IPP HURRAY!
www.hurray.isep.ipp.pt

Technical Report

Radio Link Quality Estimation in Wireless Sensor Networks: a Survey

Noucha Baccour
Anis Koubaa
Luca Mottola
Marco Antonio Zuniga
Habib Youssef
Carlo Alberto Boano
Mario Alves

HURRAY-TR-121202
Version:
Date: 12-27-2012

Radio Link Quality Estimation in Wireless Sensor Networks: a Survey

Noucha Baccour, Anis Koubaa, Luca Mottola, Marco Antonio Zuniga, Habib Youssef, Carlo Alberto Boano, Mario Alves

IPP-HURRAY!

Polytechnic Institute of Porto (ISEP-IPP)

Rua Dr. António Bernardino de Almeida, 431

4200-072 Porto

Portugal

Tel.: +351.22.8340509, Fax: +351.22.8340509

E-mail:

http://www.hurray.isep.ipp.pt

Abstract

Radio link quality estimation in Wireless Sensor Networks (WSNs) has a fundamental impact on the network performance and also affects the design of higher-layer protocols. Therefore, for about a decade, it has been attracting a vast array of research works. Reported works on link quality estimation are typically based on different assumptions, consider different scenarios, and provide radically different (and sometimes contradictory) results. This article provides a comprehensive survey on related literature, covering the characteristics of low-power links, the fundamental concepts of link quality estimation in WSNs, a taxonomy of existing link quality estimators, and their performance analysis. To the best of our knowledge, this is the first survey tackling in detail link quality estimation in WSNs. We believe our efforts will serve as a reference to orient researchers and system designers in this area.

Radio Link Quality Estimation in Wireless Sensor Networks: A Survey

NOUHA BACCOUR, University of Sfax, Tunisia and
CISTER Research Unit, Polytechnic Institute of Porto (ISEP/IPP), Portugal
ANIS KOUBÂA, Al-Imam Mohamed bin Saud University, Saudi Arabia and
Polytechnic Institute of Porto (ISEP/IPP), Portugal
LUCA MOTTOLA, Swedish Institute of Computer Science (SICS), Sweden
MARCO ANTONIO ZÚÑIGA, University of Duisburg-Essen, Germany
HABIB YOUSSEF, University of Sousse, Tunisia
CARLO ALBERTO BOANO, University of Lübeck, Germany
MÁRIO ALVES, Polytechnic Institute of Porto (ISEP/IPP), Portugal

Radio link quality estimation in Wireless Sensor Networks (WSNs) has a fundamental impact on the network performance and also affects the design of higher-layer protocols. Therefore, for about a decade, it has been attracting a vast array of research works. Reported works on link quality estimation are typically based on different assumptions, consider different scenarios, and provide radically different (and sometimes contradictory) results. This article provides a comprehensive survey on related literature, covering the characteristics of low-power links, the fundamental concepts of link quality estimation in WSNs, a taxonomy of existing link quality estimators, and their performance analysis. To the best of our knowledge, this is the first survey tackling in detail link quality estimation in WSNs. We believe our efforts will serve as a reference to orient researchers and system designers in this area.

Categories and Subject Descriptors: C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*Wireless communication*

This work is supported by the ReDCAD Research Unit (05-UR-1403) funded by the Tunisian Ministry of Higher Education and Scientific Research, and by the CISTER Research Unit (608FCT) funded by FEDER funds through COMPETE (POFC—Operational Programme "Thematic Factors of Competitiveness") and by National Funds (PT), through the FCT—Portuguese Foundation for Science and Technology, the CONET—Cooperating Objects Network of Excellence, funded by the European Commission under FP7 with grant ref. FP7-ICT-224053, the EMMON project, funded by National Funds, through FCT, under grant ref. EMMON - ARTEMIS/0003/2008, as well as by the ARTEMIS Joint Undertaking, under grant agreement ref. EMMON - Grant nr.100036, and by the MASQOTS project, ref. FCOMP-01-0124-FEDER-014922, funded by FEDER funds through COMPETE and by National Funds through FCT.
N. Baccour is currently affiliated with ReDCAD Research Unit, University of Sfax, Tunisia and CISTER/INESC-TEC, ISEP, Politécnico do Porto, Portugal; A. Koubâa is currently affiliated with COINS Research Group, Prince Sultan University, Saudi Arabia and CISTER/INESC-TEC, ISEP, Politécnico do Porto, Portugal; L. Mottola is currently also affiliated with Politecnico di Milano, Italy; M. A. Zúñiga is currently also affiliated with Delft University of Technology, Netherlands; M. Alves is currently also affiliated with CISTER/INESC-TEC, ISEP, Politécnico do Porto, Portugal.
Authors' addresses: N. Baccour (corresponding author), ReDCAD Research Unit, University of Sfax, Tunisia and CISTER, Polytechnic Institute of Porto (ISEP/IPP), Portugal; email: nabr@isep.ipp.pt; A. Koubâa, COINS Reserach Group, Al-Imam Mohamed bin Saud University, Saudi Arabia and CISTER Research Unit, Polytechnic Institute of Porto (ISEP/IPP) Portugal; L. Mottola, Swedish Institute of Computer Science (SICS), Kista, Sweden; M. A. Zúñiga, Networked Embedded Systems Group, University of Duisburg-Essen, Germany; H. Youssef, Prince Research Unit, ISITCom H Soussee, University of Sousse, Tunisia; C. A. Boano, Institute of Computer Engineering, University of Lübeck, Germany; M. Alves, CISTER Research Unit, Polytechnic Institute of Porto (ISEP/IPP), Portugal.

DOI 10.1145/2240116.2240123 http://doi.acm.org/10.1145/2240116.2240123

General Terms: Experimentation, Measurement, Performance, Design

Additional Key Words and Phrases: Link quality estimation, low-power links, wireless sensor networks, link characteristics

ACM Reference Format:
Baccour, N., Koubâa, A., Mottola, L., Zúñiga, M. A., Youssef, H., Boano, C. A., and Alves, M. 2012. Radio link quality estimation in wireless sensor networks: a survey. ACM Trans. Sensor Netw. 8, 4, Article 34 (September 2012), 33 pages.
DOI = 10.1145/2240116.2240123 http://doi.acm.org/10.1145/2240116.2240123

1. INTRODUCTION

The propagation of radio signals is affected by several factors that contribute to the degradation of its quality. The effects of these factors are even more significant on the propagation of wireless signals with low-power radios, typically used in Wireless Sensor Networks (WSNs). Consequently, radio links in WSNs are often unpredictable. In fact, their quality fluctuates over time [Cerpa et al. 2005b; Srinivasan et al. 2010a] and space [Zhou et al. 2006a; Zhao and Govindan 2003; Reijers et al. 2004; Cerpa et al. 2003], and connectivity is typically asymmetric [Zhou et al. 2006a; Cerpa et al. 2005a].

Nowadays, it is well-known that three factors lead to link unreliability: (i) the environment, which leads to multipath propagation effects and contributes to background noise, (ii) the interference, which results from concurrent transmissions within a wireless network or between cohabiting wireless networks and other electromagnetic sources; and (iii) hardware transceivers, which may distort sent and received signals due to their internal noise [Rappapport 2001; Goldsmith 2005]. In WSNs, these radio transceivers transmit low-power signals, which makes radiated signals more prone to noise, interference, and multipath distortion. Furthermore, they rely on antennas with nonideal radiation patterns, which leads to anisotropic behavior.

In the literature, several research papers focused on the statistical characterization of low-power links through estimation theory, which is commonly known as *Link Quality Estimation*, to study the behavior of low-power links. Link quality estimation in WSNs is a fundamental building block for several mechanisms and network protocols. For instance, routing protocols rely on link quality estimation to overcome low-power links' unreliability and maintain the correct network operation [Jiang et al. 2006; Woo et al. 2003; Gnawali et al. 2009; Li et al. 2005; Lim 2002; Koksal and Balakrishnan 2006; Seada et al. 2004; Cerpa and Estrin 2004]. Delivering data over links with high quality improves the network throughput by limiting packet loss and maximizes its lifetime by minimizing the number of retransmissions and avoiding route reselection triggered by links' failure. Link quality estimation also plays a crucial role for topology-control mechanisms to maintain the stability of the topology [Zhao and Govindan 2003; Cerpa et al. 2003, 2005a]. High-quality links are long-lived, therefore, efficient topology control mechanisms rely on the aggregation of high-quality links to maintain robust network connectivity for long periods, thus avoiding unwanted transient topology breakdown.

