Experimental Analysis of Link Estimation Methods in Low Power Wireless Networks

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***Abstract*—Wireless sensor networks are envisioned to be an integral part of cyber-physical systems, yet wireless networks are inherently dynamic and come with varieties of uncertainties. One such uncertainty is wireless communication itself which assumes complex spatial and temporal dynamics. For dependable and predictable performance, therefore, link estimation has become a basic element of wireless network routing. Several approaches using broadcast beacons and/or unicast MAC feedback have been proposed in the past years, but there still lacks as a systematic characterization of the drawbacks and sources of errors in beacon-based link estimation in low-power wireless networks, which leads to ad hoc usage of beacons in routing. Using a testbed of 98 XSM motes (an enhanced version of MICA2 motes), we characterize the negative impact that link layer retransmission and traffic-induced interference have on the accuracy of beacon-based link estimation, and we show that data-driven link estimation and routing achieves higher event reliability (e.g., by up to 18.75%) and transmission efficiency (e.g., by up to a factor of 1.96) than beacon-based approaches. These findings provide solid evidence for the necessity of data-driven link estimation and demonstrate the importance of addressing the drawbacks of beacon-based link estimation when designing protocols for low-power wireless networks of cyber-physical systems.**

***Index Terms*—Low-power wireless networks, sensor networks, link estimation and routing, data-driven, beacon-based**

I. Introduction

After the past decade of active research and field trials, wireless sensor networks have started penetrating into many areas of science, engineering, and our daily life. They are also envisioned to be an integral part of cyber-physical systems (CPS) such as those for alternative energy, transportation, and healthcare. In supporting mission-critical, real-time, closed loop sensing and control, CPS sensor networks represent a significant departure from traditional sensor networks which usually focus on open-loop sensing, and it is critical to ensure dependable and predictable network performance in CPS sensor networks.

Nonetheless, wireless sensor networks are inherently dynamic and susceptible to the impact of a variety of uncertainties. One such uncertainty is wireless communication itself which assumes complex spatial and temporal dynamics [1], [2], [3], [4]. Wireless communication properties significantly affect many sensor network services, and one such service is wireless routing, which is the basis of cross-node coordination in CPS sensor networks. For dependable and predictable performance, therefore, estimating link properties has become 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 [5], [6], 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 [7], [8].

The research community has proposed mechanisms to ameliorate the impact of the differences between broadcast and unicast link properties [5], [6], and MAC feedback carrying information about unicast data transmissions has also been used in link estimation [9], [10], [11], [12], [13], [14], [8]. For low-power wireless networks, however, there still lacks a systematic characterization of the drawbacks and sources of errors in estimating unicast properties via those of broadcast; some protocols [13], [14] use MAC feedback mainly for saving energy in link estimation (e.g., by reducing the frequency of broadcast beacon exchanges), and some protocols [9], [11], [14] use both broadcast-based and MAC-feedback-based link estimation. Thus one open question is, from the perspective of estimation accuracy, whether broadcast beacons should be used as the basis of link estimation in low-power wireless networks such as sensor networks. This is an important question because, as we discuss later in the paper, link estimation accuracy significantly affects data delivery reliability and transmission efficiency which are important for mission-critical networked sensing and control in CPS.

Focusing on the accuracy of estimating unicast data transmission properties, our objectives in this paper are to characterize the limitations of beacon-based link estimation, to experimentally quantify the impact that link layer retransmission and traffic-induced interference have on beacon-based estimation, and to comparatively study beacon-based and data-driven link estimation methods in low-power wireless networks.

Using a testbed of 98 XSM motes, we characterize the significant, unpredictable errors in estimating unicast properties via broadcast beacons, and we examine the impact of interference patterns on link properties 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. Using traffic traces for both bursty event detection and periodic data collection and using both grid and random network topologies, we experimentally demonstrate that data-driven link estimation and routing greatly improves the event reliability (e.g., by 18.75%) and transmission efficiency (e.g., by a factor of 1.96) of beacon-based approaches. These findings suggest that, even though broadcast beacons are useful in many aspects of wireless network design such as neighborhood management as well as routing loop detection and removal, beacons have inherent drawbacks when serving as the basis of fine-grained estimation of unicast data transmission properties; these findings also demonstrate the benefits of data-driven link estimation and routing, thus suggesting that data-driven link estimation be a basic principle for protocol design in low-power wireless networks.

The rest of the paper is organized as follows. In Section II, we systematically characterize the drawbacks of beacon-based link estimation and examine the necessity of data-driven link estimation and routing in low-power wireless networks. We compare beacon-based and data-driven link estimation and routing in Section III. We present additional performance evaluation results in Section IV. Finally, we discuss related work in Section V and make concluding remarks in Section VI.

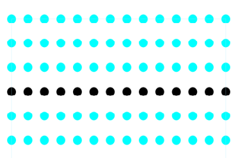
II. WHY DATA-DRIVEN LINK ESTIMATION

In this section, we characterize, via the *Kansei* [15] sensor network testbed, the sources of errors and inherent difficulties in predicting unicast data transmission properties via broadcast beacons in low-power wireless networks. We first present the experiment design and then the experimental results.

A. Experiment design

In an open warehouse with flat aluminum walls (see Figure 1(a)), Kansei deploys 98 XSM motes [16] in a 14×7 grid (see Figure 1(b)) where the separation between neighboring grid points is 0.91 meter (i.e., 3 feet). The grid deployment pattern enables experimentation with regular, grid topologies, as well as random topologies (e.g., by randomly selecting nodes of the grid to participate in experiments). XSM is an enhanced version of Mica2 [17] mote, and each XSM is equipped with a Chipcon CC1000 [18] radio operating at 433 MHz. To form multihop networks, the transmission power of the CC1000 radios is set at -14dBm (i.e., power level 3) for the experiments of this paper unless otherwise stated. XSM uses TinyOS [19] as its operating system. For all the experiments in this paper, the default TinyOS MAC protocol B-MAC [20] is used;[1] a unicast packet is retransmitted, upon transmission failure, at the MAC layer for up to 7 times until the transmission succeeds or until the 8 transmissions have all failed; a broadcast packet is transmitted only once at the MAC layer (without retransmission even if the transmission has failed). For convenience, we call the individual transmissions involved in transmitting a unicast packet the unicast-physical-transmissions.

