Routing over Bursty Wireless Links

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***Abstract*—Accurate estimation of link quality is the key to enable efficient routing in wireless sensor networks. Current link estimators focus mainly on identifying long-term stable links for routing, leaving out a potentiality large set of intermediate links offering significant routing progress. Fine-grained analysis of link qualities reveals that such intermediate links are *bursty*, i.e., stable in the short term.**

In this paper, we use short-term estimation of wireless links to accurately identify short-term stable periods of transmission on bursty links. Our approach allows a routing protocol to forward packets over bursty links if they offer better routing progress than long-term stable links. We integrate a Short Term Link Estimator and its associated routing strategy with a standard routing protocol for sensor networks. Our evaluation reveals an average of 22% reduction in the overall transmissions when routing over long-range bursty links. Our approach is not tied to any special routing protocol and integrates seamlessly with existing routing protocols and link estimators.

I. Introduction

Since the emergence of WSNs, research has mainly focused on link estimation and routing techniques [4], [5], [7] which identify and utilize consistently high quality links for packet forwarding. Links of intermediate quality, i.e. links with a PRR between 10% and 90%, are ignored to ensure routing stability and to attain high end-to-end reliability. Protocol studies [2], [8] have shown that these intermediate quality links are bursty, i.e., they frequently switch between stable and unstable periods of transmission for a limited number of consecutive packets. In this paper, we argue that: (1) Bursty links can be used for packet forwarding during their stable periods without affecting the reliability and stability of existing routing protocols; (2) These links often achieve significantly better routing progress and routing throughput than the long-term links chosen by existing routing protocols.

Today's link estimators [4], [5] measure the quality of a link in the ETX metric: the number of (re)transmissions required for a successful transmission. To achieve better connectivity and reliable packet communication, today's link estimators restrict communication to neighbors with constantly high-quality links. These high-quality links are identified based on the long-term success rate of a link collected over a time frame in the order of minutes. Widespread routing protocols in WSNs, such as BVR [5] and CTP [7], select links as suggested by their link estimator. In doing so, they limit packet forwarding only to long-term reliable links. They leave out a large class of potentially valuable communication links of intermediate quality that offer significant routing progress. Their use might therefore reduce the number of transmissions, lower energy usage in the network, and increase throughput.

Overall, this paper has three key contributions. First, it shows how short-term link estimation can be used for fine-grained estimation of bursty links to identify stable transmission periods. Thereby it enables routing protocols to forward packets over long-range bursty links and minimize the number of transmissions in the network. Second, we present an adaptive routing strategy which uses the STLE for packet forwarding over bursty links. Third, we present a Bursty Routing Protocol (BRP) - an integration of the STLE and the adaptive routing strategy with a standard routing protocol for sensor networks. As a result, we show how our approach can be integrated with existing routing protocols and link estimators. Our evaluation measures that routing with the STLE provides a reduction in transmission costs, i.e., number of transmissions, of 22% on average and 40% in the best case.

II. System Overview

Typically, routing protocols in WSNs aim to establish a routing tree: Some number of nodes in the network would advertise themselves as base stations, i.e., as tree roots. All other nodes join the tree with ETX as the routing metric. Figure 1 shows an example of such a routing tree rooted at the base station D. A path from source S to the destination D consists of a sub-sequence of immediate parents of each node, for example $S \rightarrow 1 \rightarrow 2 \rightarrow 3 \rightarrow D$. If we consider all links in this path to be 100% reliable, the minimum number of transmissions required by a packet to travel from the source to the destination is four. Now consider a situation in which an intermediate link $S \rightarrow 2$ or $1 \rightarrow D$ has become temporarily reliable. Routing over these links could result in a path sequence $S \rightarrow 2 \rightarrow 3 \rightarrow D$ or $S \rightarrow 1 \rightarrow D$, respectively. Hence, using these links for routing could reduce the total number of transmissions to three in the former and two in the later case. However, a traditional routing protocol cannot make use of such an opportunity because it uses a long-term link estimate. Hence, this design is intentionally unable to realize short-term changes in the link quality. Similarly, even if these short-term changes are captured, traditional routing schemes adapt slowly to ensure routing stability.

In contrast, our proposed technique takes advantage of the availability of intermediate links. It estimates links on a short-term basis by overhearing packets. In this particular case for example, node-2 overhears the packets addressed to

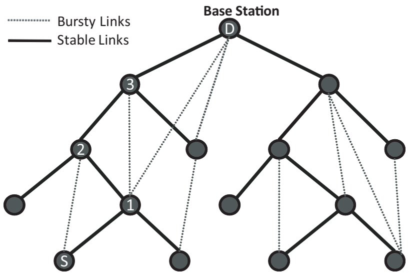

Fig. 1. Bursty links offer routing shortcuts that can reduce the number of overall transmissions in the network

node-1 by source S. After node-2 successfully overheard a certain number of consecutive packets from S, it informs S about the short-term availability of this link. Thereafter, S starts forwarding its packets to node-2 to reduce the number of overall transmissions for a packet to reach its ultimate destination. Our evaluation results in Section IV show that this technique significantly reduces the number of overall transmissions in the network. Thus, it allows to reduce energy consumption and increase network life time.