Link quality estimation in WSNs is a challenging problem due to the lossy and dynamic behavior of the links. Therefore, it is vital for WSN protocol designers to correctly account for low-power link characteristics. A vast array of research works tackled the empirical characterization of low-power links through real-world measurements with different platforms, under varying experimental conditions, assumptions, and scenarios [Cerpa et al. 2003, 2005b]; [Srinivasan et al. 2008, 2010a]; [Zhao and Govindan 2003; Ganesan et al. 2002; Lal et al. 2003; Zhou et al. 2004; Srinivasan and Levis 2006b; Son et al. 2006; Xu and Lee 2006; Lymberopoulos et al. 2006; Lee et al. 2007; Tang et al. 2007; Liang et al. 2010]. These works presented radically different (and sometimes contradicting) results which raise the need for a survey that deeply

Table I. Content of the Article

Topic	Section
Radio communication hardware	2
Overview of Low-Power Links	3
Spatial characteristics	3.1
Temporal characteristics	3.2
Link Asymmetry	3.3
Interference	3.4
External interference	3.4.1
Internal interference	3.4.2
Experimenting with interference	3.4.3
Counteracting interference	3.4.4
Fundamentals of Link Quality Estimation	4
Steps for Link Quality Estimation	4.1
Link monitoring	4.1.1
Link measurements	4.1.2
Metric evaluation	4.1.3
Requirements for Link Quality Estimation	4.2
A Survey on Link Quality Estimators	5
Hardware-based LQEs	5.1
Software-based LQEs	5.2
PRR-based	5.2.1
RNP-based	5.2.2
Score-based	5.2.3
Performance of Link Quality Estimators	6
Conclusions and Future Directions	7

analyzes their outcomes. This article fills this gap and provides a comprehensive survey of the most relevant key observations drawn from empirical studies on low-power links in WSNs. Such observations are useful for the design of efficient link quality estimators as well as other mechanisms at higher layers (e.g., node deployment, routing, mobility management), as they heavily depend on the underlying radio links.

This article aims at providing WSN researchers and practitioners with a useful understanding of low-power links. To this end, we start with an overview of the most common WSN radio technology, presented in Section 2. Next, we analyse the empirical characterization of low-power links in Section 3, and discuss their statistical estimation in Section 4. Section 5 presents a novel taxonomy and classification of the existing link quality estimators, whereas Section 6 discusses their performance. Section 7 concludes the work. Table I presents the organization of this article.

Overall, we make four contributions:

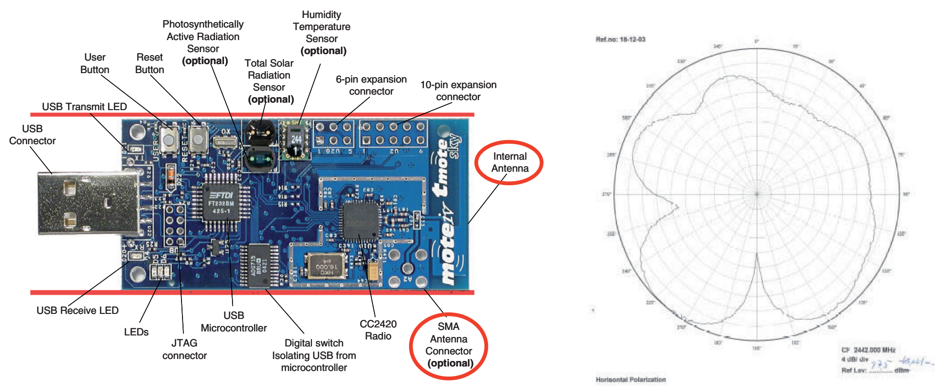
(1) We present a comprehensive survey on low-power link characteristics.
(2) We overview the fundamental concepts of link quality estimation in WSNs.
(3) We present a taxonomy of existing link quality estimators.
(4) We discuss the performance of existing link quality estimators, based on existing simulation and experimental work.

2. RADIO COMMUNICATION HARDWARE

As link quality strongly depends on the radio hardware platform, it is important to survey the characteristics of radios typically employed in WSN nodes. These

Table II. Characteristics of Typical WSN Radios

Model	Frequency	Max Data Rate	Modulation	TX Current	RX Current	TX Power
CC1000	3000-1000 Mhz	76.8 kbps	2-FSK	18.5 mA	9.6 mA	10 dBm
nRF903	433 or 915 Mhz	76.8 kbps	GFSK	19.5 mA	22.5 mA	10 dBm
TR1000	916 Mhz	115.1 kbps	OOK/ASK	12 mA	3.8 mA	0 dBm
CC2420	2.4 Ghz	250 kbps	DSSS/O-QPSK	17.4 mA	19.7 mA	0 dBm
CC2500	2.4 Ghz	512 kbps	2-FSK	12.8 mA	21.6 mA	1 dBm
PH2401	2.4 Ghz	1 mbps	GFSK	<20 mA	<20 mA	2 dBm



(a) integrated microstrip antenna

(b) radiation pattern with horizontal mounting

Fig. 1. TMote antenna details.

characteristics are summarized in Table II. To tackle the energy issue, early hardware platforms such as ChipCon CC1000 and RFM TR1000 leveraged radio chips operating in sub-GHz frequencies. These transceivers offer low power consumption in both transmission and receive modes. On the other hand, the low data rate prevented using these devices in scenarios different from low-rate data collection.

The need for higher data rate motivated the design of radios working in the 2.4 GHz ISM band, such as the well-known ChipCon's CC2400 and CC2500 families. Compliance to IEEE 802.15.4 also fostered a wider adoption of these radio chips, which are commonly found in several current WSN platforms. The tendency for high data rate is brought to an extreme when Bluetooth or WiFi chips are used. These are often found in hybrid configurations where a high-data-rate radio is coupled to a low-power one. For instance, the BTnode [BTNode 2012] platform uses a Bluetooth-compliant device next to a CC1000 chip. Such design allows greater flexibility and alternative uses of the WSN devices, for example, as passive sniffers of ongoing traffic for debugging purposes [Dyer et al. 2007].

The radio hardware platform used often represents one of the main causes of low-power links' unreliability. First, sensor devices are often shipped with low-gain antennas integrated in the board. For instance, in the widespread TMote/TelosB devices (Figure 1(a)) [Polastre et al. 2005], the antenna is integrated in the PCB (Printed Circuit Board), and the actual radiation pattern is irregular (Figure 1(b)), although designed to be omnidirectional. Such irregularity stems from several factors, such as, the presence of the node circuitry. These aspects complicate the operation of MAC and routing protocols, which are traditionally based on the assumption of uniform communication ranges and symmetric links. A common design choice in real-world deployments is the replacement of the standard antenna [Raman and Chebrolu 2008], as it brings increased communication range and higher reliability without incurring extra energy costs. For instance, antennas of up to 8.5 dBi were used in harsh environments by exploiting the on-board SMA connectors [Werner-Allen et al. 2006]. Directional antennas, which are able to direct the transmission power in given directions, were also proposed. However, they lack flexibility in freely reconfiguring the network topology and node locations [Raman et al. 2006].

Second, real-world deployments showed how the performance of popular radio transceivers have a strong dependency on environmental factors such as temperature [Bannister et al. 2008; Boano et al. 2010a], as well as how higher transmission frequencies tend to be more susceptible to humidity [Thelen et al. 2005]. These factors drastically impact the quality of WSN links, particularly the ones deployed outdoors.

Third, radio hardware inaccuracy creates asymmetry in link connectivity, that is, the quality of the link in one direction is different from that in the other direction. In fact, nodes neither have the same effective transmission power nor the same noise floor or receiver sensitivity. This discrepancy in terms of hardware calibration leads to link asymmetry [Zhao and Govindan 2003; Cerpa et al. 2003; Lymberopoulos et al. 2006; Zuniga and Krishnamachari 2007].

3. OVERVIEW OF LOW-POWER LINKS

Several research efforts were devoted to an empirical characterization of low-power links. These studies were carried out using: (i) different WSN platforms having different radio chips (TR1000, CC1000, CC2420, etc.), (ii) different operational environments (indoor, outdoor), and (iii) different experimental settings (e.g., traffic load, channel). Therefore, they presented radically different (and sometimes contradicting) results. Nonetheless, these studies commonly argued that low-power links experience complex and dynamic behavior.

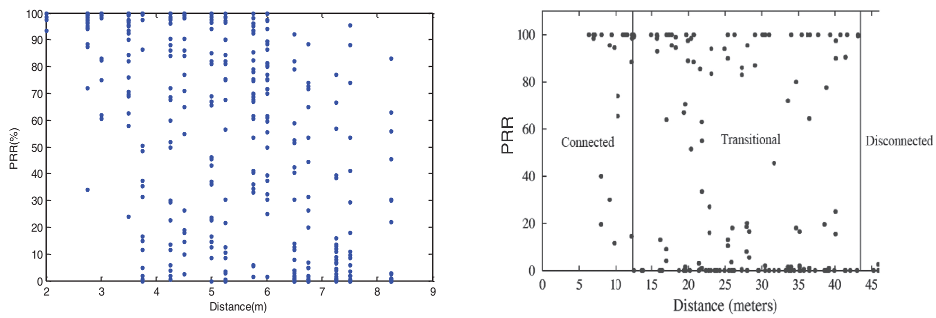
Although several low-power link characteristics are shared with those of traditional wireless networks, such as ad hoc, mesh, and cellular networks, the extent of these characteristics is more significant with low-power links (e.g., a large transitional region or extremely dynamic links) and makes them even more unreliable. This might be an artifact of the communication hardware used in WSNs [Srinivasan et al. 2010a; Tang et al. 2007].