(a) Kansei



(b) 14×7 grid

Fig. 1: Sensor network testbed *Kansei*

To demonstrate the difficulty in precisely estimating unicast properties via those of broadcast beacons, we let the mote on the left end of the middle row (shown as black dots in Figure 1(b)) be the *sender* and the rest 13 motes of the middle row as the *receiver*s, and we measure the unicast and broadcast properties of the links between the sender and individual receivers. (We have observed similar phenomena as what we will present in Section II-B for other sender-receiver pairs.) The sender transmits 15,000 broadcast and 15,000 unicast packets to each of the receivers with a 128-millisecond inter-packet interval, and each packet has a data payload of 30 bytes. Based on packet reception status (i.e., success or failure) at the receivers, we measure unicast and broadcast link properties. Note that, in practice, broadcast beacons are transmitted at a much larger interval (e.g., 30 seconds) than 128ms, and we use 128ms mainly for saving experimentation time. The phenomena observed with the 128ms inter-beacon interval applies to cases where larger intervals are used since wireless channel coherence-time is much shorter than 120ms in general [21], for instance, being ∼4ms; we will also show that the observed drawbacks of beacon-based estimation are corroborated through multi-hop routing experimentation in Section III.

To examine the impact of traffic-induced interference on link properties and link estimation, we randomly select 42 motes out of the light-colored (of color cyan) 6 rows as *interferer*s, with 7 interferers from each row on average. Each interferer transmits unicast packets (of payload length 30 bytes) to a destination randomly selected out of the other 41 interferers. The load of the interfering traffic is controlled by letting interferers transmit packets with a certain probability d whenever the channel becomes clear. Ng $et\ al.$ [22] showed that the optimal traffic injection rate is 0.245 in a regular linear topology, and the optimal traffic injection rate will be even lower in general, two-dimensional network. Thus our measurement study focuses more on smaller d's than on larger ones, but we still study larger d's to get a sense on how systems behave in extreme conditions. More specifically, we use the following d's in our study: 0, 0.01, 0.04, 0.07, 0.1, 0.4, 0.7, and 1. Thus the interference pattern is controlled by d in this case. (Note that phenomena similar to what we will present in Section II-B have been observed for other interfering traffic patterns, for instance, with different spatial distribution and different number of interferers.)

[1] Since we do not focus on power management in this paper, we configure B-MAC to run in full duty-cycle in our study.

B. Experimental results

Unlike in 802.11 networks where unicast and broadcast differ in a variety of ways such as MAC coordination method (i.e., whether data transmission is preceded by the RTS-CTS handshake) and transmission rate, the main difference between unicast and broadcast in mote networks (where TinyOS B-MAC or 802.15.4 MAC is usually used) lies in link layer error control. That is, upon transmission failure, a unicast packet is usually retransmitted at link layer to improve delivery reliability, whereas a broadcast packet is not retransmitted. This link layer retransmission affects the accuracy of estimating unicast link properties via those of broadcast beacons. The accuracy of beacon-based link estimation is also degenerated by traffic-induced interference. In what follows, we present our empirical results on the impact of link layer retransmission and traffic-induced interference on the accuracy of beacon-based link estimation.

Impact of link layer retransmission. In beacon-based link estimation, unicast ETX (i.e., the expected number of physical transmissions taken to successfully deliver a unicast packet) along a link is estimated as $\frac{1}{P_b}$, where P_b is the broadcast reliability along the link. Note that, for simplicity of discussion, here we only consider the ETX along one direction of a link, but the observations are applicable to the case where ETX is computed based on bi-directional link properties, and we corroborate this in our routing experimentation in Section III where the ETX computation considers bi-directional link properties. Based on the measured data on broadcast reliability and unicast ETX in our experiments, Figure 2 shows the errors in estimating unicast ETX via broadcast reliability, where the error is defined as the estimated unicast ETX minus the directly measured unicast ETX and then divided by the measured unicast ETX. We see that the estimation error tends to be large, e.g., up to 88.78%. The estimation error also changes with interference pattern, which makes it difficult to compensate for the estimation errors in practice since interference patterns may well be unknown and unpredictable. Note that, even though the estimation error does have the general trend of decreasing with increasing link reliability (as can be seen by examining Figures 2 and 5 together) and the estimation errors tend to be relatively small when links are reliable, this fact does not help beacon-based link estimation in practice because the routes with the smallest ETX tend to have less-than-perfect-reliable but longer links as observed in Section III of this paper and [8], [23].

Given a certain interference pattern (more specifically, interfering traffic load in this case), one major cause for the significant errors in beacon-based link estimation is the temporal correlation among unicast-physical-transmissions, that is, the fact that the status (i.e., success or failure) of the individual physical transmissions of a unicast are correlated due to short-term, bursty variation in environment-induced fading and traffic-induced interference. (Note that, independent of and in parallel with our work, short-term, bursty variations in wireless link properties have also been observed in [24].) As a result

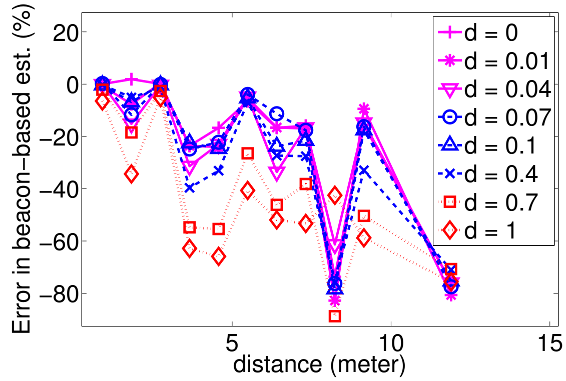


Fig. 2: Errors in estimating unicast ETX via broadcast reliability. *Note* that, due to factors such as radio and environment variations, properties of the wireless links in a specific network setup are usually not monotonic functions of the sender-receiver distance [4]; accordingly, we will observe that the phenomena presented in this paper tend not to be monotonic with respect to distance. We have also observed that phenomena studied in this paper are complex and tend not to be correlated or monotonic with other parameters such as receiver-side SINR or link reliability. In this paper, we use distance mainly to identify individual links associated with a sender, and for clarity of presentation, we do not present confidence intervals unless they are necessary for certain claims of the paper.

