Towards Short-Term Wireless Link Quality Estimation

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Abstract

Commonly, routing in sensor networks is limited to long-term stable links. Unstable links, although often promising to be of large routing progress, are not considered for packet forwarding as link estimators typically cannot handle their dynamics.

In this paper we introduce short-term link estimation to capture link dynamics at a high resolution in time and to identify when these render a link temporarily reliable or unreliable. We identify such dynamics based on packet overhearing, predict short-term availability and unavailability, and adapt neighbor tables, thereby enlarging the set of links useable by any routing algorithm. Additionally, we show that short-term link estimation integrates seamlessly into today's sensor network link estimators and routing protocols.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication

General Terms

Wireless Sensor Networks

Keywords

radio dynamics, unstable links, link estimation

1 Introduction

Accurate estimation of link quality forms the basis for efficient routing in sensor networks. Commonly, link estimators predict current link quality to neighboring nodes based on the recent success rate, typically collected over a time frame on the order of minutes. A widespread metric is the number of expected (re)transmissions to reach a neighboring node.

The low-power radio links in sensor networks exhibit inevitable fluctuations in their transmission success rate. Especially, regarding links of intermediate quality these fluctuations often show dynamics on a sub-second granularity, well beyond the resolution of today's link estimators. In this paper we present short-term link estimation (STLE) that aims to take such fine-grained link dynamics into account and to increase the prediction quality for successful packet transmissions, especially for highly dynamic links. STLE integrates into routing protocols by adapting neighbor tables to accurately reflect the current situation of a dynamic link. As a result, short-term link estimation can represent link dynamics at a time scale of individual packets and adapt to changes in the order of milliseconds.

Overall, short-term link estimation has three key contributions: (1) to predict the probability of successful packet transmission of any link type by taking short-term dynamics into account, (2) to suggest links of low to intermediate quality for routing when they have become temporarily reliable, and (3) to integrate easily with today's long-term link estimators and routing protocols.

The remainder of this paper is structured as follows. We present existing approaches to wireless link estimation in Section 2 and relate our work to them. Section 3 presents the short-term link estimator (STLE) and its integration into long-term link estimators and routing protocols in detail. Next, Section 4 evaluates the proposed design. Section 5 presents our ongoing and future work on STLE and Section 6 concludes.

2 Related Work

The identification of reliable links in sensor networks has received much attention in the recent years. However, to the best of our knowledge, there is no thorough analysis of short-term dynamics in link quality. This paper aims to fill this gap by quantifying their extent and characteristics.

Pioneering multi-hop routing in sensor networks, Woo et al. [15] investigated several approaches for online link estimation. Their study uses aggregate packet reception rates as an indicator of link quality. A passive window mean estimator with an exponentially weighted moving average (WMEWMA) was found to be the optimal choice for detecting high-quality links in this kind of loss model. Such an estimator counts the packets received from a neighboring node within a time window, typically on the order of

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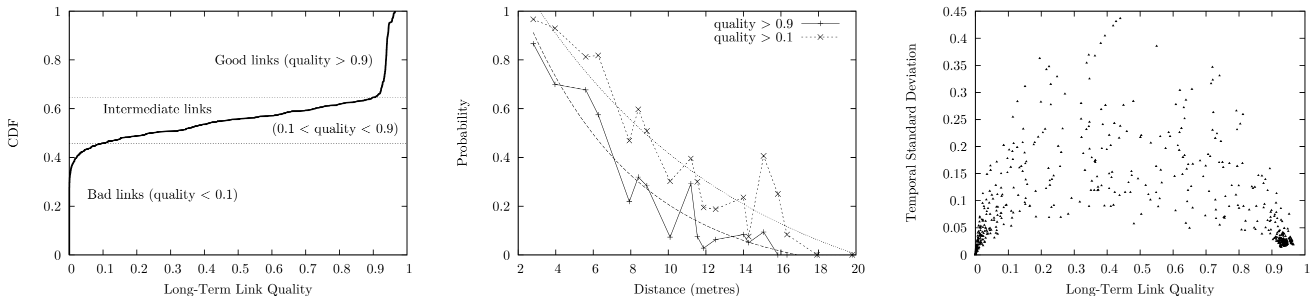


(a) Empirical distribution of long-term link quality in our testbed. Intermediate quality links comprise roughly one third of all useful links.