In this section, we synthesize the vast array of empirical studies on low-power links into a set of high-level observations. We classify these observations into spatial and temporal characteristics, link asymmetry, and interference. We believe that such observations are helpful not only to design efficient Link Quality Estimators (LQEs) that take into account the most important aspects that affect link quality, but also to design efficient network protocols that deal with links' unreliability. Beforehand, we briefly present a set of basic metrics that were examined by previous empirical studies to capture low-power link characteristics.

—*PRR (Packet Reception Ratio)*. Sometimes referred to as PSR (Packet Success Ratio). It is computed as the ratio of the number of successfully received packets to the number of transmitted packets. A similar metric to the PRR is the PER (Packet Error Ratio), which is *1 - PRR*.

—*RSSI (Received Signal Strength Indicator)*. Most radio transceivers (e.g., the CC2420) provide an *RSSI register*. This register provides the signal strength of the received packet. When there are no transmissions, the register gives the noise floor.

—*SNR (Signal to Noise Ratio)*. It is typically given by the difference in decibel between the pure (i.e., without noise) received signal strength and the noise floor.



(a) The transitional region, for an outdoor environment, using TelosB sensor motes and -25 dBm as output power (using the RadiaLE testbed [Baccour et al. 2011]).

(b) The three reception regions, for an outdoor habitat environment, using Mica 2 sensor motes and -10 dBm as output power [Cerpa et al. 2003].

Fig. 2. Spatial characteristics: PRR as a function of distance between receiver node and sender node.

—*LQI (Link Quality Indicator)*. It is proposed in the IEEE 802.15 standard [IEEE 802.15.4 Standard 2003], but its evaluation is vendor-specific. For the CC2420 [Chipcon AS 2007], which is the most widespread radio, LQI is measured based on the first eight symbols of the received packet as a score ranging from 50 to 110 (higher values are better).

3.1. Spatial Characteristics

It was demonstrated in several works that the transmission range is not isotropic (i.e., a circular shape), where packets are received only within a certain distance from the sender [Kotz et al. 2003]. In fact, the transmission range is defined by three regions, each with an irregular shape, dynamic bounds (changing over the time), and specific features [Zhao and Govindan 2003; Reijers et al. 2004; Cerpa et al. 2003; Zuniga and Krishnamachari 2004]. These regions are: (i) connected region, where links are often of good quality, stable, and symmetric, (ii) transitional region, where links are of intermediate quality (in long-term assessment), unstable, not correlated with distance, and often asymmetric, and (iii) disconnected region, where links have poor quality and are inadequate for communication. Particularly, the transitional region was the subject of several empirical studies because links within this region are extremely unreliable and even unpredictable [Srinivasan et al. 2010a; Zhao and Govindan 2003; Reijers et al. 2004; Cerpa et al. 2003; Zuniga and Krishnamachari 2004]. These intermediate-quality links, referred also as *intermediate links*, are commonly defined as links having an average PRR between 10% and 90%.

Observation 1. Link quality is not correlated with distance, especially in the transitional region. To observe the transitional region, most empirical studies conducted measurements of the PRR at different distances from the sender. Figure 2(b) is an illustration of the three communication regions through PRR measurements. This figure shows that link quality is not correlated with distance, especially in the transitional region. Indeed, two receivers placed at the same distance from the sender can have different PRRs, and a receiver that is farther from the sender can have higher PRR than another receiver nearer to the sender. This observation can be clearly understood from Figure 2(a).

Observation 2. The extent of the transitional region depends on: (i) *the environment (e.g., outdoor, indoor, presence of obstacles), and* (ii) *the radio hardware characteristics (e.g., the transmission power, the modulation schema, the radio chip) [Zuniga and Krishnamachari 2007].* However, the quantification of this extent by empirical studies shows contradicting observations. Measurements of PRR according to distance, for different environments, radios, and power settings were carried out. Cerpa et al. [2003] performed measurements in indoor (office) and outdoor (habitat) environments using Mica 1 and Mica 2 platforms and different power levels, namely −10 dBm, −6 dBm, and 1 dBm. They found that the width of the transitional region is significant, ranging from 50% up to 80% of the transmission range. On the other hand, Zhao and Govindan [2003] performed measurements with almost the same settings as of Cerpa et al. [2003], but they found the transitional region width smaller, almost one-fifth up to one-third of the transmission range.

Observation 3. The percentage of intermediate quality links (i.e., located in the transitional region) was found significant in some empirical studies and insignificant in others, which lead to contradicting results. Zhao and Govindan [2003] performed experiments with Mica 1 platform in an office building while varying the traffic load. They found that the percentage of intermediate quality links ranges from 35% to 50%. On the other hand, Srinivasan et al. [2010a] performed experiments with more recent platforms, Micaz and TelosB, in different environments and with varying traffic loads. They found that the number of intermediate links ranges from 5% to 60%. Based on this observation, they claimed that the number of intermediate links observed with recent platforms is lower than that observed with old platforms. This was justified by the fact that recent platforms integrate IEEE 802.15.4-compliant radios (e.g., the CC2420) that have more advanced modulation schemes (e.g., Direct Sequence Spread Spectrum (DSSS)) compared to old platforms. Mottola et al. [2010] refuted this observation while conducting experiments in road tunnels using motes having IEEE 802.15.4-compliant radios. They observed a large transitional area in two of their tunnels and found a high number of intermediate quality links due to the constructive/destructive interference. We believe that this aspect remains an open issue and needs to be supported by additional experiments for two reasons. First, intermediate quality links were defined differently, namely "links with PRR less than 50%" by Zhao and Govindan [2003] and "links with PRR between 10% and 90%" by Srinivasan et al. [2010a]. Second, experimental studies that analyzed the percentage of intermediate quality links were based on different network settings (e.g., traffic load, power level, radio type, environment type, etc.) and also different window sizes for PRR calculation, so comparison would not be completely legitimate.

Observation 4. Link quality is anisotropic. Empirical studies observed another important spatial characteristic of low-power links often referred as *radio irregularity*, which means that link quality is anisotropic [Zhou et al. 2004, 2005, 2006a; Reijers et al. 2004; Ganesan et al. 2002]. To demonstrate the existence of radio irregularities, Zhou et al. [2006a] observed the RSSI and the PRR according to different receiver's directions, but with fixed distance between the transmitter and the receiver. They showed that the radio communication range, assessed by the RSSI, exhibits a nonspherical pattern. They also argued the existence of a nonspherical interference range, located beyond the communication range (refer to Figure 3). Within this interference range the receiver cannot interpret correctly the received signal, but this received signal can prevent it from communicating with other transmitters as it causes interference. The existence of the nonspherical radio communication and interference ranges was confirmed by Zhou et al. [2005]. They reported that in WSNs, several MAC protocols assume the following: If node B's signal can interfere with node A's signal, preventing A's signal from being received at node C, then node C must be within node B's communication range. Based on experimentation with Mica 2 motes, Zhou et al. [2005] showed that this assumption is definitely invalid, since node C may be in the interference range of node B and not in its communication range, as illustrated in Figure 3. The communication range assessed

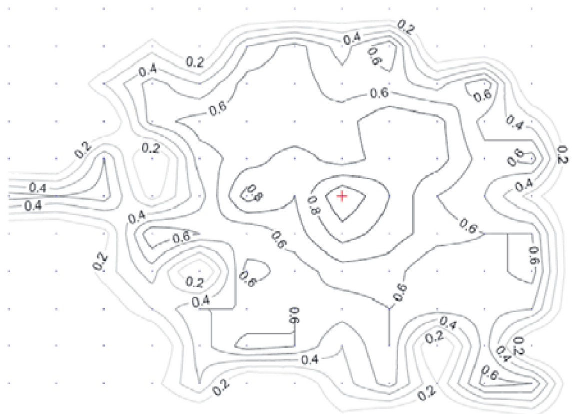


Fig. 3. Radio irregularity and interference range [Zhou et al. 2004]. Node B cannot communicate with node C as it is out of its communication range. However, B prevents C from communicating with A due to the interference between the signal sent by B and that sent by A.

Fig. 4. Contour of PRR from a central node: anisotropy of link quality [Ganesan et al. 2002].

by the PRR was also shown to be nonspherical or anisotropic [Ganesan et al. 2002], as shown in Figure 4. A natural reason for radio irregularity is the anisotropic radiation pattern of the antenna due to the fact that antennas do not have the same gain along all propagation directions [Zhou et al. 2006a].

Observation 5. Sensor nodes that are geographically close to each other may have high spatial correlation in PRRs. Zhao and Govindan [2003] investigated the spatial correlation in PRRs, measured between a source node and different receiver nodes. They observed that receiver nodes that are geographically close to each other and that are located in the transitional region have higher coefficient of correlation in their PRRs, compared to nearby receiver nodes located in the connected or disconnected regions. Nevertheless, the coefficient of correlation in the transitional region is not that significant, less than 0.7. Srinivasan et al. [2010b] introduced the κ Factor, a new metric that captures spatial correlation in PRR between links, using the cross-correlation index. The κ Factor was shown to perform better than exiting metrics for the measurement of spatial correlation between links.