of this short-term temporal correlation, the probability of a physical transmission failure conditioned on an immediately preceding physical transmission failure is higher than the probability of a transmission failure at a random moment in time. Given that broadcast beacons are usually well separately in time when compared with the interval between consecutive physical (re)transmissions involved in a unicast, the reliability of unicast-physical-transmissions tends to be lower than that of broadcast beacons. This conjecture is corroborated by Figure 3 where we show the difference between the reliability

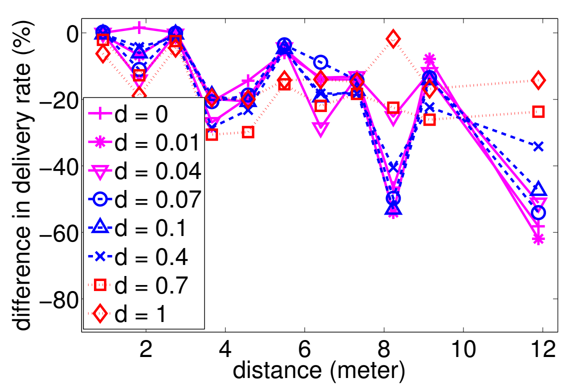


Fig. 3: The mean reliability of each unicast-physical-transmission minus that of broadcast

of each unicast-physical-transmission and that of broadcast in different interference scenarios. As a result, beacon-based estimation tends to underestimate unicast ETX, which can also be observed from Figure 2. As we will discuss shortly, the temporal correlation among unicast-physical-transmissions is also affected by interference pattern, thus the error in beacon-based estimation changes with interference pattern as we see from Figure 2.

To further understand the temporal correlation among unicast-physical-transmissions, we analyze the autocorrelation coefficient ρ among the individual physical transmissions of unicasts, and examine its relation to time, interference pattern, and link properties. Given the observations $x_1, x_2, \ldots, x_n$ of a time series, the autocorrelation coefficient $\rho(h)$ for lag h $(-n < h < n)$ [25] is

$$\rho(h) = \frac{\hat{\gamma}(h)}{\hat{\gamma}(0)}$$

where

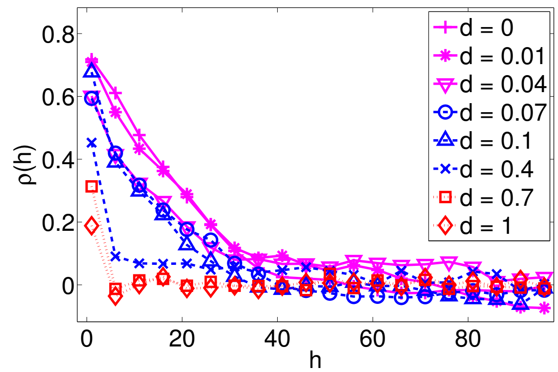
$$\begin{aligned} \hat{\gamma}(h) &= \tfrac{1}{n} \textstyle\sum_{t=1}^{n-|h|} (x_{t+|h|} - \bar{x})(x_t - \bar{x}) \\ \bar{x} &= \tfrac{1}{n} \textstyle\sum_{t=1}^{n} x_t \end{aligned}$$

For a link of length 9.15 meters (i.e., 30 feet), Figure 4(a) shows the autocorrelation coefficients for the status of unicast-physical-transmissions. We see that autocorrelation coefficient decreases as the lag h increases; this is because the correlation between individual unicast-physical-transmissions is due to short-term, bursty variation in environment-induced fading and traffic-induced interference. We also see that autocorrelation coefficient tends to decrease as interference load increases; this is partly because the increased load of random interfering traffic increases the degree of randomization in traffic-induced interference. For links of different lengths, Figure 4(b) shows the autocorrelation coefficients for lag 4. We see that autocorrelation coefficient also varies across links. (Similar phenomena are observed for other links and lag values.) The complex correlation patterns among unicast-physical-transmissions partly explain why it is difficult to address the difference between broadcast and unicast-physical-transmission and thus the significant errors in beacon-based estimation.

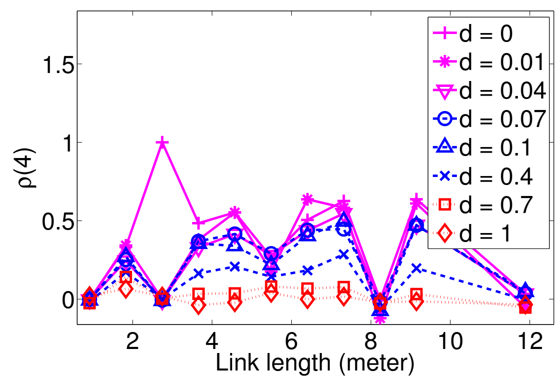
Note that the negative impact of temporal link correlation on beacon-based estimation remains even if we use opportune transmission [24] which delays retransmission after a unicast-physical-transmission failure while trying to transmit as many packets as possible when channel condition is good. This is because, in the case of opportune transmission, the reliability of unicast-physical-transmissions will be higher than that of broadcast beacons, which will make beacon-based estimation overestimate link ETX (in contrast with the underestimation error when opportune transmission is not used).

Impact of traffic-induced interference. Figure 5 shows the network conditions, in terms of unicast ETX, in different interference scenarios. We see that, as interference changes, unicast ETX changes significantly (e.g., up to 32.44)[2], and unicast ETX tends to increase with increasing interference traffic load. In event-detection sensor networks [26], there is no data traffic in the network most of time, yet a huge burst of data packets are generated within a short period of time (e.g., a

[2]Note that, even though the maximum number of transmissions per packet at the MAC layer is set to 8 in our measurement study, link ETX can exceed 8. This is because a unicast packet may not be successfully delivered even after 8 transmissions at the MAC, and the ETX of a link is defined as the inverse of its reliability.



