Challenges in Short-term Wireless Link Quality Estimation

Muhammad Hamad Alizai, Olaf Landsiedel,
Klaus Wehrle
Distributed Systems Group
RWTH Aachen University, Germany
firstname.lastname@rwth-aachen.de

Alexander Becher
sd&m AG
Düsseldorf, Germany
alexander.becher@sdm.de

Abstract

Identifying reliable low-power wireless links for packet forwarding in sensor networks is a challenging task. Currently, link estimators mainly focus on identifying high-quality stable links, leaving out a potentially large set of intermediate quality links capable of enhancing routing progress in a multihop network.

In this paper we present our ongoing work on short-term link estimation that captures link dynamics at high resolution in time. A short-term link quality is calculated based on the recent transmission characteristics of a link. This short-term quality of a link, combined with its long term reliability enables to determine if an intermediate quality link is temporarily available for transmission. Consequently adapting the neighbor table of a node and offering more forwarding choices to routing protocols.

1 Introduction

Instability in low-power wireless sensor networks (WSN) connectivity has so far been regarded as a difficult problem that existing routing algorithms try their utmost to avoid. In doing so, they forego a large class of potentially valuable communication links. An understanding of the patterns underlying the seemingly irregular variations of the wireless channel would enable algorithms to make use of this previously disregarded class of links.

To achieve better connectivity and reliable packet communication, today's link estimators restrict communications only to the neighbors with constantly high-quality links. These high quality links are identified based on the long term success rate of a link, typically collected over a time frame on the order of minutes. However, this approach has certain pitfalls. First, neighbors with intermittent connectivity might reach farther into the network. Their use would therefore reduce the number of hops, reduce energy usage in the network, and increase its lifetime. Second, in a sparse network with a low density of nodes, a node might have no high-quality neighbor in its communication range, requiring a mechanism to deal with unstable connectivity.

In this paper we present our on going work on short-term link estimation (STLE) [2] that takes fine-grained link dynamics - in the order of milliseconds - into account and increases 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. 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.

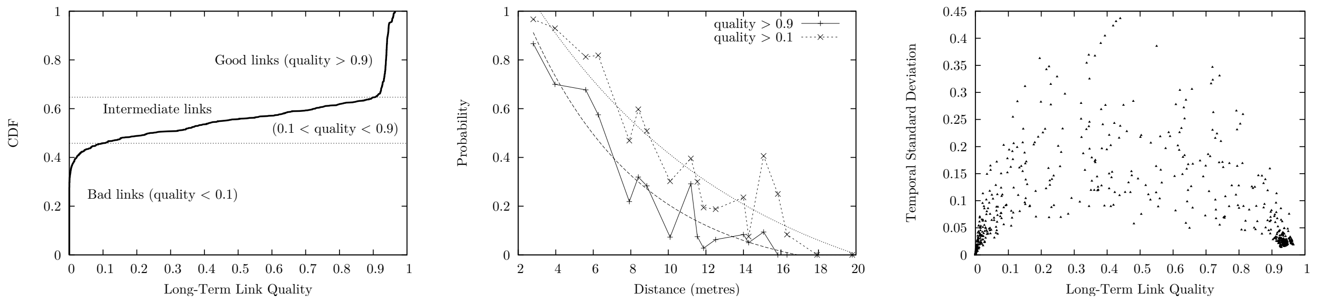
2 Related Work

The identification of reliable links in WSN 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.

While investigating several approaches for online link estimation, Woo et al. [20] identified window mean estimator with an exponentially weighted moving average (WMEWMA) to be an optimal choice to aggregate packet reception rate as an indicator of link quality. Four-bit link estimation [6] extends this WMEWMA estimator into a hybrid link estimator that accumulates information from all layers of the sensor node networking stack. However, estimation techniques based on WMEWMA performs poorly on medium quality links. These links often offer the highest routing progress [3] suggesting the need for more precise estimation methods for medium quality links.

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 [4, 14]. 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 WSN [1,13,15–17,21–23]. For example, Koksal et al. [9] develop metrics to model long-term link quality and short-term link dynamics. Additionally, Cerpa et al. [3] provide statistical models of radio links in WSN, including short-term and long-term temporal characteristics.In contrast to these approaches, STLE does not aim to provide link models, but to identify phases of reliable or unreliable connectivity at runtime.



(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.

Approaches such as Solicitation-based forwarding (SOFA [10]) 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.

3 Short-term Link Estimation

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 [3,13,21] and our own measurements: (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. Long-term link estimators are not designed to identify short-term link dynamics. As a result, they adapt slowly to changing link conditions, limiting their use to the identification of long-term stable links.

3.1 Deriving a Short-term Link Estimator

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.

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. 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.

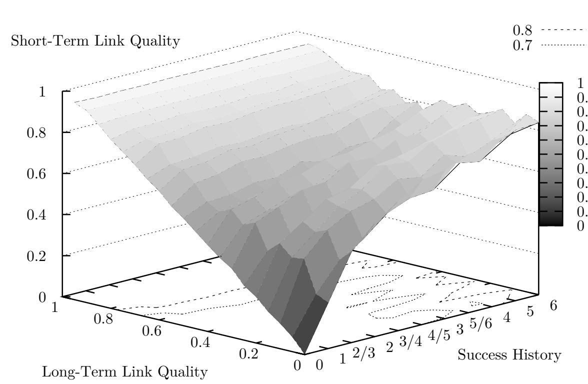
Furthermore, short-term link estimator does not send probe packets to test for link availability, it bases on packet overhearing. Hence, a node overhears packets sent by neighboring nodes and collects statistics on the current reachability. When a node considers the incoming direction of an unreliable 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.