Observation 6. The spatial variation of link quality is due to constructive/destructive interference. Beyond the connected region, the direct signal is weak due to path loss.

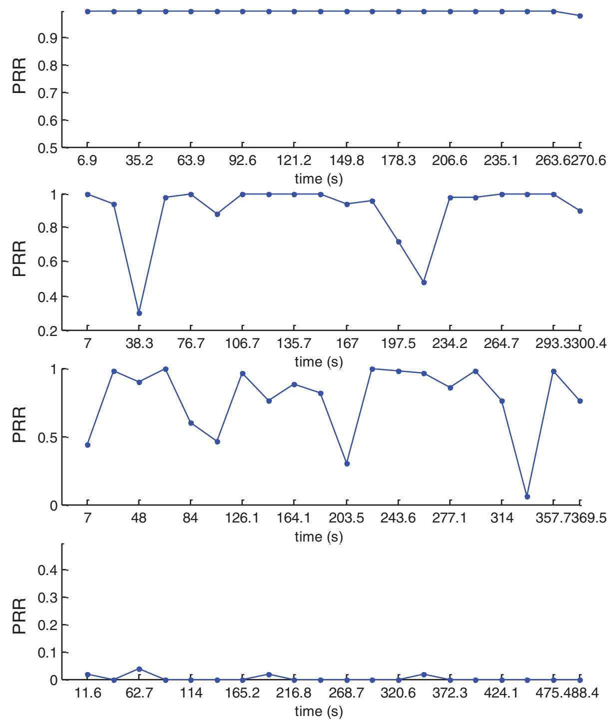


Fig. 5. Links with very low or very high average PRRs are more stable than links with moderate average PRRs. Outdoor environment, using TelosB sensor motes and −25 dBm as output power (using RadiaLE testbed [Baccour et al. 2011]).

Multipath effects can be either *constructive*, that is, strengthen the direct signal leading to a good-quality link, or *destructive*, that is, interfere with the direct signal [Cerpa et al. 2003], and thus be detrimental to link quality. Being constructive or destructive does not depend on the receiver distance or direction. It rather depends on the nature of the physical path between the sender and the receiver (e.g., presence of obstructions) [Rappapport 2001; Goldsmith 2005].

3.2. Temporal Characteristics

We showed that link quality varies drastically over space. This section explores link quality variation over time.

Observation 1. Links with very low or very high average PRRs are more stable than links with moderate average PRRs. Several studies [Cerpa et al. 2003, 2005; Zhao and Govindan 2003] claimed that links with very low or very high average PRR, which are mainly located in the connected and disconnected regions respectively, have small variability over time and tend to be stable. In contrast, links with intermediate values of average PRR, which are mainly located in the transitional region, show a very high variability over time, as PRRs vary drastically from 0% to 100% with an average ranging from 20% to 80% [Cerpa et al. 2003]. These intermediate links are hence typically unstable. This observation is illustrated in Figure 5. The temporal variation of these links can be mitigated by applying an adaptive power control scheme, where transmission power at each node is dynamically adjusted [Liu et al. 2010].

Observation 2. Over short time spans, links may experience high temporal correlation in packet reception, which leads to short periods of 0% PRR or 100% PRR. Srinivasan et al. [2010a] examined the distribution of PRRs over all links in the testbed, for different Inter-Packet-Intervals (IPIs). They found that by increasing the IPI, the number of intermediate links increases as well. This finding was justified by the fact that low IPIs correspond to a short-term assessment of the link. In such short-term assessment, most links experience high temporal correlation in packets reception. That means that over these links, packets are either all received or not. Consequently, the measured PRR over most links is either 100% or 0%. For instance, Srinivasan et al. [2010a] found that for a low IPI equal to 10 milliseconds (PRRs are measured every 2 seconds) 95% of links have either perfect quality (100% PRR) or poor quality (0% PRR), that is, only 5% of links have intermediate quality. High IPIs corresponds to a long-term assessment of the link. The increase of the IPI leads to the decrease in the temporal correlation in packets reception. That means that links may experience *bursts* (a shift between 0% and 100% PRR) over short periods and the resulting PRR assessed in the long-term period is intermediate. This last observation was also made by Cerpa et al. [2005b].

Recently, several metrics were introduced for the measurement of link burstiness. Munir et al. [2010] define a burst as a period of continuous packet loss. They introduced *Bmax*, a metric that computes the maximum burst length for a link, that is, the maximum number of consecutive transmission failures. *Bmax* is computed using an algorithm that takes as input: (i) the data trace of packet successes and failures for each link, and (ii) *B'min*, which is the minimum number of consecutive successful transmissions between two consecutive failure bursts. The authors assume a predeployment phase for the determination of *Bmax* with respect to each link in the network. However, computed *Bmax* values may change during the network operation due to environmental changes. Brown et al. [2011] resolved this problem by introducing BurstProbe, a mechanism for assessing link burstiness through the computation of *Bmax* and *B'min* during the network operation. The β factor is another metric for assessing link burstiness [Srinivasan et al. 2008]. It is used to identify bursty links with long bursts of successes or failures. The β factor is computed using Conditional Probability Distribution Functions (CPDFs), which determine the probability that the next packet will be received after n consecutive successes or failures. It requires a large data trace and thus might be inappropriate for online link burstiness assessment.

Observation 3. The temporal variation of link quality is due to changes in the environment characteristics. Several studies confirmed that the temporal variation of link quality is due to changes in the environment characteristics, such as climate conditions (e.g., temperature, humidity), human presence, interference, and obstacles [Cerpa et al. 2005b; Zhao and Govindan 2003; Reijers et al. 2004; Lin et al. 2006; Tang et al. 2007; Lin et al. 2009]. Particularly, Tang et al. [2007] found that the temporal variation of LQI, RSSI, and Packet Error Rate (PER), in a "clean" environment, (i.e., indoor, with no moving obstacles and well air-conditioned) is not significant. The same observation was made by Mottola et al. [2010]. Lin et al. [2009] distinguished three patterns for link quality temporal variation: small fluctuations, large fluctuations/disturbance, and continuous large fluctuations. The first is mainly caused by multipath fading of wireless signals; the second is caused by the shadowing effect of humans, doors, and other objects; and the last is caused by interference (e.g., Wi-Fi). A deeper analysis of the causes of links' temporal variation was presented by Lal et al. [2003], Lee et al. [2007], and Srinivasan et al. [2008]. Lal et al. [2003] reported that the transitional region can be identified by the PRR/SNR curve using two thresholds (refer to Figure 6). Above the first threshold the PRR is consistently high, about 100%, and below the second threshold the PRR is often less than 25%. In between is the transitional region,

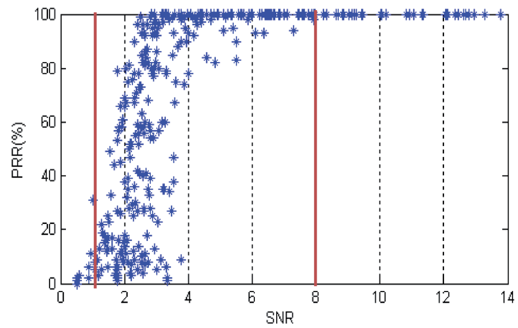


Fig. 6. The PRR/SNR curve. For *SNR* greater than 8 dBm, the *PRR* is equal to 100%, and for *SNR* less than 1 dBm, the *PRR* is less than 25%. In between, a small variation in the *SNR* can cause a big difference in the *PRR*; links are typically in the transitional region. Outdoor environment, using TelosB sensor motes and −25 dBm as output power (using the RadiaLE testbed [Baccour et al. 2011]).

where a small variation in the SNR can cause a shift between good and bad quality link, which results in a bursty link. In fact, SNR is the ratio of the pure received signal strength to the noise floor. When no interference is present, the noise floor varies with temperature, and so is typically quite stable over time periods of seconds or even minutes [Srinivasan et al. 2010a]. Therefore, what makes the SNR vary according to time, leading to link burstiness, is mainly the received signal strength variation [Srinivasan et al. 2008]. The variation of the received signal strength may also be due to the constructive/destructive interference in the deployment environment [Mottola et al. 2010].

3.3. Link Asymmetry

Link asymmetry is an important characteristic of radio links as it has a great impact on the performance of higher-layer protocols. Several studies analyzed the asymmetry of low-power links [Srinivasan et al. 2010a; Zhao and Govindan 2003; Reijers et al. 2004; Cerpa et al. 2003, 2005a; Ganesan et al. 2002; Tang et al. 2007; Zuniga and Krishnamachari 2007]. Link asymmetry is often assessed as the difference in connectivity between the uplink and the downlink. A wireless link is considered as asymmetric when this difference is larger than a certain threshold, for example, when the difference between the uplink PRR and the downlink PRR is greater than 40% [Srinivasan et al. 2010a; Cerpa et al. 2003].