(b) Probability of finding a high-quality or medium-to-high-quality neighbor depending on physical distance in our testbed.

(c) Temporal variation of link quality. Each point represents a (directional) node pair.

Figure 1. Low-power radio links in sensor networks exhibit inevitable fluctuations in their quality.

30 seconds. The window mean values are then smoothed by an exponentially weighted moving average. However, the WMEWMA estimator performs poorly on medium quality links. These links often offer the highest routing progress [2], which suggests the need for more precise estimation methods for medium quality links.

Four-bit link estimation [4] extends the WMEWMA estimator into a hybrid link estimator that accumulates information from all layers of the sensor node networking stack: from the physical layer it takes signal and decoding statistics such as RSSI and LQI, from the link layer it collects successful transmissions and corresponding acknowledgments, and the network layer contributes routing information, such as the progress towards a sink node. It uses this information to coordinate neighbor table management between the link and network layer and to supplement conventional broadcast-based link quality estimates by unicast-based quality estimates. Similar to WMEWMA, the four-bit link estimator uses an exponentially weighted moving average (EWMA) to compute the current quality of a link. The prototype implementation described in the publication uses a window size of five data packets for unicast-based estimates and an EWMA history constant of $\alpha = 0.2$. We discuss these parameter settings at the end of this section.

The assumption underlying the majority of existing link estimation concepts is that packet losses inside one measurement period occur independently of each other (*i. e.*, they follow a Bernoulli distribution). This assumption has been challenged before in research [3, 10]. The analysis of our data in Section 4 supports the hypothesis that the assumption of independent packet losses is not appropriate at the fine-grained time-scales dealt with in this paper.

In addition to online link estimators, there has been significant research in link modelling and link measurements for wireless sensor networks [1, 9, 12–14, 16–18]. For example, Zhou et al. [17] investigate the impact of spatial irregularities on various protocols, and Koksal et al. [6] develop metrics to model long-term link quality and short-term link dynamics. Additionally, Cerpa et al. [2] provide statistical models of radio links in wireless sensor networks, including short-term and long-term temporal characteristics. Based on their statistical link model, the authors develop a corresponding link cost model that they integrate into multihop routing. In contrast to these approaches, STLE does not aim to provide link models, but to identify phases of reliable or unreliable connectivity at runtime.

Approaches such as Solicitation-based forwarding (SOFA [7]) remove the need for long-term link estimation and test link availability by sending a short hand-shake packet as a probe before sending any data packets. However, our evaluation of STLE in Section 4 shows that a successful hand-shake should not be taken as a success guarantee for subsequent data transmissions and indicate a need for more sophisticated models.

Both SOFA and four-bit link estimation include concepts for identifying and adapting to short-term link quality dynamics. However, their concepts seem limited and the reasons behind the particular parameter values chosen were not published. Hence, it remains unclear whether they represent optimal settings. This paper intends to clarify the need for short-term estimation and to quantify the benefits of different sets of parameters.

3 Short-Term Link Estimator

In this section we introduce short-term link estimation in detail, putting a special focus on its integration into long-term link estimators and routing protocols. We present our approaches on the identification of temporarily available and unavailable links and evaluate these in Section 4.

Our interest in short-term link estimation is motivated by two key observations indicated by research [2, 9, 16] and our own measurements[1]: (1) Links of intermediate quality amount to about half the number of high-quality stable links (see Figure 1(a)) and (2) this percentage grows with the physical distance (see Figure 1(b)).

Although links of intermediate quality offer further choices for routing and often promise long distance connectivity, Figure 1(c) shows that this class of links is subject to large and frequent temporal variations. Their dynamic connectivity poses a special challenge to any link estimator.

3.1 Limitations of Long-Term Estimators

Long-term link estimators are not designed to identify short-term link dynamics. As a result, they adapt slowly to

[1] Section 4.1 describes our measurement procedure in detail.

