Unraveling the Subtleties of Link Estimation and Routing in Wireless Sensor Networks

Hongwei Zhang
Department of Computer Science
Wayne State University, USA
hzhang@cs.wayne.edu

Lifeng Sang, Anish Arora
Department of Computer Sci. & Eng.
The Ohio State University, USA
{sangl, anish}@cse.ohio-state.edu

ABSTRACT: We answer the following questions for routing in wireless sensor networks: 1) should broadcast beacon or data serve as the basis of link estimation? 2) how to use MAC feedback in data-driven link estimation and routing? 3) how to address the issue of biased link sampling in data-driven link estimation and routing.

Categories and Subject Descriptors: C.2.2 [Network Protocols]: Routing protocols

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Wireless communication assumes complex spatial and temporal dynamics, thus estimating link properties is a basic element of routing in wireless networks. One commonly used approach of link estimation is letting neighbors exchange broadcast beacon packets, and then estimating link properties of unicast data transmissions via those of broadcast beacons. Nonetheless, there are significant differences between unicast and broadcast link properties, and it is difficult to precisely estimate unicast link properties via those of broadcast due to temporal correlations in link properties and dynamic, unpredictable network traffic patterns [9].

The research community has proposed mechanisms to ameliorate the impact of the differences between broadcast and unicast link properties, and MAC feedback carrying information about unicast data transmissions has also been used in link estimation [2, 3, 4, 5, 6, 8, 9]. Nonetheless, there has been no systematic characterization of the inherent drawbacks in estimating unicast properties via those of broadcast, some protocols [6, 8] use MAC feedback mainly for saving energy in link estimation (e.g., by reducing the frequency of broadcast beacon exchanges), and some protocols [2, 4, 8] use both broadcast-based and MAC-feedback-based link estimation. One open question here is, from the perspective of estimation accuracy, whether broadcast beacons should be used as the basis of link estimation in low-power sensor networks. This is an important question because link estimation accuracy significantly affects routing performance.

In the context of data-driven link estimation that uses MAC feedback for unicast data transmissions, MAC feedback of mote networks carries rich information (e.g., both the number of physical transmissions and the time taken for a unicast transmission), and different methods of using these information have been proposed [2, 3, 6]. But there has been no systematic study on the accuracies of these different data-driven link estimation methods, and thus it is still unclear what the guidelines should be for using the rich information in MAC feedback.

In data-driven link estimation, if a link is not currently used for data transmission, its current properties will most likely be unknown to the associated node (since the correlation among links associated with the same node tends to be complex and difficult to predict). This introduces the issue of *biased link sampling* (BLS) where properties of actively used links are constantly sampled and updated but properties of unused links are not sampled and unknown. BLS is not a problem if link properties are mostly static and do not change temporally. Nonetheless, temporal link dynamics is usually unavoidable due to dynamics in network traffic pattern and thus traffic-induced interference [9, 10], dynamics in environment [1, 7], and/or node mobility. Accordingly, data-driven link estimation and routing may not converge to the optimal solution since, due to BLS, a route that is not currently used but has become optimal may not be discovered. Despite their importance, the stability of data-driven link estimation and routing (i.e., the stability of a node's best route or next-hop forwarder) and the severity that BLS affects routing optimality have not bee well studied, and only ad hoc, if any, solutions have been proposed in existing protocols. For instance, CARP [5], four-bit-estimation [2], and NADV [6] do not examine the BLS issue; LOF [9] and SPEED [3] exploratively sample alternative routes at randomized but high frequency (i.e., once every few and every single packet transmission respectively), which can reduce routing performance; EAR [4] implicitly addresses the BLS issue by letting every node constantly overhear unicast transmissions around it, which not only is not energy-efficient in battery-powered sensor networks (since overhearing increases nodes' duty cycle) but can also lead to estimation errors since, due to MAC coordination mechanisms such as RTS-CTS handshake, the properties of overheard unicast transmissions may well be different from those of unicast transmissions to a node itself. Thus, the lack of a thorough understanding of the BLS issue is an important problem since it affects the performance of a basic service in sensor networks — routing.

Focusing on the accuracy of estimating unicast data transmission properties and the BLS issue, our objectives in this work are to characterize the limitations of beacon-based link estimation, to comparatively study different data-driven link estimation methods, and to study the open, unexplored

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question of how serious the BLS issue is and how to effectively address it in the presence of (potentially unpredictable) network dynamics.