Observation 1. Asymmetric links are mainly located at the transitional region. It was shown that links with very high or very low average PRRs, which are mainly those of the connected and disconnected regions, respectively, tend to be symmetric. On the other hand, links with moderate PRRs, those of the transitional regions, tend to be asymmetric [Cerpa et al. 2003, 2005a].

Observation 2. Link asymmetry is not correlated with distance. The spatial variation of link asymmetry was the subject of several studies [Reijers et al. 2004; Cerpa et al. 2003, 2005a; Ganesan et al. 2002]. Ganesan et al. [2002] found that the percentage of asymmetric links is negligible at short distances from the transmitter and increases significantly with higher distances. This observation confirms the one made by [Cerpa et al. 2003, 2005a] stating that asymmetric links are mainly those in the transitional region. On the other hand, Cerpa et al. [2003, 2005a] found that the percentage of asymmetric links increases as well as decreases as the distance from the transmitter increases. Thus, they argued that link asymmetry is not correlated with distance.

Observation 3. Link asymmetry may or may not be persistent. Srinivasan et al. [2010a] studied the temporal variation of link asymmetry. They found that very few links (2 of the 16 observed asymmetric links in the testbed) were long-term asymmetric links (i.e., consistently asymmetric) while many links were transiently asymmetric. On the other hand, Mottola et al. [2010] found that when links are stable, which is the case in their experiments, link asymmetry also tends to persist. Consequently, link asymmetry might be transient only for unstable links (i.e., their quality varies with time), and ultimately depends on the target environment.

Observation 4. Hardware asymmetry and radio irregularity constitute the major causes of link asymmetry. Most studies stated that one of the causes of link asymmetry is hardware asymmetry, that is, the discrepancy in terms of hardware calibration; namely nodes neither have the same effective transmission power nor the same noise floor (receiver sensitivity) [Zhao and Govindan 2003; Cerpa et al. 2003; Lymberopoulos et al. 2006; Zuniga and Krishnamachari 2007]. Ganesan et al. [2002] claimed that at large distances from the transmitter, small differences between nodes in hardware calibration may become significant, resulting in asymmetry. The radio irregularity caused by the fact that each antenna has its own radiation pattern that is not uniform is another major cause of link asymmetry [Zhou et al. 2006a; Lymberopoulos et al. 2006].

3.4. Interference

Interference is a phenomena inherent to wireless transmissions, for example, because the medium is shared among multiple transmitting nodes. In the following, we provide a bird's eye view on the current state-of-the-art related to interference in low-power wireless networks. Our goal is not to be exhaustive, but rather to present the essential information to complement the rest of the material in this survey, giving the reader a foundation to understand how interference may affect link quality estimation.

Interference can be either *external* or *internal*. External interference may occur from colocated/coexisting networks that operate in the same frequency band as the WSN; internal interference may occur from concurrent transmission of nodes belonging to the same WSN. In the following, we survey relevant work on both external and internal interference, and conclude this section with a brief account of works dealing with experimenting and counteracting interference.

3.4.1. External Interference. WSNs operate on unlicensed ISM bands. Therefore they share the radio spectrum with several other devices. For example, in the 2.4 GHz frequency, WSNs might compete with the communications of Wi-Fi and Bluetooth devices. Furthermore, a set of domestic appliances such as cordless phones and microwave ovens generates electromagnetic noise which can significantly harm the quality of packet receptions [Sikora and Groza 2005; Petrova et al. 2007; Yang et al. 2010]. External interference has a strong impact on the performance of WSN communications because it increases packet loss rate, which in turn increases the number of retransmissions and therefore the latency of communications.

Observation 1. The colocation of 802.15.4 and 802.11b networks affects transmission in both networks due to interference (unless the 802.15.4 network uses channel 26), but the transmission in 802.11b networks is less affected. Srinivasan et al. [2010a] observed that 802.11b transmissions: (i) can prevent clear channel assessment at 802.15.4 nodes, which increases latencies and (ii) represent high-power external noise sources for 802.15.4, which can lead to packet losses. They also observed that 802.11b nodes do not suspend transmission in the presence of 802.15.4 transmission, since 802.11b transmission power is 100 times larger than that of 802.15.4. However, this

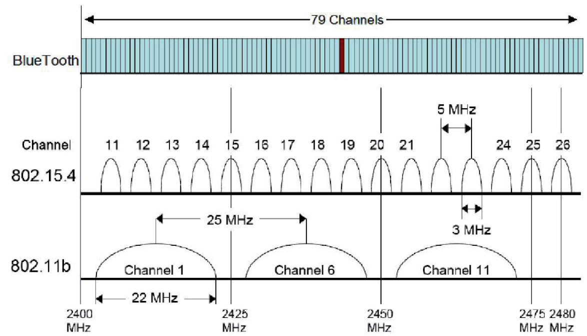


Fig. 7. IEEE 802.15.1 (Bluetooth), IEEE 802.11b, and IEEE 802.15.4 spectrum usage [Srinivasan et al. 2010a].

observation was refuted by Liang et al. [2010]. Indeed, they reported that when the 802.15.4 transmitter is close to the 802.11b transmitter, the 802.11b node may suspend its transmission due to elevated channel energy. Furthermore, when this happens, IEEE 802.11b only corrupts the IEEE 802.15.4 packet header, that is, the remainder of the packet is unaffected. The impact of interference generated by Wi-Fi devices strongly depends also on the traffic pattern. Boano et al. [2011] presented experimental results using different Wi-Fi patterns and compared the different PRRs under interference. Srinivasan et al. [2010a] noticed that only 802.15.4 channel 26 is largely immune to 802.11b interference, as it does not overlap with 802.11b channels (refer to Figure 7).

Observation 2. The colocation of IEEE 802.15.4 and 802.15.1 (Bluetooth) networks affects mostly the transmissions in the IEEE 802.15.4 network. Bluetooth is based on Frequency Hopping Spread Spectrum (FHSS) technology. This technology consists in hopping to a new frequency after transmitting or receiving a packet, using a pseudorandom sequence of frequencies known to both transmitter and receiver. Thanks to this technology, Bluetooth is highly resistant to interference. Consequently, when 802.15.4 and Bluetooth networks coexist, packet losses at Bluetooth devices are not that important as compared to those observed with 802.15.4. The results by Boano et al. [2011] show that interference from Bluetooth devices has a much lower impact than the one from Wi-Fi devices or microwave ovens on WSN communications.

Observation 3. The colocation of IEEE 802.15.4 networks and domestic appliances can significantly affect the transmission in the IEEE 802.15.4 networks. Using a spectrum analyzer, Zhou et al. [2006b] showed the impact of interference generated by a microwave oven, which can cover almost half of the 2.4 GHz available spectrum. Their results were confirmed by Boano et al. [2011], who measured the periodic pattern of microwave oven interference through fast RSSI sampling using off-the-shelf sensor motes. The authors highlighted the periodicity of the generated interference and quantified its impact on the PRR of WSN communications.

Observation 4. External interference often spreads along several (adjacent) channels [Sikora and Groza 2005; Petrova et al. 2007]. Due to the characteristics of external wideband interferers such as Wi-Fi devices, interference often spreads throughout spatially nearby channels (refer to Figure 7). Another example of the latter are microwave ovens, that spread noise over almost half of the 2.4 GHz available spectrum, as explained earlier.

3.4.2. Internal Interference. Like external interference, internal interference can have a strong impact on the performance of WSN communications.

Observation 1. In the presence of concurrent transmission, the three reception regions can still be identified by the Signal-to-Interference-plus-Noise-Ratio (SINR). Most studies on low-power link characterization, including those stated previously, were performed using collisions-free scenarios to observe the pure behavior of the channel. Son et al. [2006] addressed low-power link characterization under concurrent transmissions. They reported that concurrent transmission leads to interference, which has a great impact on link quality. Based on Signal-to-Interference-plus-Noise-Ratio (SINR) measurements, conducted with Mica 2 motes equipped with CC1000 radios, the authors found the following key observations: First, when the SINR exceeds a critical threshold, the link is of high quality,[1] that is, the PRR is greater than 90%, and it belongs to the connected region. Below this threshold, transmission on that link can be successful despite the existence of concurrent transmission, but the resulting PRR is inferior to 90% (transitional and disconnected regions). Second, Son et al. [2006] claimed that the identified SINR threshold can vary significantly between different hardware. In fact, this threshold depends on the transmitter hardware and its transmission power level, but it does not depend on its location.

Observation 2. Concurrent transmissions have a great impact on the link delivery ratio even when nodes are not visible to each other. Mottola et al. [2010] conducted experiments in real road tunnels, with controlled concurrent transmissions. They set up a specific scenario where two nodes communicate and a third node, which is not visible to the first two (i.e., "far from" the two nodes and the PRR to each of them is equal to zero), concurrently transmits its data. They found that the third node was able to create significant noise for the communicating nodes so that the delivery ratio over that link (assessed by the PRR) was very low, even lower than expected.