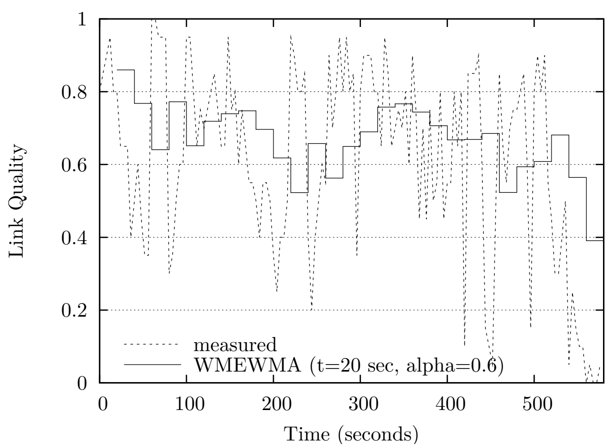


Figure 2. Measured and estimated packet reception rate of a medium quality link. Data was measured using one burst of 20 packets every four seconds.

changing link conditions, limiting their use to the identification of long-term stable links. Figure 2 illustrates the slow adaptation of the WMEWMA estimator, showing the probability of successful packet reception on a dynamic, medium-quality link from our testbed, along with the resulting link quality estimated by WMEWMA. Note that WMEWMA cannot identify phases of temporarily reliable or unreliable connectivity.

3.2 Design of STLE

Commonly, links in a wireless network can be classified into three categories: good links that are reliable in the long term; intermediate, unreliable links often with frequently changing quality; and bad links that very seldom transmit a packet successfully. Figure 1(a) shows that the ratio between good links and intermediate links is 2:1 in our testbed measurements. Furthermore, our measurements indicate that any link – no matter of what long-term quality – can temporarily change its characteristics and thereby temporarily become a reliable link for routing or become an unreliable one.

Unreliable Links

We consider an intermediate or broken link temporarily available when it successfully transmits a number of packets over a short interval. We define a corresponding threshold based on the link's long-term reliability: for example, a link of intermediate quality needs to transmit less packets before being considered temporarily available than a link of bad quality. We expect that the probability of a successful packet transmission depends on the success rate of any recently sent packets, i.e. the more packets were transmitted successfully in the recent history, the higher the probability is that an upcoming packet is transmitted successfully, too. Furthermore, we expect that a long history of successful transmission indicates with a high probability that not only the next packet but also following ones are transmitted successfully.

Reliable links

Similarly, a number of successfully transmitted packets indicate that a reliable link is currently available, while failed ones indicate that a link is currently not available. Overall, we expect that a single successful transmission indicates that a long-term reliable link is currently available.

Online Data Collection

To identify temporary reliable or unreliable links, the short-term link estimator collects a short-term history of recent transmissions and their success or failure. STLE does not send probe packets to test for link availability, it bases on packet overhearing. Hence, a node overhears packets sent by neighboring nodes and collects statistics on the current reachability. When a node considers the incoming direction of an unreliable link temporarily stable and concludes that it offers a routing improvement, it sends a message to the link neighbor to inform it about a short-term link availability. The neighboring node may then consider routing subsequent packets over the newly available link. If the node is selected as next hop, link-layer acknowledgments continuously provide information about link availability.

STLE is designed to be self-calibrating. Each node collects statistics on the transmission success rate depending on long-term link quality and short-term history. Based on these statistics, it decides online which short-term history corresponds to a significant short-term change in link quality with the required confidence.

