenge is **how to validate this composite LQE**. The performance evaluation of LQEs is not a trivial task. One of the reasons is the impossibility, or at least the difficulty, to provide a quantitative evaluation of the accuracy of LQEs. In fact, there is no objective link quality metric to which a given link quality estimate can be compared. Furthermore, there are LQEs that are based on the packet reception ratio, some others are based on packet retransmission count, while others are hybrid and more complex. Thus, comparing their performance becomes challenging as they have different natures.
- The fourth challenge is **how can a particular LQE be used to boost the performance of higher layer protocols** e.g., tree-routing protocols, the most widely used for data collection wireless sensor networks.

This paper makes three main contributions. First, we propose F-LQE [22] (Section 3), a novel LQE for wireless sensor networks. In contrast to existing LQEs (Section 2), which assess link quality based on one or two link properties, F-LQE combines multiple metrics using Fuzzy Logic. Fuzzy logic provides a rigorous algebra to describe and combine different and imprecise metrics. The overall quality of the link is a result of the evaluation of a Fuzzy IF-THEN rule, which combines the different metrics, viewed as linguistic variables. The evaluation of the fuzzy rule returns the membership of the link in the fuzzy subset of good links. Second, we conduct a comparative performance study of LQEs, including F-LQE, PRR, WMEWMA, ETX, and four-bit (Section 4), based on a thorough experimental evaluation. This comparative study allowed us to show that F-LQE is more reliable and more stable than existing LQEs. Third, we investigate the use of F-LQE for improving collection tree routing, specifically the Collection Tree Protocol (CTP). Hence, we first design a routing metric based on F-LQE called F-LQE/RM (Section 5); then, we compare its impact on the performance of CTP with that of representative routing metrics (Section 6). Experimental results show that F-LQE/RM outperforms these routing metrics: it improves the end-to-end-delivery, reduces the number of packet retransmissions, reduces the hop count, and improves the topology stability. We conclude the paper by presenting some lessons learned throughout our experience on link quality estimation in WSNs, for the readers' convenience (Section 7). Table 1 outlines the organization of this paper.

2. Related work

In this section, we position our work, especially our introduced LQE, within the related literature.

2.1. Short-term link quality estimators

Few recent research works, such as [23–25] argue that intermediate-quality links, also referred as bursty links,

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