Findings. Using a testbed of 98 XSM motes, we examine the impact of interference patterns on link properties, and we characterize the significant, unpredictable errors in estimating unicast properties via broadcast beacons in low-power wireless sensor networks. We also demonstrate the complex, unpredictable nature of temporal correlations in link properties, which, together with uncertainties in interference patterns, motivates the approach of data-driven link estimation and routing. Through experimentation with a realistic event traffic trace, we also show that data-driven link estimation and routing greatly improves the event reliability (e.g., by 18.75%) and energy efficiency (e.g., by a factor of 1.96) of beacon-based approaches. These results provide solid empirical evidence on the drawbacks of beacon-based estimation and the benefits of data-driven link estimation and routing.

Having justified the necessity of data-driven link estimation and routing, we classify existing methods of using unicast MAC feedback into two broad categories represented by two seemingly similar protocols: *L-NT* where the number of physical transmissions for each unicast is directly used to estimate the expected number of transmissions along a link, and *L-ETX* where we use the number of physical transmissions for each unicast to calculate the reliability of unicast physical transmissions which is then used to estimate the expected number of transmissions along a link. Through mathematical and experimental analysis, we show that L-ETX achieves higher estimation accuracy than L-NT, and thus L-ETX uses the optimal routes with a higher probability than L-NT does. For instance, Figure 1 shows, for a

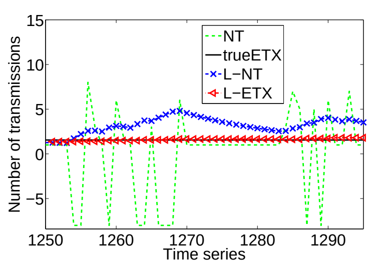

Figure 1: Time series of estimated ETX values in L-NT and L-ETX for a link of length 30 feet. To easily represent a unicast failure (after 7 retransmissions), we present -8 as the NT value for the corresponding transmission.

link of length 30 feet, the time series of the estimated ETX values via L-NT and L-ETX respectively. Using a realistic event traffic trace, we show that L-ETX achieves higher event reliability (e.g., by 25.18%) and energy efficency (e.g., by a factor of 3.75) than L-NT, and that, compared with L-NT, L-ETX is able to find longer yet more reliable links to use in routing. We also find out that link estimation is much more stable in L-ETX than in L-NT, which enables stable routing structures in L-ETX. Additionally, we show that L-ETX outperforms other variants of L-NT too. These findings elucidate important subtleties of data-driven link estimation and provide new insight into the question of how to use MAC feedback in designing routing protocols for low-power sensor networks.

Focusing on traffic-induced dynamics (i.e., varying network conditions due to changes in network traffic pattern) and through mathematical analysis and testbed-based experimentation, we examine the stability of optimal routes and the severity of BLS in L-ETX. For a wide range of dynamic traffic scenarios (e.g., dynamic events, dynamic data collection, and their mix) and network setups (e.g., grid and random networks) we study, we find out that nodes' best forwarders and the optimal routing structure are rather stable even though the properties of individual links and routes may vary significantly as traffic pattern and network condition change. In cases where the optimal routing structure does change, we prove that data-driven link estimation and routing is guaranteed to converge to the optimal structure when network conditions worsen, and the convergence is quick (e.g., with a median sample size requirement of no more than 7); when network conditions improve, the optimal forwarder chosen for heavy traffic load tends to remain a good suboptimal forwarder for lighter traffic load, even though data-driven routing may not converge to the optimal structure.

These findings provide the foundation for addressing the BLS issue in the presence of traffic-induced dynamics. In contrast to existing approaches, for instance, these findings demonstrate the need to address the BLS issue, the drawbacks of frequent explorative sampling in mostly static networks, and the feasibility of an energy-efficient, light-weight approach to addressing the BLS issue. These findings also demonstrate that it is possible to maintain an optimal, stable routing structure despite the fact that the properties of individual paths vary in response to network dynamics. Since routing stability enables predictable routing performance, these findings also suggest that we may regard stability as a basic evaluation criterion for routing metrics.

Detailed discussion of this work can be found at the technical reports [10] and [11].

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