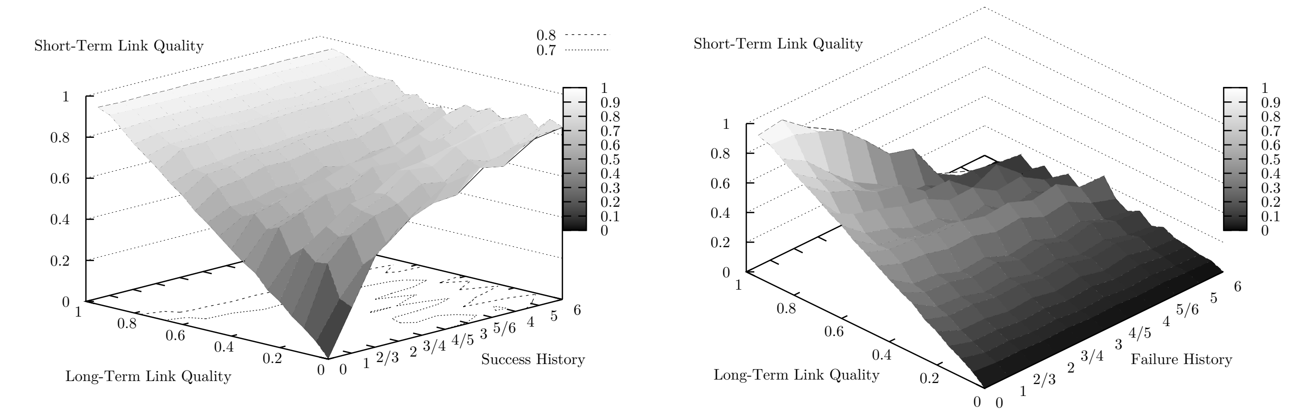
3.3 Integration with Long-Term Link Estimators and Routing Protocols

STLE is designed to embed deeply into the routing protocol and to cooperate with long-term link estimators. Modern sensor network routing protocols such as BVR [5] use the number of expected transmissions to a destination as routing metric, computed by combining the distance (in hops) and the number of expected retransmissions. Both long-term and short-term link estimation aim to predict the number of necessary retransmissions on a link, each on their respective temporal granularity. Consequently, when no short-term estimation for a link is available, the routing protocol will use the long-term prediction as fallback, probably resulting in conservative link selection.

As explained above, neighboring nodes overhear ongoing data flows and may suggest themselves to the forwarding node as next hop alternatives, when they (1) identify the link from the forwarding node as short-term reliable and (2) conclude that they offer a better routing choice for the ongoing flow. As a result, the forwarding node has an increased number of choices for routing. Apart from the number of expected transmissions to a destination as used in BVR, other routing metrics such as link load, queue length or battery levels can be integrated similarly.

The message that STLE sends to inform a forwarding node about a temporary availability of a link also constitutes a simple test for link asymmetry. Furthermore, should the advertised link become unreliable, transmission will fail and the routing protocol will fall back to any second best link, either suggested by STLE or a backup long-term stable link.

We expect STLE to integrate well with power management schemes. Nodes can reach a decision after overhearing only a small number of packets (three to six), corresponding to a time span of no more than 200 ms. Every node that is awake for at least this period of time can use STLE.



(a) Influence of recent transmission success rate on short-term link quality. A label of k/h stands for k successes during the last h transmissions, and h is a shorthand for h/h.

(b) Influence of recent transmission failure rate on short-term link quality. A label of k/h stands for k failures during the last h transmissions, and h is a shorthand for h/h.

Figure 3. Influence of success and failure of recent transmissions events on short-term link quality.

4 Evaluation

After introducing the basic design concepts of short-term link estimation and their integration with long-term link estimation and routing protocols, this section presents experimental results to evaluate the concept of STLE and to determine the required thresholds for link classification.

4.1 Experimental Setup

To evaluate the concept of short-term link estimation, we executed a number of experiments in our indoor testbed. The testbed consists of a regular 6×6 grid of Telos B motes [8] with CC2420 transceivers [11] with a spacing of approximately 2.80 m inside a 20 m $\times$ 20 m indoor auditorium.

Every node transmitted a burst of 20 sequentially numbered packets (at maximum rate, which is about 180 packets per second) before passing the role of the sender along through its USB connection. For every packet, the receivers logged the sequence number, the received signal strength, and the chip correlation (LQI) value provided by the radio chipset.

We ran this experiment for 5,500 seconds. Nodes transmitted packets with a length of 15 bytes at -25 dBm on IEEE 802.15.4 channel 26, with a center frequency of 2,480 MHz, which is the least affected by WiFi interference. Additionally, we executed experiments on the default channel 11 (frequency 2,405 MHz) which show similar results as discussed below, just with a lower percentage of successful delivery, probably due to WiFi interference.

4.2 Thresholds for STLE

After introducing the experimental setup, we next evaluate STLE based on the gathered experimental traces.