(a) Autocorrelation coefficient for a link of length 9.15 meters



(b) Autocorrelation coefficient for lag 4

Fig. 4: Autocorrelation coefficient for the status of unicast-physical-transmissions

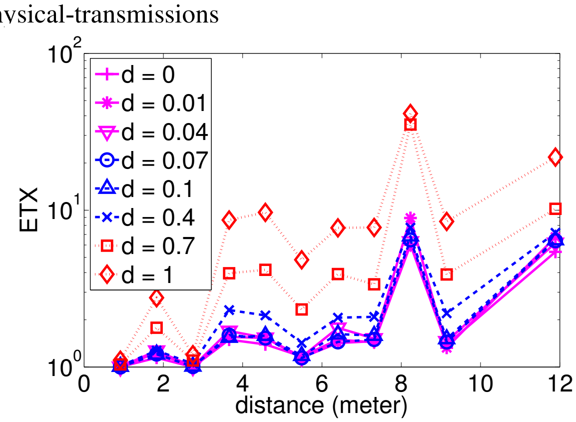


Fig. 5: Unicast ETX in different interference scenarios

few seconds) once an event occurs. Therefore, network traffic-induced interference and thus unicast ETX tend to vary significantly depending on whether there is an active event. To reduce control overhead, broadcast beacons are usually exchanged at low frequencies (e.g., once every 30 seconds) in practice, thus the network conditions experienced and sampled by broadcast beacons may well reflect those in the absence rather than in the presence of bursty event traffic. Consequently, beacon-based estimation may well lead to significant sampling errors (i.e., broadcast beacons fail to sample the network conditions for data transmissions) in event-detection sensor networks. Note that, besides the impact on link ETX, we also see from Figures 2-4 that traffic-induced interference affects temporal link correlation and errors in beacon-based estimation, which further corroborates the drawbacks of beacon-based estimation in low-power wireless networks.

Summary. From the testbed based experimental analysis, we see that beacon-based link estimation introduces significant estimation errors in low-power wireless networks such as the XSM mote networks. Unlike in [8] where MAC feedback does not indicate the number of physical transmissions for a unicast, the MAC components of mote networks expose the number of physical transmissions for each unicast, and this enables us to derive the status of each unicast-physical transmission and thus the properties of unicast-physical-transmissions such as their reliability and correlation as shown in Figures 3 and 4. These new observations give insight into the complexity of temporal correlation among unicast-physical-transmissions and the impact of interference patterns, which represent inherent difficulties in beacon-based link estimation and thus motivate the necessity of estimating unicast properties via MAC feedback information about unicast data transmissions themselves. Note that, even though temporal link correlation has been well studied in the literature [24], [27], [7], this paper, to the best of our knowledge, is the first to examine the temporal correlation among unicast-physical-transmissions and its relation to interference pattern.

Estimating unicast properties via unicast MAC feedback is expected to address the drawbacks of beacon-based estimation whether or not the intervals between packet retransmissions at MAC layer are well controlled through mechanisms such as opportune transmission [24]. This is because the unicast MAC feedback contains information about the link properties experienced by the individual unicast-physical-transmissions no matter whether the packet retransmission interval (i.e., interval between consecutive unicast-physical-transmissions in a unicast) is large or small. Note that, even though they should not be used as the basis of link estimation, broadcast beacons will still be useful for purposes such as maintaining routing topology and disseminating control information (e.g., results of link estimation). This implies that we should clearly identify the roles that beacons play in routing, and detailed study of it should be a worthwhile future work to pursue.

III. Routing performance

Having discussed the inherent drawbacks of beacon-based link estimation in Section II, we experimentally compare the performance of beacon-based and data-driven link estimation and routing in this section. We first present the methodology and then the experimental results.

A. Methodology

We use a publicly available event traffic trace for a field sensor network deployment [28] to evaluate the performance of different protocols. The traffic trace corresponds to the packets generated in the 7×7 grid of a field MICA2 mote network when a vehicle passes across the middle of the network. When the vehicle passes by, each mote except for the base station detects the vehicle and generates two packets, which correspond to the start and the end of the event detection respectively and are separated 5-6 seconds on average. Overall, 96 packets are generated each time the vehicle passes by. The cumulative distribution of the number of packets generated during the event is shown in Figure 6. (Interested readers can find the detailed description of the traffic trace in [28].) Since

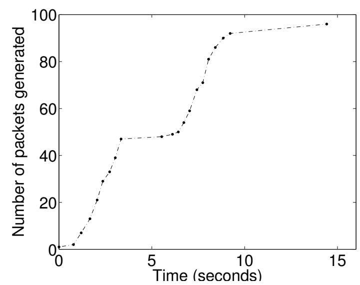


Fig. 6: The distribution of packets generated in the event traffic trace

the above event traffic trace is collected from 49 nodes that are deployed in a 7×7 grid, we randomly select and use a 7×7 subgrid of the Kansei testbed (as shown in Figure 1(b)) in our experiments. To form a multi-hop network, we set the radio transmission power at -14dBm (i.e., power level 3). The mote at one corner of the subgrid serves as the base station, the other 48 motes generate data packets according to the aforementioned event traffic trace, and the destination of all the data packets is the base station. In our study, each data packet has a 10-byte payload. *We also evaluate protocols with other traffic patterns, e.g., periodic data traffic, and other network setups, e.g., random networks. We observe phenomena similar to what we will present, but we relegate the detailed discussion to Section IV.*

To understand the importance and benefits of data-driven link estimation and routing, we study the performance of the following link estimation and routing protocols:[3]

[3] In this paper, we sometimes use the same name for the protocol, the estimation method, and the routing metric. The context of its usage will clarify its exact meaning.