Observation 3. Internal interference from adjacent channels has a significant influence on the packet delivery rate. Several work showed that cross-channel interference can cause a significant increase in the packet loss ratio [Incel et al. 2006; Toscano and Bello 2008; Wu et al. 2008; Xing et al. 2009]. Wu et al. [2008] showed on MicaZ motes that with adjacent channel interference, the PRR decreases 40% compared to when no interference is present on the adjacent channel. The authors also showed that when interference is generated two channels away, the impact on the PRR is minimal. Xing et al. [2009] proposed an algorithm that reduces the overhead of multichannel interference measurements by exploiting the spectral power density of the transmitter.

3.4.3. Experimenting with Interference. Studying and comparing the performance of protocols under interference is difficult due to the intrinsic nature of radio propagation. Testing and debugging protocols using heterogeneous devices generating interference can be indeed a costly, inflexible, and labor-intensive operation. Several researchers studied the performance of protocols under interference by manually switching on wireless devices and analyzing the communications between wireless sensor nodes [Petrova et al. 2007; Musaloiu-E. and Terzis 2007], or evaluated their protocols by deploying nodes in proximity of Wi-Fi access points [Iyer et al. 2011; Tang et al. 2011], which are approaches that do not permit high levels of repeatability. Boano et al. [2011] developed JamLab, a facility for testing protocols under interference in existing testbeds. They use off-the-shelf sensor motes to record and playback interference patterns as well as to generate customizable and repeatable interference in real time. This

[1]This is interpreted by the fact that the strength of the received signal is much higher than those of the noise level and the received signal from the interfering node.

tool can be used to analyze the performance of existing MAC protocols under interference and derive several techniques to improve their efficiency under heavy interference [Boano et al. 2010b].

3.4.4. Counteracting Interference. The research community has come up with several techniques to mitigate the impact of interference. While Bluetooth interference, due to its FHSS mechanisms, cannot be predicted or actively avoided, several work proposed solutions to mitigate IEEE 802.11 and microwave oven interference. Chowdhury and Akyildiz [2009] proposed a mechanism to adapt WSN transmissions to exploit the periodicity of microwave ovens and mitigate the impact of their interference. By increasing preamble length, using multiheaders, and using forward error correction techniques, Liang et al. [2010] increased the level of protection of packets challenging Wi-Fi interference. Furthermore, other techniques were proposed to improve coexistence with colocated Wi-Fi networks. Huang et al. [2010] characterize the white spaces in Wi-Fi traffic, and exploit their model and analysis to significantly improve the protocol performance when operating under heavy Wi-Fi interference (in answer to Observation 1, Section 3.4.1). To avoid wide-band interference, Sha et al. [2011] showed how in multichannel protocols it is preferable to hop several channels away from the interfered one. Several studies evaluated the impact of interference on the performance of MAC protocols [Boano et al. 2010b; Dutta et al. 2010]. Boano et al. [2010b] suggested the use of multiple hand-shaking attempts coupled with packet trains and suitable congestion backoff schemes to better tolerate interference. Noda et al. [2011] presented a channel quality metric that quantifies spectrum usage and can be used by protocols to avoid interfered channels. The authors showed how the metric has a strong correlation with the PRR.

4. FUNDAMENTALS OF LINK QUALITY ESTIMATION

Empirical observations on low-power links raised the need for link quality estimation as a fundamental building block for higher-layer protocols. In fact, link quality estimation enables these protocols to mitigate and to overcome low-power link unreliability. For instance, sophisticated routing protocols rely on link quality estimation to improve their efficiency by avoiding bad quality links. Also topology control mechanisms rely on link quality estimation to establish stable topologies that resist to link quality fluctuations.

In this section, we present an overview of different aspects of link quality estimation. First, we define the link quality estimation process and decompose it into different steps. Then, we present requirements for the design of efficient link quality estimators.

4.1. Steps for Link Quality Estimation

Basically, link quality estimation consists in evaluating a *metric*, that is, a mathematical expression, within an estimation window w (e.g., at each w seconds, or based on w received/sent packets). We refer to this metric as Link Quality Estimator (LQE). The LQE evaluation requires *link measurements*. For example, to evaluate the PRR estimator, link measurements consist in extracting the sequence number from each received packet. *Link monitoring* defines a strategy to have traffic over the link allowing for link measurements. Hence, the link quality estimation process involves three steps: link monitoring, link measurements, and metric evaluation. These steps are described next and illustrated in Figure 8.

4.1.1. Link Monitoring. There are three kinds of link monitoring: (i) active link monitoring, (ii) passive link monitoring, and (iii) hybrid link monitoring. Note that not only does link quality estimation rely on link monitoring, but also on other mechanisms, such as routing and topology control [Gnawali et al. 2009].

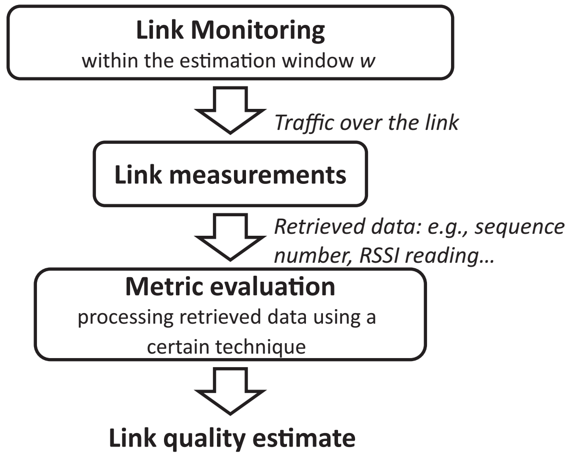


Fig. 8. Steps for link quality estimation.

Active link monitoring. In active link monitoring, a node monitors the links to its neighbors by sending probe packets. Probe packets can be sent either by broadcast [Couto et al. 2003], or by unicast [Kim and Shin 2006]. Broadcast probe packets involve no link-level acknowledgments or retransmissions, in contrast to unicast probe packets. Probe packets are generally sent at a certain rate, which yields a trade-off between energy efficiency (low rates) and accuracy (high rates). An adaptive beaconing rate [Gnawali et al. 2009] might provide a good balance for this trade-off.

Broadcast-based active link monitoring is simple to implement and incurs a small overhead compared to unicast-based [Kim and Shin 2006]. For that reason, many network protocols and mechanisms rely on it. On the other hand, unicast based active link monitoring allows for more accurate link measurements because of its resemblance to actual data transmission over the link [Zhang et al. 2010]. However, it is still considered as a costly mechanism for WSN due to the communication overhead.

Passive link monitoring. Unlike active link monitoring, passive link monitoring exploits existing traffic without incurring additional communication overhead. In fact, a node listens to transmitted packets, even if these packets are not addressed to it (overhearing) [Lal et al. 2003; Woo and Cullera 2003]. It can also listen to acknowledgments of messages sent by different neighbors [Jiang et al. 2006; Li et al. 2005].

Passive link monitoring has been widely used in WSNs due to its energy efficiency compared to active link monitoring [Cerpa et al. 2005b; Li et al. 2005; Lal et al. 2003; Xu and Lee 2006; Woo and Culler 2003a; Yunqian 2005; Wang et al. 2007]. However, passive monitoring incurs the overhead of probing idle links [Kim and Shin 2006]. Lal et al. [2003] found that overhearing involves expense of significant energy. In addition, when the network operates at low data rate or unbalanced traffic, passive link monitoring may lead to the lack of up-to-date link measurements. Consequently, it leads to inaccurate link quality estimation.

Hybrid link monitoring. The use of a hybrid mechanism combining both active and passive monitoring may yield an efficient balance between up-to-date link measurements and energy efficiency [Kim and Shin 2006]. For instance, Gnawali et al. [2009] introduced a hybrid link monitoring mechanism for performing both link quality estimation and routing advertisements. Active link monitoring consists in broadcasting beacons with a nonfixed rate. Rather, a specific algorithm is used to adaptively tune the beaconing rate: Initially, the beaconing rate is high and decreases exponentially until it reaches a certain threshold. When the routing layer signals some problems such as loop detection, the beaconing rate resets to its initial value. Active link monitoring is coupled with passive link monitoring, which consists in hearing received acknowledgments from neighbors (that represent next hops).

Finally, it was argued by several recent studies that link quality estimation where link monitoring is based on data traffic is much more accurate than that having link monitoring based on beacon traffic [Gnawali et al. 2009; Zhang et al. 2008, 2010; Puccinelli and Haenggi 2010]. The reason is that there are several differences between unicast and broadcast link properties [Zhang et al. 2008]. It is thereby difficult to precisely estimate unicast link properties via those of broadcast.

4.1.2. Link Measurements. Link measurements are performed by retrieving useful information: (i) from received packets/acknowledgements or (ii) from sent packets. Data retrieved from received packets/acknowledgments, such as sequence numbers, timestamp, RSSI, and LQI, is used to compute *receiver-side* link quality estimators. On the other hand, data retrieved from sent packets, for example, sequence numbers, timestamp, and packet retransmission count, allows for the computation of sender-side link quality estimators.