To calibrate STLE we need to identify a *threshold* when an intermediate or bad link should be considered temporary reliable. Figure 3(a) depicts the probability of a successful packet transmission based on the average long-term link quality and a short-term history of consecutively transmitted packets. The figure indicates that e. g. for a link with 10 % long-term link quality, the transmission success probability for the next packet exceeds 80% when the four preceding packets were transmitted successfully. We consider links of such instantaneous quality useful for routing, thus STLE suggests such a 10 %-quality link for routing. In the same way, STLE considers a 60 %-quality link to be short-term reliable after just one successful transmission.

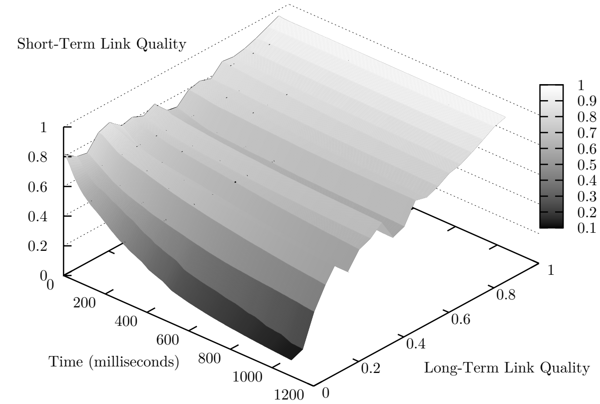


Figure 4. Temporal extent of influences on short-term link quality. We show the short-term link quality over the immediate future after six consecutive successful transmissions.

Figure 3(b) depicts the probability of a successful packet transmission based on the average long-term link quality and a short-term history of consecutively failed packet transmissions. It indicates that for two or more consecutive losses any link should be temporarily considered broken and be removed from the routing table.

In addition to the identification of short-term stability, we evaluate the duration of this stability. To allow routing protocols to benefit from STLE and adapt to dynamics the link should exhibit a temporal stability in the order of hundred milliseconds to seconds. Figure 4 depicts the average duration of the short-term stability based on the long-term link quality and indicates that once identified short-term stabilities have a duration that enables their incorporation into routing protocols.

The short-term link estimator operates in a self-calibrating manner. Nodes can perform the calibration process described above on-line. By collecting traces from overhearing, they can compute the number of consecutive successful transmissions required to indicate successful transmission of follow-up packets with a probability above a user-defined threshold, in our case 80%. As a result, we believe STLE can easily adapt to different radio types, noise levels and deployment characteristics.

5 Future Work

After designing and evaluating the concept of short-term link estimation, our ongoing work focuses on the integration into sensor network routing protocols. Although our evaluation shows that STLE can reliably identify when unstable links have become temporary stable and vice versa, only an integration can fully evaluate the benefits of STLE. Thus, we are currently implementing STLE extensions to the link estimator in the Beacon Vector Routing (BVR) protocol to analyze performance improvements of STLE.

In addition to the integration into routing protocols, we need to evaluate STLE in different testbeds and platforms to calibrate its models and thresholds.

6 Conclusion

Observing that long-distance links are often unstable links, we introduce the concept of short-term link estimation to identify when links are temporarily reliable. Our practical identification of short-term dynamics bases on overhearing and does not require probe packets. As a result, STLE operates with low overhead in terms of bandwidth and energy. Our evaluation indicates that STLE can reliably identify short-term stable and unstable links. It adapts routing tables accordingly to thereby reduce the number of transmissions a packet takes towards its destination. Additionally, the evaluation shows that short-term stability exhibits a duration in the order of hundred milliseconds, allowing STLE to adapt routing tables on neighboring nodes. Furthermore, we show that STLE flexibly integrates into long-term link estimation and today's sensor network routing protocols.

Overall, we identify short-term link estimation in sensor networks as a very young field of research which – to our best knowledge – did not receive much attention in the past. Furthermore, we note that short-term link estimation is not limited to wireless sensor networks and can possibly be applied to (mobile) ad-hoc and mesh networks, too.

7 References

[1] G. Anastasi, M. Conti, E. Gregori, A. Falchi, and A. Passarella. Performance Measurements of Mote Sensor Networks. In *7th ACM International Symposium on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWiM)*, Venice, Italy, October 2004.