III. System Design

In this section we discuss the design of BRP, which consists of two basic components: (1) the STLE, which identifies periods of good transmissions in long-range bursty links by overhearing communication channels, (2) an adaptive routing strategy, which makes use of bursty links identified by STLE for forwarding packets, and its integration in existing routing protocols.

A. Short Term Link Estimation

The main task of STLE is to identify reliable periods of transmissions in intermediate links that offer better routing progress than long-term stable links. For this purpose, STLE overhears data packets send by neighboring nodes and records the recent history of success or failure over a link for the last h packets. Based on this recent transmission history, STLE decides whether a link is currently reliable or unreliable for transmission and informs the routing protocol accordingly. The prototype implementation of BRP consists of the STLE and the adaptive routing strategy with CTP, a standard collection routing protocol for sensor networks shipped with TinyOS. However, the STLE and its routing strategy are not bound to any specific routing protocol. It can easily be integrated with BVR and other routing strategies that support higher data rates for bandwidth limited systems.

1) Algorithm: Before elaborating the algorithmic details of STLE, we define three roles for any node in the network: a) *source-node*: the node which is actively sending or forwarding packets b) *parent*: the parent of any source-node in traditional routing and c) *overhearing-node*: node(s) which can overhear the communication between the source-node and its parent. A node in the network can assume any or all of these three roles at a time. The STLE algorithm works as follows:

Link Reliability: When overhearing a packet from a source-node, the overhearing-node infers the success rate - derived from the packet sequence number - of the link with that source-node. If the loss equals zero, i.e. if the overhearing-node was able to overhear a sufficient number of consecutive packets sent by the source-node to its parent, the overhearing-node declares the bursty link between itself and the source-node as active and triggers the next phase of the algorithm. If the overhearing-node was unable to overhear a sufficient number of consecutive packets (see Section III-A2) sent by the source-node to its parent - the overhearing-node drops the oldest packet sequence number for that source-node from its history and waits for the next packet.

Link Feasibility: In this phase, the overhearing-node queries the routing protocol for the path-ETX of the packet's destination, i.e., the parent of the source-node. If the path-ETX of the parent-node is greater than that of the overhearing-node, the overhearing-node declares the bursty link between itself and the source-node active. Consequently, the active bursty link can offer a better routing progress than the traditional path used by the source-node. However, if the path-ETX of the parent-node is not known or less than the path-ETX of overhearing-node, the overhearing-node temporarily ignores the source-node.

Link Announcement: If the path-ETX of the parent-node is greater than that of the overhearing-node, the overhearing-node informs the source-node about the active bursty link. It volunteers itself to become the temporary parent of the source-node as long as this bursty links remains active.

The path-ETX information used by the STLE at the overhearing-node can easily be obtained by using the neighborhood information maintained by any traditional routing protocol. We assume that there is a high probability that the original parent of the source-node is also a neighbor of the overhearing-node. This is because the overhearing-node can listen to the ongoing communication between the source-node and its parent. Additionally, the link announcement message, sent by the overhearing-node to the source-node, establishes a simple check to test for link-asymmetry.

Link Unavailability: At the source-node, the STLE declares a link unavailable for transmission after it fails to receive a number of acknowledgments (see Section III-A2) for the data packets sent over the bursty link.

2) History Size Thresholds: The STLE requires two thresholds for its operation: (1) a threshold to determine after how many successful transmissions, i.e. packets overheard, we define a link temporary available and (2) after selecting it for routing, threshold to define how many transmission failures we allow before considering a link temporary unavailable. Experiments by Becher et. al. [2] suggest a value of three, i.e. a history of size of three, for the first threshold and one for the second. However, these numbers were derived for a single testbed. As part of our evaluation, we repeat their experiments for widespread testbeds such as MoteLab [1] and TWIST [6] to calibrate STLE. Overall, our experimental results suggest the same thresholds as Becher et. al. Hence, we believe that