- *ETX*: a distance vector, beacon-based routing protocol whose objective is to minimize the expected number of transmissions (ETX) from each source to its destination. The ETX metric is estimated based properties of broadcast beacons. This is similar to the protocol proposed in [23].
- *RNP*: same as protocol ETX except that the ETX metric is estimated as the *required number of packets* (RNP) [27] which tries to capture the temporal correlation in link properties. Note, however, that RNP cannot precisely capture temporal correlations among unicast-physical-transmissions since RNP is still estimated based on broadcast beacons.
- *L-ETX*: a distance-vector routing protocol whose objective is to minimize the ETX from each source node to its destination. Using an exponentially-weighted-moving-average (EWMA) estimator, the ETX metric of each link (and thus each route) is estimated via unicast MAC feedback on the transmission status (i.e., success or failure) and the number of physical-layer transmissions taken to deliver each unicast packet. In L-ETX, periodic, broadcast beacons are never used. We use the approach of *initial link sampling* [8] to jump-start the routing process, where a node proactively takes 7 samples of MAC feedback (by transmitting 7 unicast packets) for each of its candidate forwarders and then chooses the best forwarder based on the initial sampling results. After the initial sampling phase, the ETX metric of a link is updated based on MAC feedback for each unicast data transmission. This is similar to the protocol proposed in [8].

Note that, for ETX and RNP, we consider bi-directional link reliability as proposed in [23] and [27] respectively, and the per-node beaconing frequency is set as one beacon every 30 seconds.

For each protocol we study, we ran the event traffic trace sequentially for 40 times, and we measure the following protocol performance metrics:

- *Event reliability (ER)*: the number of unique packets received at the base station divided by the total number of unique packets generated for an event. This metric reflects the amount of useful information that can be delivered for an event.
- *Transmission efficiency* as measured by the *number of transmissions per packet delivered (NumTx)*: the total number of physical transmissions incurred in delivering packets of an event divided by the number of unique packets received at the base station. This metric affects network throughput; it also reflects the energy efficiency of a protocol, since it not only affects the energy spent in transmission but also the degree of duty cycling which in turn affects the energy spent at the receiver side.

B. Experimental results

Figures 7 and 8 show the event reliability and the average number of transmissions (as well as their 95% confidence intervals) required for delivering each packet in different protocols respectively. We see that L-ETX achieves higher event reliability (e.g., up to 18.75%) than both ETX and RNP. L-ETX also achieves higher energy efficiency than ETX and RNP, by a factor of 1.43 and 1.96 respectively.

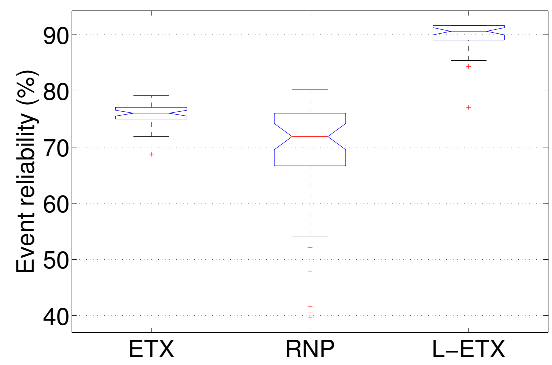


Fig. 7: Event reliability

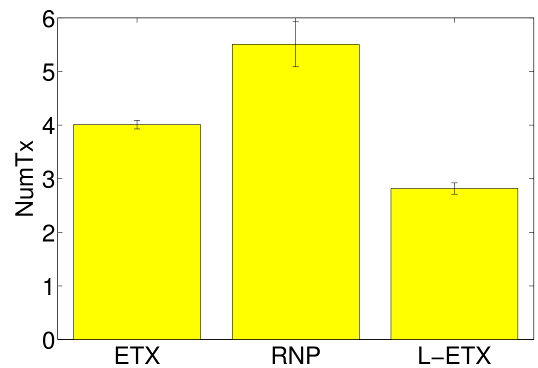


Fig. 8: Average number of transmissions per packet delivered

To explain the above observations and to understand the detailed routing behavior, we present in Figures 9 and 10 the average route hop length and route transmission count respectively for *successfully* delivered packets coming from nodes at different grid-hops away from the base station. We also present in Table I the detailed information about the properties of the links used in different protocols, where we consider, for a specific protocol, *all the links that are*

Metric	ETX	RNP	L-ETX
Average per-hop geo-distance (meter)	2.44	2.54	4.17
Average per-hop physical tx reliability (%)	76.23	68.05	68.43
Average per-hop unicast reliability (%)	80.99	75.15	93.10
Per-hop ETX	2.61	3.11	1.94

TABLE I: Per-hop properties

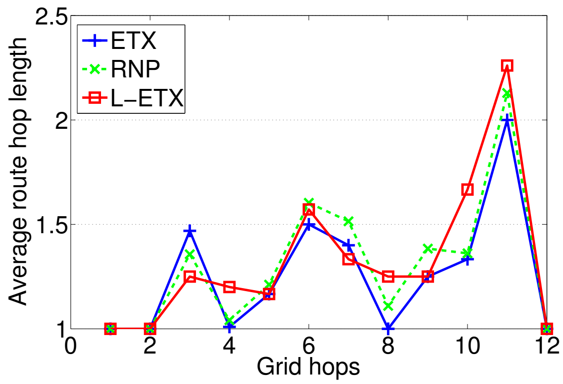


Fig. 9: Average route hop length for nodes different grid-hops away from the base station