4.1.3. Metric Evaluation. Based on link measurements, a metric is evaluated to produce an estimation of the link quality. Generally, this metric is designed according to a certain estimation technique, which can be a simple average or a more sophisticated technique such as filtering, learning, regression, fuzzy logic, etc. For example, Woo et al. [2003] introduced the WMEWMA estimator, which uses the EWMA filter as the main estimation technique: based on link measurements, the PRR is computed and then smoothed to the previously computed PRR using an EWMA filter. More examples are given in Section 5 and Table III.

4.2. Requirements for Link Quality Estimation

Efficient link quality estimation has several requirements, which are described next.

Energy efficiency. As energy may be a major concern in WSNs, LQEs should involve low computation and communication overhead. Consequently, some complex estimation techniques such as learning might be not appropriate in WSNs. Moreover, LQEs should also involve low communication overhead. Typically, an active monitoring with high beaconing rate should be avoided as it is energy consuming.

Accuracy. It refers to the ability of the LQE to correctly characterize the link state, that is, to capture the real behavior of the link. The accuracy of link quality estimation greatly impacts the effectiveness of network protocols. In traditional estimation theory, an estimated process is typically compared to a real known process using a certain statistical figure (e.g., least mean square error or regression analysis). However, such comparison is not possible in link quality estimation, since: (i) there is no metric that is widely considered as the "real" figure to measure link quality; and (ii) link quality is represented by quantities of different nature: some estimators are based on the computation of packet reception ratio, some are based on packet retransmission count, and some are hybrid of these, as described in Section 6. Nevertheless, the accuracy of LQEs can be assessed indirectly, that is, resorting to a metric that subsumes the effect of link quality estimation. For instance, Fonseca et al. [2007] studied the impact of their four-bit LQE on the performance of CTP (Collection Tree Protocol), a hierarchical routing protocol [Gnawali et al. 2009]. They found that four-bit leads to better end-to-end packet delivery ratio, compared with the original version of CTP. Hence, four-bit might be more accurate as it can correctly select routes composed of high quality links. On the other hand, Baccour et al. [2011] analyzed the accuracy (referred as reliability) of LQEs by analyzing their statistical properties, namely their temporal behavior and the distribution of link quality estimates.

Reactivity. It refers to the ability to quickly react to persistent changes in link quality [Kim and Noble 2001]. For example, a reactive LQE enables routing protocols and topology control mechanisms to quickly adapt to changes in the underlying connectivity. Reactivity depends on two factors: the estimation window w and the link monitoring scheme. Low w and active monitoring with high beaconing rate can lead to reactive LQE, though it is important to note that some LQEs are naturally more reactive than others regardless of the w value or the link monitoring schema. In fact, LQEs that are computed at the sender-side were shown to be more reactive than those computed at the receiver-side [Baccour et al. 2011]. More details are given in Section 6.

Stability. It refers to the ability to tolerate transient (short-term) variations in link quality. For instance, routing protocols do not have to recompute information when a link quality shows transient degradation, because rerouting is a very energy- and time-consuming operation. Lin et al. [2009] argued that stability is met through long-term link quality estimation. Long-term link quality estimation was performed by the means of the EWMA filter with a large smoothing factor ($\alpha = 0.9$). Hence, they introduced the *Competence* metric that applies the EWMA filter to a binary function indicating whether the current measured link quality is within a desired range. Stability of LQEs can be assessed by the coefficient of variation of link quality estimates, which is computed as the ratio of the standard deviation to the mean [Woo and Cullera 2003]. It can also be assessed by studying the impact of the LQE on routing; typically a stable LQE leads to stable topology, for example, few parent changes in the case of hierarchical routing [Baccour et al. 2009].

As a matter of fact, reactivity and stability are at odds. For instance, consider using PRR as LQE, if we compute the PRR frequently (small w), we obtain a reactive LQE as it captures link dynamics at a fine grain. However, this reliability will be at the cost of stability because the PRR will consider some transient link quality fluctuation that might be ignored. Thus, a good LQE is the one that provides a good trade-off between reactivity and stability. Lin et al. [2009] suggest combining their long-term metric Competence, considered as a stable but not reactive LQE, with a short-term metric such as ETX, considered as a reactive but unstable LQE, to obtain a good trade-off. They introduced routing schemes based on this principle. For example, in a tree-based routing scheme, a node selects a potential parent as the neighbor having the best Competent link, among all neighbors having low route cost, where route cost is computed based on ETX. The authors argued that such a routing scheme selects links that are good in both the short and the long term, and leads to stable network performance. On the other hand, Woo et al. [2003] argued that using an EWMA filter with convenient smoothing factor would strike a balance between reactivity and stability.

Several efforts were carried out for the design of efficient LQEs. In the next section, we survey, classify, and discuss the most relevant LQEs that are suitable for WSNs.

5. A SURVEY ON LINK QUALITY ESTIMATORS

LQEs in WSNs can be classified in two categories: hardware based and software based, as illustrated in Figure 9. Table III presents a comparison of LQEs in WSNs.

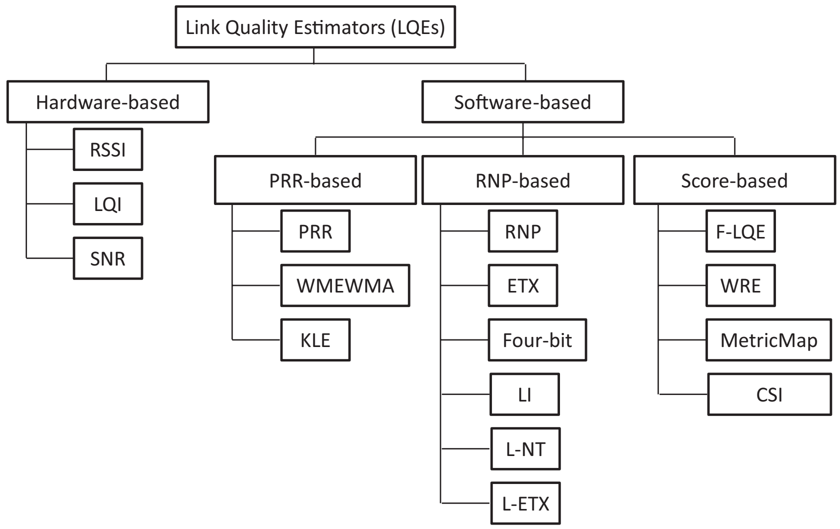
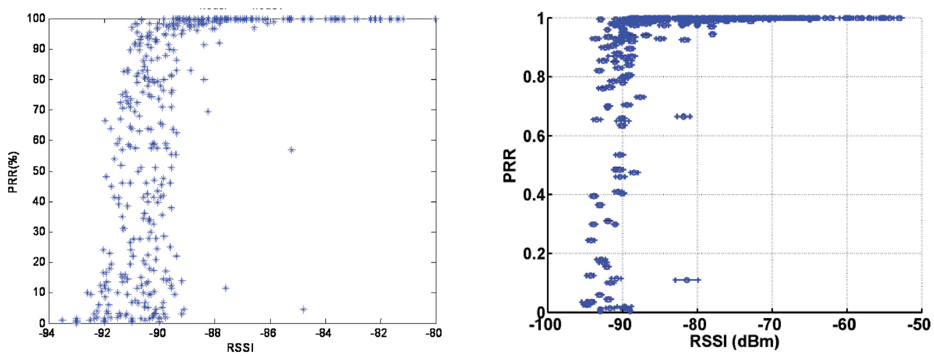


Fig. 9. Taxonomy of LQEs.

Table III. Comparison and Classification of LQEs

			Technique	Asymmetry support	Monitoring	Location
Hardware-based	RSSI, LQI, and SNR		Read from hardware and may average	No	Passive or Active	Receiver
Software-based	PRR-based	*PRR*	Average	No	Passive or Active	Receiver
		WMEWMA [Woo and Culler 2003a]	Filtering	No	Passive	Receiver
		KLE [Senel et al. 2007]	Filtering	No	-	Receiver
	RNP-based	*RNP* [Cerpa et al. 2005b]	Average	No	Passive	Sender
		LI [Lal et al. 2003]	Probability	No	Passive	Receiver
		ETX [Couto et al. 2003]	Average	Yes	Active	Receiver
		Four-bit [Fonseca et al. 2007]	Filtering	Yes	Active and Passive	Sender and receiver
		L-NT and L-ETX [Zhang et al. 2010]	Filtering	No	-	Sender
	Score-based	WRE [Xu and Lee 2006]	Regression	No	Passive	Receiver
		MetricMap [Wang et al. 2007]	Training and classification	No	Passive	Receiver
		F-LQE [Baccour et al. 2009]	Fuzzy logic	Yes	Passive	Receiver
		CSI [Puccinelli and Haenggi 2008]	Weighted sum	No	Active	Receiver



(a) Outdoor environment, using TelosB sensor motes (using the RadiaLE testbed [Baccour et al. 2011]).

(b) Indoor environment, using MicaZ sensor motes [Srinivasan et al. 2006].

Fig. 10. PRR vs RSSI curve.