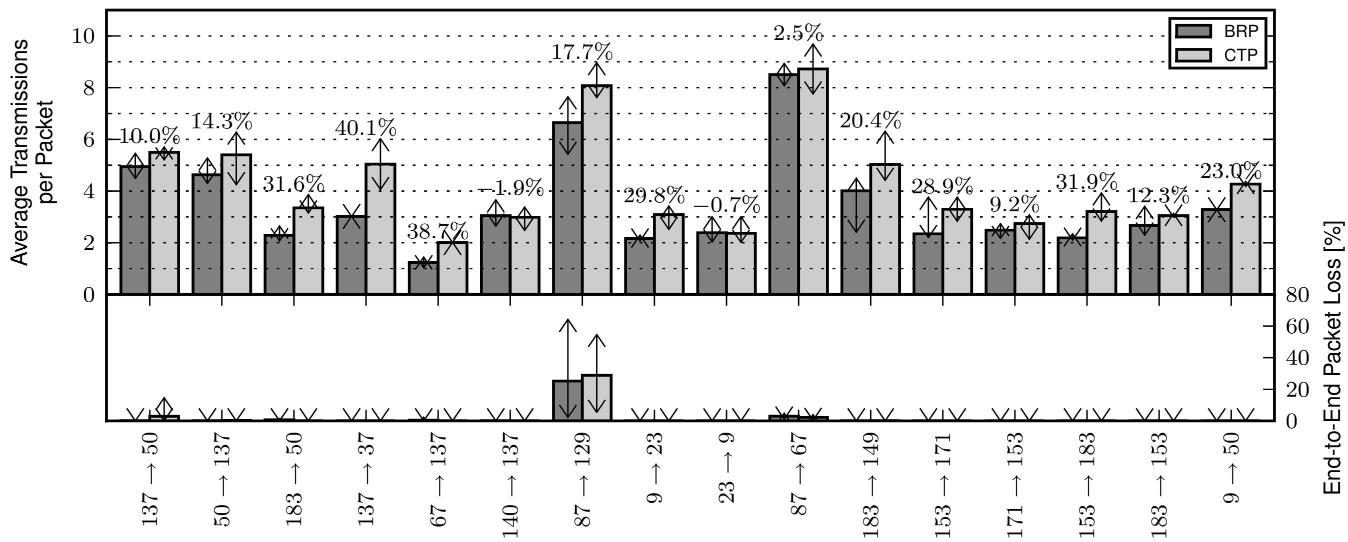

Fig. 2. Transmission cost reduction and reliability comparison of BRP and CTP. The graph above shows average number of transmissions per packet using BRP and traditional CTP for our experiments on MoteLab. The graph below shows end-to-end packet loss for the same experiments. The bar represents a node pair's average of five experiments. The inter-packet interval is 250 ms. The error bars represent the highest and the lowest average of the five experiments. The MoteLab topology and node addresses can be seen at www.motelab.eecs.harvard.edu.

these thresholds are valid in general and not only for a single deployment.

B. An Adaptive Routing Strategy

After discussing the operation of the STLE, we now detail a greedy and adaptive routing strategy based on it. Whenever the STLE at the source-node informs the routing strategy about an active bursty link, the routing strategy makes the overhearing-node its temporary parent and starts forwarding packets to it. However, this information is not propagated by the routing protocol to its descendant nodes, because these short term changes would trigger further parent changes down the tree. Eventually, it might destabilize the routing protocol and result in loops. This is one of the primary reasons why stability prevails over adaptability in today's routing protocols and link estimators. Hence, our routing strategy supplements their design considerations. When the STLE declares a bursty link inactive, the adaptive routing strategy proceeds as follows:

- It queries the STLE for another active bursty link. If such a link is available, the routing strategy starts forwarding packets over it.
- If there is no active bursty link, the adaptive routing strategy will regress to traditional routing until the STLE again finds an active bursty link.

Our goal is to enhance routing performance without affecting the stability and reliability of traditional routing protocols. Therefore, we neither replace the existing link estimators nor alter the stable routing topology maintained by traditional routing protocols. Rather, our approach is an additional component that assists routing protocols and link estimators in identifying the previously ignored class of bursty links which can enhance routing performance.

Test-bed	**Transmission Reduction %** One Sender	**Transmission Reduction %** Simultaneous Senders	**Throughput Increase %**
MoteLab	18.98	21.72	5.65
TWIST	16	19.33	10.43

TABLE I
SUMMARY OF THE PERFORMANCE RESULTS FOR MOTELAB AND TWIST

IV. EVALUATION

We perform our experiments on MoteLab and TWIST. Our major performance measure is a reduction in the number of transmissions in the network by enhancing routing progress. We compare the transmission cost of BRP with the original CTP. Figure 2 shows our results for 16 different node-pairs as senders and collection roots. We repeated our experiments for BRP and CTP five times for each of the 16 node-pairs to intensively validate our results. In most of the cases BRP performs better than CTP, averaging to approximately 22% overall reduction in the transmission costs i.e. the total number of transmissions from source to destination for single node-pairs.