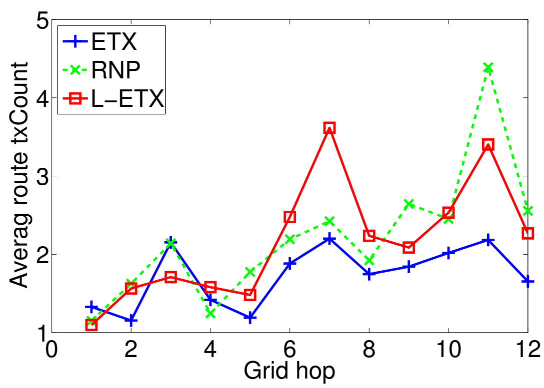


Fig. 10: Average route transmission count for nodes different grid-hops away from the base station

used to transmit any data packet whether or not the packet is received by the base station in the end. Note that, for conciseness, we do not present confidence intervals for these measured parameters. Figure 9 shows that the routes taken by successfully delivered packets in ETX are of similar hop length as those in L-ETX, and Figure 10 shows that the route transmission count for successfully delivered packets in ETX tends to be slightly smaller than that in L-ETX; yet Table I shows that the links used in L-ETX are much longer than those used in ETX and the per-hop ETX in L-ETX is less than that in protocol ETX. This seemingly contradicting observations implies that packets that have been lost in ETX tend to go through long and unreliable routes. Similar phenomena are also observed in RNP. Table I shows that the average per-hop unicast reliability in L-ETX is significantly higher (e.g., up to 17.95) than that in ETX and RNP, which enables L-ETX to achieve a significantly higher event reliability. The facts that L-ETX achieves higher event reliability and that L-ETX uses more reliable links and thus fewer number of transmissions enable L-ETX to deliver packets with fewer number of transmissions on average. (Note: a counterintuitive observation from Table I is that links used in ETX have higher physical transmission reliability than those in L-ETX, yet the unicast reliability in ETX is lower than that in L-ETX. The reason for this is that the physical transmission failures are more separated and consecutive physical transmission failures are rarer in L-ETX so that they do not degenerate unicast reliability in L-ETX that much.)

Table II shows the route stability in ETX, RNP, and L-ETX,

Two consecutive routes (%)	ETX	RNP	L-ETX
Same	98.24	93.63	99.94
Diff. routes but same hop length	1.62	2.71	0.03
Increased hop length	0.07	1.79	0.03
Decreased hop length	0.07	1.87	0

TABLE II: Route stability: data-driven vs. beacon-based estimation

which is measured by comparing the routes taken by every two consecutive packets. We see that the routes used in L-ETX are also slightly more stable than those in beacon-based routing protocols ETX and RNP.

IV. Additional performance evaluation results

In Section III, our study is mainly based on the regular 7×7 event traffic trace and testbed configuration. In this section, we comparatively study ETX and L-ETX with other traffic patterns and network configurations. We also compare the achievable throughput in ETX and L-ETX respectively. (Note that, in this section, we do not study the protocol RNP since it performs slightly worse than ETX as shown in Figures 7 and 8.)

Other traffic load. Using the same event traffic trace as in Section III-A, we control the set of nodes that actually generate source packets to imitate events of different sizes. We have experimentally compared ETX and ETX using two event size: 3×3 where the nodes in the farthest 3×3 subgrid from the base station generate packets, and 5×5 where the nodes in the farthest 5×5 subgrid from the base station generate packets. We observe similar phenomena for both event size configurations, and here we only present the data for the 5×5 configuration only.

For the same testbed setup as in Section III-A, Figure 11 shows the event reliability, and Figure 12 shows the average number of transmissions per packet delivered, as well as its confidence interval at 95% confidence level, in different protocols. We see that, in the case of lighter traffic load, L-ETX still achieves higher event reliability and energy efficiency (as measured in the number of transmissions required in delivering a packet to the base station) than ETX. Compared with the case shown in Figure 7, the event reliability of ETX is slightly higher because the traffic load and thus traffic-induced interference and collision are lower in this case.

Periodic traffic. To understand routing performance in periodic data collection applications, we experimentally compare performance of different routing protocols in delivering

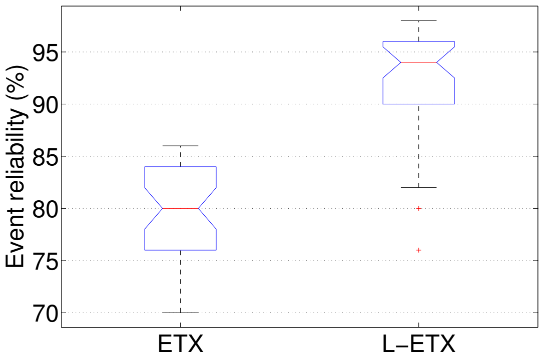


Fig. 11: 5×5: event reliability

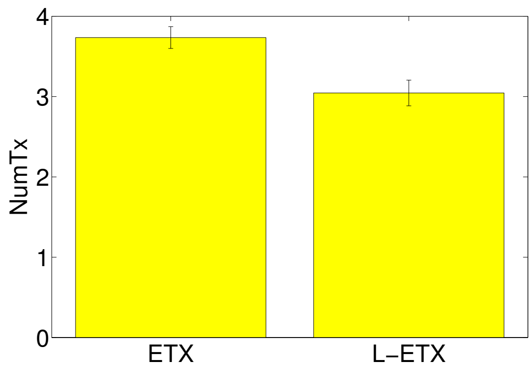


Fig. 12: 5×5: average number of transmissions per packet delivered and its 95% confidence level confidence interval

periodic traffic. To this end, we let all the nodes except for the base station in a 7×7 grid periodically generate packets, where the time interval between any two consecutive packets is a random variable uniformly distributed between 10 seconds and 20 seconds. For the same testbed setup as in Section III-A, Figure 13 shows the packet delivery reliability,