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.

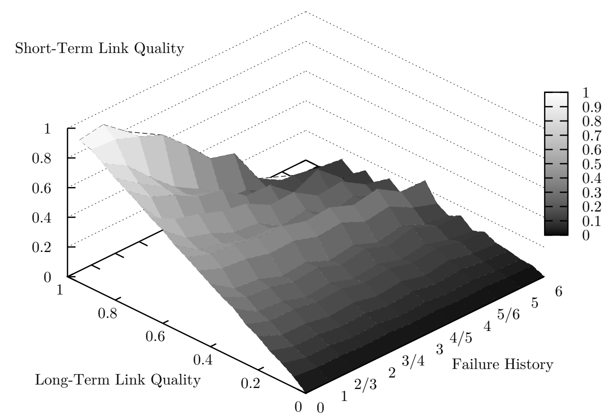
3.2 Integration with Long-Term Link Estimators and Routing Protocols

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 [7] 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 forward-



(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 2. Influence of success and failure of recent transmissions events on short-term link quality.

ing 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.

3.3 Use Case for STLE

Packet overhearing technique employed in STLE can benefit from the bursty traffic patterns observed in WSN. Typical applications [8, 11, 18, 19] of WSN involve monitoring environment for events that are of interest to the users. Although these events occur rarely, but their occurrence results in large bursts of packets that represent major fraction of the overall network traffic. In such situations, STLE, after overhearing first few packets, can identify intermediate quality links temporarily available for transmission.

For example, consider a sensor network based fence monitoring system [19]. During normal conditions, i.e. when there is no intruder breaking into the fence, the network will generate very limited or no traffic. However, as soon as an intruder is detected by the system, large bursts of packets will be generated by the distributed event detection algorithm. In this situation, STLE recognizes intermediate quality links currently stable for transmission, and informs routing algorithm of the availability of such links by online adaptation of neighbor tables. We believe that this technique will significantly reduce the hop count a packet has to traverse from its source to destination. Thereby minimizing the energy consumption and increasing network life time.

4 Evaluation

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 [12] with a spacing of approximately 2.80 m inside a $20\,\text{m} \times 20\,\text{m}$ indoor auditorium. Every node transmitted a burst of 20 sequentially numbered packets with a length of 15 bytes at -25 dBm. We ran this experiment for 5,500 seconds.

To calibrate STLE we need to identify a *threshold* when an intermediate or bad link should be considered temporary reliable. Figure 2(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 2(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.

5 Future Work and Challenges

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.

Cerpa et al. [5] discuss the impact of packet size on packet reception rate. In our experiment, all packets sent were of the same length. The effect of different packet sizes on packet reception rate remains to be investigated.

In practice, nodes do not transmit at the same short intervals used during our measurements. We have yet to investigate whether the correlations derived in section 4 hold for longer intervals between reception events. Devising other mechanisms, such as sending probe packets to evaluate link quality, could also be used but it will raise the communication overhead significantly.

6 Conclusion

Intermediate quality links constitute a significant fraction of wireless links in low-power WSN. STLE captures short-term link dynamics of these links at a high resolution in time and predicts their temporary availability or unavailability. Our measurements indicate that these intermittent links, if utilized, can significantly improve the performance of routing algorithms by offering further choices for forwarding packets. Moreover, STLE is more suitable for networks showing bursty traffic patterns such as in typical applications of WSN.

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. Becher, O. Landsiedel, G. Kunz, and K. Wehrle. Towards short-term link quality estimation. In *Proc. of The Fith workshop on Embedded Networked Sensors (Emnets 2008)*, June 2008.

[3] 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.

[4] 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 *Proc. of the 6th ACM Interational Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc)*, May 2005.

[5] 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 *MobiHoc '05: Proceedings of the 6th ACM international symposium on Mobile ad hoc networking and computing*, 2005.

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

[7] 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.

[8] T. He, S. Krishnamurthy, J. A. Stankovic, T. Abdelzaher, L. Luo, R. Stoleru, T. Yan, L. Gu, J. Hui, and B. Krogh. Energy-efficient surveillance system using wireless sensor networks. In *MobiSys '04: Proc. of the 2nd international conference on Mobile systems, applications, and services*, 2004.

[9] 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.

[10] 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.

[11] K. Lorincz and M. Welsh. A robust, decentralized approach to rf-based location tracking. Technical report, Harvard University, 2004.

[12] 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)*, 2003.

[13] 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.

[14] 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)*, November 2006.

[15] 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.

[16] 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.

[17] 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.

[18] M. Welsh, G. Werner-Allen, K. Lorincz, O. Marcillo, J. Johnson, M. Ruiz, and J. Lees. Sensor networks for high-resolution monitoring of volcanic activity. In *SOSP '05: Proc. of the twentieth ACM symposium on Operating systems principles*, 2005.

[19] G. Wittenburg, K. Terfloth, F. L. Villafuerte, T. Naumowicz, H. Ritter, and J. H. Schiller. Fence monitoring - experimental evaluation of a use case for wireless sensor networks. In *In Proc. of 4th European Conference on Wirless Sensor Networks EWSN*, 2007.

[20] 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.

[21] 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.

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

[23] 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.