Figure 2 also presents the end-to-end packet loss for our experiments. In most of the cases, the packet loss is negligible. From these results, it is fair to conclude that BRP does not affect the reliability of the underlying routing protocol and at the same time reduces the number of transmissions in the network. The only measurable end-to-end packet loss observed in our experiments is for the node-pair $87 \rightarrow 129$ and $87 \rightarrow 67$. However, Figure 2 shows that BRP performs better than CTP even in such lossy scenarios. Table I summarizes our evaluation results for MoteLab and TWIST.

Another property of bursty links that we investigate is timeliness: how often do they occur and for how long are they active. Figure 3 presents empirical traces from our performance evaluation experiments. It clearly shows that bursty links are regularly available over time and are reliable for variable durations. Some of these links are active for only a few milliseconds (e.g $153 \rightarrow 183$), while others for seconds and even minutes (e.g $140 \rightarrow 37$). However, due to the slow adaptivity of traditional routing, i.e. CTP, even these relatively long-term reliable links with higher routing progress would not be utilized.

V. Related Work

The majority of existing link estimation techniques assume that individual packet loss events on a link are statistically independent of each other and that they follow a Bernoulli distribution. However, studies such as [2], [8] mark this assumption as inappropriate when wireless links are estimated over shorter time scales. For example, Becher et. al. [2] analyze the impact of recent transmission success and failure rate on the future quality of a link at fine-grain time scales. The conclusion of their study is that any link, no matter of what quality, becomes temporarily reliable after h consecutive packets are received over that link. Srinivasan et. al. [8] define a factor β, which measures the burstiness of a wireless link. β is calculated by using conditional probability distribution functions (CDFs), which determine the probability that the next packet will be received after n consecutive successes or failures. β is used to identify bursty links with long bursts of successes or failures and statistically independent links, with ideal bursty ($\beta = 1$) and independent ($\beta = 0$) links marking the two ends of spectrum.

Opportunistic Routing [3] in 802.11 based wireless networks reports a throughput increase of 35% by utilizing long range wireless links. However, it has a relatively high overhead with regard to computational cost, storage, and communication which we deem not feasible in resource constrained sensor networks. Overall, our short-term link estimator and its integration with routing protocols is designed according to lessons learned from afformentioned experimental studies on bursty wireless links. However, our work does not aim at modeling and developing the analytical or experimental understanding of wireless links. Instead, we take a step further and use these experimental models for packet forwarding over bursty links, and hence, enabling better utilization of wireless links.

VI. Discussion

In this paper, we presented a simple greedy approach to utilize bursty links of intermediate quality for packet forwarding. Our evaluation results show that, by transmitting over long range intermediate links, the number of transmissions in the network can be reduced. We believe that the improvement of 22% over traditional routing by transmitting over links with high loss rates is a credible and a realistic result.

In our prototype implementation, the development of a simple and a light-weight algorithm that illustrates the true effect of bursty links has been one of the primary objectives. After evaluating the effectiveness of transmissions over such

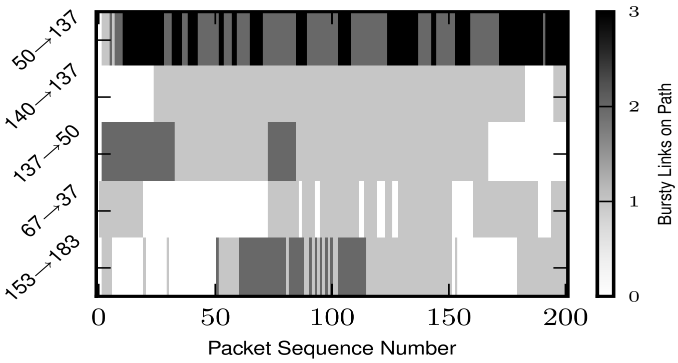

Fig. 3. Timeliness of bursty links for 50 second empirical traces for selected node-pairs: The graph shows the variability in the duration for which intermediate links are reliable. Most of the successful packets took one or more bursty links on the path from source to destination. Only the white segments in the graph represent complete packet transmissions on traditional path.

links, we identify the following aspects as future work: 1) Employing a more perceptive approach for calibrating STLE in different network environments to successfully predict the short-term reliability of a link, 2) Classifying overhearing nodes based on their success history to avoid repeated selection of a node that did not offer significant improvement over the traditional path, 3) Limiting link selection to the ones that offer at least one hop reduction to avoid even the rare occurrence of bad results, 4) Integrating BRP with low-power listening techniques, 5) Extending this work towards 802.11 networks to show that our approach has a broader relevance in the wireless domain.

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