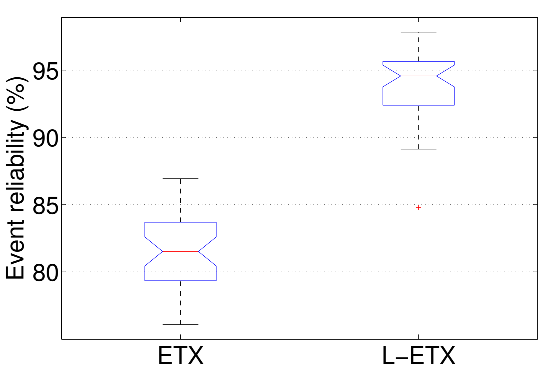


Fig. 13: Periodic traffic: packet delivery reliability

and Figure 14 shows the average number of transmissions per

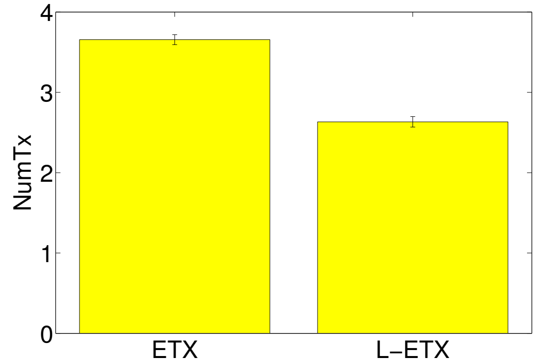


Fig. 14: Periodic traffic: average number of transmissions per packet delivered and its 95% confidence level confidence interval

packet delivered in different protocols. We see that L-ETX outperforms ETX in delivering periodic traffic.

Sparser network. To understand whether the relative performance among different protocols is consistent across different network densities (e.g., number of neighbors for each node), we change the radio transmission power to -17dBm (i.e., power level 2). Then for the same node deployment and traffic trace as in Section III-A, Figure 15 shows the event reliability,

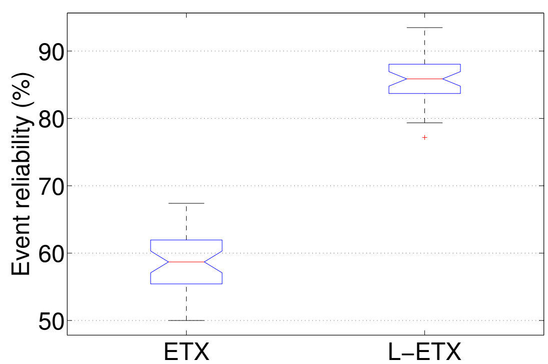


Fig. 15: Sparser network: event reliability

and Figure 16 shows the average number of transmissions per packet delivered in different protocols. We see that L-ETX achieves higher event reliability and energy efficiency than ETX. Compared with the case when the radio transmission power is -14dBm, the event reliability in a protocol is lower when the power level is -17dBm because the routing hop length increases as a result of the reduced power level.

Random topology. Instead of deploying 49 nodes in a regular 7×7 grid, we deploy 49 nodes in a randomly selected set of 49 grid points from the 14×7 grid space as shown in Figure 1(b). Then for the same traffic trace as in Section III-A, Figure 17 shows the event reliability, and Figure 18 shows the average number of transmissions per packet delivered in different

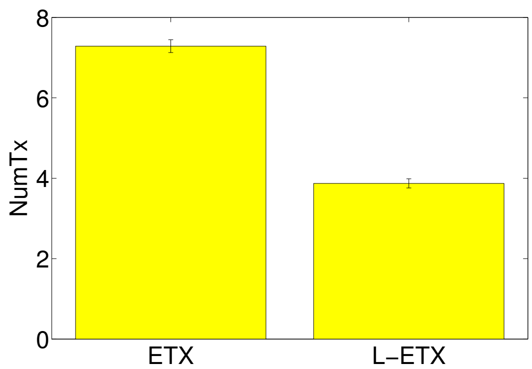


Fig. 16: Sparser network: average number of transmissions per packet delivered and its 95% confidence level confidence interval

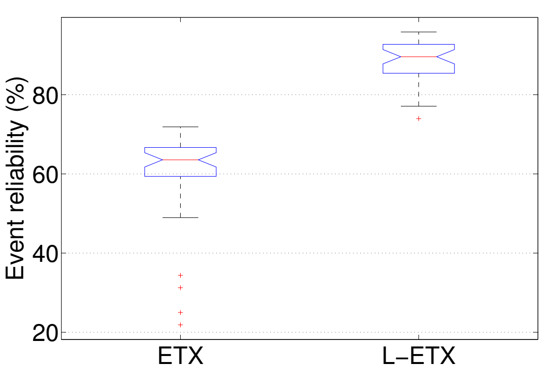


Fig. 17: Random topology: event reliability

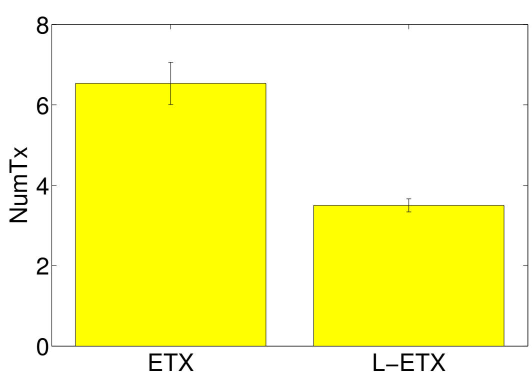


Fig. 18: Random topology: average number of transmissions per packet delivered and its 95% confidence level confidence interval

protocols. We see that L-ETX achieves significantly higher event reliability and energy efficiency than ETX. Compared with the case when nodes are deployed in a 7×7 grid, the event reliability in a protocol is lower in the random topology because the routing hop length increases as a result of increased average spacing between nodes.

Network throughput. To measure network throughput, we let source nodes send packets to the base station at the highest speed allowable by the system (e.g., system software and radio). We use the same testbed setup as in Section III-A, but in order not to overload the network too much, we only let nodes in the farthest 2×2 subgrid from the base station generate traffic. Table III shows the number of unique packets

Protocol	ETX	L-ETX
Throughput (packets/second)	6.07	8.49

TABLE III: Throughput

that are delivered to the base station per second. We see that L-ETX achieves a higher throughput than ETX. Given that the highest one-hop throughput is about 42.93 packets/second for Mica2 motes with B-MAC (the default MAC component of TinyOS) and that, in multi-hop networks, even an ideal MAC can achieve no more than $\frac{1}{4}$ of the throughput that a single-hop transmission can achieve [29], the theoretical upper limit on achievable throughput in multi-hop Mica2 networks is 10.73 packets/second. The throughput in L-ETX is 8.49 packets/second in our experiment, which is 79.12% of the upper limit.