[2] A. Cerpa, J. L. Wong, L. Kuang, M. Potkonjak, and D. Estrin. Statistical model of lossy links in wireless sensor networks. In *Proc. of the 4th International Symposium on Information processing in Sensor Networks (IPSN)*, April 2005.

[3] A. Cerpa, J. L. Wong, M. Potkonjak, and D. Estrin. Temporal properties of low power wireless links: Modeling and implications on multi-hop routing. In *Proceedings of the 6th ACM Interational Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), Urbana-Champaign, IL, USA*, May 2005.

[4] R. Fonseca, O. Gnawali, K. Jamieson, and P. Levis. Four-bit wireless link estimation. In *Proceedings of the Sixth Workshop on Hot Topics in Networks (HotNets)*, November 2007.

[5] R. Fonseca, S. Ratnasamy, J. Zhao, C. T. Ee, D. E. Culler, S. Shenker, and I. Stoica. Beacon vector routing: Scalable point-to-point routing in wireless sensornets. In *2nd Symposium on Networked Systems Design and Implementation (NSDI)*, May 2005.

[6] C. E. Koksal and H. Balakrishnan. Quality-aware routing metrics for time-varying wireless mesh networks. *IEEE Journal on Selected Areas in Communications*, 24(11):1984–1994, November 2006.

[7] S.-B. Lee, K. J. Kwak, and A. T. Campbell. Solicitation-based forwarding for sensor networks. In *Proc. of the Conference on Sensor and Ad Hoc Communications and Networks (SECON)*, September 2006.

[8] J. Polastre, R. Szewczyk, and D. Culler. Telos: enabling ultra-low power wireless research. In *Proc. of the Fourth International Symposium on Information Processing in Sensor Networks (IPSN)*, April 2003.

[9] N. Reijers, G. Halkes, and K. Langendoen. Link layer measurements in sensor networks. In *1st IEEE Int. Conf. on Mobile Ad-hoc and Sensor Systems*, October 2004.

[10] K. Srinivasan, P. Dutta, A. Tavakoli, and P. Levis. Understanding the causes of packet delivery success and failure in dense wireless sensor networks. In *Proceedings of the 4th International Conference on Embedded Networked Sensor Systems (SenSys), Boulder, Colorado, USA*, November 2006.

[11] Texas Instruments. *CC2420 Datasheet: Single-Chip 2.4 GHz IEEE 802.15.4 Compliant and ZigBee(TM) Ready RF Transceiver*, March 2007.

[12] P. von Rickenbach, S. Schmid, R. Wattenhofer, and A. Zollinger. A robust interference model for wireless ad-hoc networks. In *5th International Workshop on Algorithms for Wireless, Mobile, Ad Hoc and Sensor Networks (WMAN)*, April 2005.

[13] P. Wang and T. Wang. Adaptive routing for sensor networks using reinforcement learning. In *Proc. of the Sixth IEEE International Conference on Computer and Information Technology (CIT)*, 2006.

[14] Y. Wang, M. Martonosi, and L.-S. Peh. A supervised learning approach for routing optimizations in wireless sensor networks. In *Proc. of the 2nd International Workshop on Multi-hop Ad-hoc Networks: from Theory to Reality (REALMAN)*, 2006.

[15] A. Woo, T. Tong, and D. Culler. Taming the underlying challenges of reliable multihop routing in sensor networks. In *Proc. of the 1st International Conference on Embedded Networked Sensor Systems (SenSys)*, November 2003.

[16] J. Zhao and R. Govindan. Understanding packet delivery performance in dense wireless sensor networks. In *Proc. of the 1st International Conference on Embedded Networked Sensor Systems (SenSys)*, November 2003.

[17] G. Zhou, T. He, S. Krishnamurthy, and J. A. Stankovic. Impact of radio irregularity on wireless sensor networks. In *Proceedings of the Second International Conference on Mobile Systems, Applications, and Services (MobiSys 2004)*, June 2004.

[18] M. Zuniga and B. Krishnamachari. Analyzing the transitional region in low power wireless links. In *Proc. of the Conference on Sensor and Ad Hoc Communications and Networks (SECON)*, 2004.