V. Related work

Link properties in wireless sensor networks and 802.11 networks have been well studied in [3], [4], [1], and [2]. Experiment-based interference models have also been proposed for Mica2 radios [30] and 802.11 radios [31]. It is observed that wireless links assume complex properties, such as wide-range non-uniform packet delivery rates, loose correlation between distance and packet delivery rate, link asymmetry, and temporal variations. Orthogonal to these studies, our study on link properties focuses specifically on link estimation, the differences between broadcast and unicast link properties, and the impact of interference patterns on the differences in low-power wireless networks.

To address the challenges of wireless communication, routing metrics such as ETX [23], [14] and ETT/WCETT [32] have been proposed to identify good routes for data delivery. The metric PRD [33] has been proposed for energy-efficient geographic routing in sensor networks, and metrics such as RNP [27] and mETX [34] have also been proposed to take into account temporal link properties in route selection. While focusing on routing metrics, these studies did not examine the impact of link estimation methods, and they used beacon-based approach to estimate the corresponding routing metrics.

Differences between broadcast and unicast and their impact on the performance of AODV were first discussed in [5] and

[6], and the authors discussed reliability-based mechanisms (e.g., those based on RSSI or SNR) for blacklisting bad links. The authors also proposed mechanisms, such as enforcing SNR threshold on control packets, to ameliorate the negative impact of the differences, and the authors of [5] studied the impact of packet size, packet rate, and link reliability threshold on the end-to-end delivery rate in AODV. Nonetheless, the proposed solutions were still based on beacon exchanges among neighbors. Since it has been shown that reliability-based blacklisting does not perform as well as ETX [23], [35], [14], we do not study [5] and [6] in detail in this paper.

MintRoute [14] used data feedback in link estimation, but it also used beacons and treats beacon transmissions as the same as data transmissions; MintRoute also assumed a fixed data-to-beacon ratio which was used in deciding the amount of data that should be transmitted in each time interval which was in turn used for link estimation. Methods of using both MAC feedback and beacon packets in link estimation were also proposed in [9] and [11], but they did not systematically characterize the impact that link layer retransmission and traffic-induced interference have on the accuracy of beacon-based estimation. Even though periodic broadcast beacons may be necessary for purposes such as neighbor discovery and routing loop recovery, the approach of incorporating periodic beacons in link estimation is debatable, especially for event-detection sensor networks where broadcast beacons may mislead link estimation since there may be very little data traffic and thus little unicast MAC feedback in event detection networks. The measurement study in [9] and [11] focuses on TelosB and 802.11 networks respectively; our study focuses on another platform — XSM motes — and thus extends the scope of the observation that data-driven link estimation should be treated as the basis of wireless routing.

SPEED [10], NADV [13], and CARP [12] also used MAC feedback in route selection. While focusing on real-time packet delivery, a general framework for geographic routing, and temporal link dynamics respectively, [10], [13], and [12] did not focus on characterizing the inherent drawbacks in beacon-based link estimation. Most closely related to our work is LOF [8] where the authors studied the inherent difficulty in precisely estimating unicast link properties via those of broadcast in 802.11b networks. We complement [8] by examining the issue in low-power sensor networks; even though our study shows that the observations and protocol design decisions for 802.11b networks carry over to low-power sensor networks, these findings are not obvious because the radios, the MAC protocols, and the traffic patterns in low-power sensor networks differ from those in 802.11b sensor network backbones, and these factors greatly affect link properties and network protocol performance. We also systematically study the properties of individual unicast-physical-transmissions and compare them with broadcast properties, which sheds new insight into the temporal correlation in unicast-physical-transmissions and the impact of interference patterns; this was, however, infeasible in [8] due to the limitations (e.g., not providing information on the number of physical transmissions for a unicast transmission) of their 802.11b radios.

Other routing metrics and protocols [36], [37], [34], [38], [39], [40], [41] have also been proposed for various optimization objectives (e.g., energy efficiency). The findings of this paper can be applied to these schemes to help improve the accuracy of estimating link and path properties. Directed diffusion [42] provides a framework for routing in sensor networks, and the findings of this paper can also be applied to this framework to help select high-performance routes in data forwarding.

Rather than selecting the next-hop forwarder before data transmission, opportunistic routing protocols that take advantage of spatial diversity in wireless transmission have been proposed [43], [44], [45], [46]. In these protocols, the forwarder is selected, through coordination among receivers, in a reactive manner after data transmission. Link estimation can still be helpful in these protocols since it can help effectively select the best set of listeners [43]. Therefore, findings of this paper can be useful in opportunistic routing too.

VI. Concluding remarks

Through testbed based study, we have characterized the impact that link layer retransmission and traffic-induced-interference have on link estimation accuracy, and we have shown that the complexity and uncertainty in link correlation and interference patterns make it inherently difficult to precisely estimate unicast data transmission properties via those of broadcast beacons. Using a variety of traffic patterns and network setups, we have also experimentally demonstrated the benefits of data-driven link estimation in improving data delivery reliability and transmission efficiency. These findings provide solid empirical evidence on the inherent drawbacks and sources of errors in beacon-based link estimation and suggest that we treat data-driven link estimation as a basic principle in protocol design for low-power wireless networks.

The experimental analysis of this paper is based on networks of CC1000 radios. Even though we expect the findings of this paper to be valid for networks of IEEE 802.15.4 radios, systematic evaluation of this conjecture is a part of our future work. We have focused on accurate estimation of the ETX routing metric in this paper, identifying accurate estimation methods for other routing metrics such as mETX [34] and CTT [41] is also an important task to pursue for supporting different optimization objectives in routing. It is expected that the observations of this paper also apply when other retransmission techniques such as opportune transmission [24] is used, and detailed study of this is worthwhile. We have shown that broadcast beacons should not be treated as the basis of wireless link estimation, but they will still be an important part of wireless network protocol design; it will be interesting to systematically study the roles that broadcast beacons play in wireless routing and wireless networks in general.

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