5.1. Hardware-Based LQEs

Three LQEs belong to the family of hardware-based LQEs: LQI, RSSI, and SNR. These estimators are directly read from the radio transceiver[2] (e.g., the CC2420). Their advantage is that they do not require any additional computation. However, their adequacy in characterizing links was the subject of several research works. We summarized the literature related to this issue in the following observations.

Observation 1. RSSI can provide a quick and accurate estimate of whether a link is of very good quality (connected region). This observation was justified by the following: First, empirical studies such as Srinivasan et al. [2006a] proved the existence of a RSSI value (−87 dBm [Srinivasan et al. 2006a]) above which the PRR is consistently high (99% [Srinivasan et al. 2006a]), that is, belonging to the connected region. Below this threshold, a shift in the RSSI as small as 2 dBm can change a good link to a bad one and vice versa, which means that the link is in the transitional or disconnected region [Srinivasan et al. 2010a]. This observation is illustrated in Figure 10(b) and Figure 10(a). Second, RSSI was shown very stable (standard deviation less than 1 dBm) over a short time span (2 s), thereby a single RSSI reading (over a packet reception) is sufficient to determine if the link is in the transitional region or not [Srinivasan et al. 2010a].

Observation 2. LQI can determine whether the link is of very good quality or not. However, it is not a good indicator of intermediate quality links due to its high variance, unless it is averaged over a certain number of readings. Srinivasan et al. [2010a] argued that when the LQI is very high (near 110) the link is of perfect quality (near 100% of PRR). Further, in this situation LQI has low variance so that a single LQI reading would be sufficient to decide if the link is of perfect quality or not. On the other hand, for other LQI values, corresponding to intermediate quality links, the variance of LQI becomes significant and a single LQI reading is not sufficient for accurate link quality estimation. Srinivasan and Levis [2006b] showed that LQI should be averaged over a large packet window (about 40 up to 120 packets) to provide accurate link quality estimation, but this will be at the cost of agility and responsiveness to link quality

[2]Some radio transceivers do not provide LQI.

changes. The LQI high variance is due to the fact that LQI is a statistical value [Srinivasan et al. 2006a].

Bringing Observations 1 and 2 together, it might be reasonable to use a single RSSI or LQI reading to decide if the link is of high quality or not. Such a decision is based on RSSI and LQI thresholds, beyond which a link can maintain high quality, for example, a PRR of at least 95% [Lin et al. 2006]. Importantly, these thresholds depend on the environment characteristics. For example, Lin et al. [2006] found that RSSI threshold is around −90 dBm on a grass field, −91 dBm on a parking lot, and −89 dBm in a corridor. For LQI and RSSI values below these thresholds, neither of these metrics can be used to differentiate links clearly. Nevertheless, an average LQI, with the convenient averaging window, allows a more accurate classification of intermediate links [Srinivasan and Levis 2006b]. On the other hand, Mottola et al. [2010] claimed that RSSI should not be used to classify intermediate links.

Observation 3. The variance of LQI can be exploited for link quality estimation. Empirical studies [Srinivasan and Levis 2006b] pointed out that links of intermediate and bad quality have high LQI variance, therefore the LQI needs to be averaged over many samples to give meaningful results. Boano et al. [2009] proposed the use of the variance of LQI to distinguish between good links, having very low LQI variance and bad links, having very high LQI variance using as few as 10 samples. However, in that work, the authors did not provide a mapping function or a mathematical expression that exploit the variance of LQI to provide a link quality estimate.

Observation 4. LQI is a better indicator of the PRR than RSSI. Srinivasan and Levis [2006b], Tang et al. [2007], and Polastre et al. [2005] argued that average LQI shows stronger correlation with PRR, compared to average RSSI. Hence, LQI is a better indicator of PRR than RSSI. On the other hand, Srinivasan and Levis [2006b] and Tang et al. [2007] claimed that RSSI has the advantage of being more stable than LQI (i.e., it shows lower variance), except for multipath affected links. In fact, which of LQI and RSSI is better for link quality estimation is an unanswered question, reflected by several contradicting statements and results.

Observation 5. SNR is a good indicator and even predictor of the PRR but it is not accurate, especially for intermediate links. Theoretically, for a given modulation schema, the SNR leads to an expected bit error rate, which can be extrapolated to packet error rate and then to the PRR [Zuniga and Krishnamachari 2007]. Hence, an analytical expression that gives the PRR as a function of SNR can be derived [Zuniga and Krishnamachari 2007]. Srinivasan et al. [2010a] justified the observed link characteristics (e.g., link temporal variation and link asymmetry) with SNR behavior. Particularly, they assume that changes in PRR must be due to changes in SNR. However, other studies [Yunqian 2005; Senel et al. 2007; Aguayo et al. 2004] showed that the theoretical relationship between SNR and PRR reveals many difficulties. These difficulties arise from the fact that mapping between SNR and PRR depends on the actual sensor hardware and environmental effects such as temperature [Senel et al. 2007]. As a result, these studies concluded that SNR cannot be used as a standalone estimator, but it may help to enhance the accuracy of the PRR estimation. Further, Lal et al. [2003] recommended not to use SNR as link quality estimator, when links are inside the transitional region.

Observation 6. SNR is a better link quality estimator than RSSI. The RSSI is the sum of the pure received signal and the noise floor at the receiver. On the other hand, the SNR describes how strong the pure received signal is in comparison with the receiver noise floor. As the noise floor at different nodes can be different, the SNR metric should be better than RSSI [Srinivasan et al. 2010a].

Hardware-based LQEs share some limitations: first, these metrics are only measured for successfully received packets; thus, when a radio link suffers from excessive packet losses, they may overestimate the link quality by not considering the information of lost packets. Second, despite the fact that hardware metrics provide a fast and inexpensive way to classify links as either good or bad, they are incapable of providing a fine-grain estimation of link quality [Fonseca et al. 2007; Gomez et al. 2010].

The aforesaid limitations of hardware-based LQEs do not mean that this category of LQEs is not useful. In fact, each of these LQEs provides a particular information on the link state, but none of them is able to provide a holistic characterization of the link quality. Currently, there is a growing awareness that the combination of hardware metrics with software metrics can improve the accuracy of the link quality estimation [Baccour et al. 2010; Fonseca et al. 2007; Gomez et al. 2010; Rondinone et al. 2008; Boano et al. 2010c]. For example, Fonseca et al. [2007] use LQI as a hardware metric to quickly decide whether the link is of good quality. If it is the case, the node is included in the *neighbor table* together with the link quality, assessed using four-bit as a software metric. Gomez et al. [2010] confirm that LQI can accurately identify high-quality links, but it fails to accurately classify intermediate links due to its high variance. They exploited this observation to design LETX (LQI-based ETX), a link estimator that is dedicated for routing. The authors first build a piecewise linear model of the PRR as a function of average LQI. This model allows to estimate the PRR given one LQI sample. LETX is then computed as the inverse of the estimated PRR. LETX is used to identify high-quality links in the route selection process. Rondinone et al. [2008] also suggest combining hardware and software metrics though a multiplicative metric between PRR and RSSI, and Boano et al. [2010c] propose a fast estimator suitable for mobile environments by geometrically combining PRR, SNR, and LQI.

5.2. Software-Based LQEs

Software-based LQEs can be classified into three categories, as illustrated in Figure 9: (i) PRR based: either count or approximate the PRR, (ii) RNP based: either count or approximate the RNP (Required Number of Packet retransmissions), and (iii) Score based: provide a score identifying the link quality. Table III summarizes the main characteristics of these LQEs.

5.2.1. PRR Based. PRR is a receiver-side estimator that is simple to measure and was widely used in routing protocols [Jiang et al. 2006; Couto et al. 2003]. Further, it was often used as an unbiased metric to evaluate the accuracy of hardware-based estimators. In fact, a hardware-based estimator that correlates with PRR is considered as a good metric.

Discussion. The efficiency of PRR depends on the adjustment of the time window size. Cerpa et al. [2005a] showed that for links with very high or very low PRRs, accurate link quality estimation can be achieved within narrow time windows. On the other hand, links with medium PRRs need much larger time windows to converge to an accurate link quality estimation.

The objective of LQEs that *approximate* the PRR is to provide more efficient link quality estimates than the PRR. In the following, we review the most relevant LQEs in this category.

The Window Mean with Exponentially Weighted Moving Average (WMEWMA) [Woo and Culler 2003a] is a receiver-side LQE based on passive monitoring. It smoothes PRR estimates using the EWMA filter, which provides more stable but sufficiently agile estimation compared to PRR.

Discussion. To assess the performance of WMEWMA, Woo and Cullera [2003] introduced a set of LQEs that approximate the PRR using filtering techniques other than EWMA. Then, they compared WMEWMA to these filter-based LQEs, in terms of: (i) reactivity assessed by the settling time and the crossing time, (ii) accuracy evaluated by the mean square error, (iii) stability assessed by the coefficient of variation, and (iv) efficiency assessed by the memory footprint and computation complexity. WMEWMA was found to outperform the other filter-based LQEs. The work by Woo and Cullera [2003] laid the foundation for subsequent work on filter-based LQE, although their solution required a more thorough assessment, for example, based on real-world data traces instead of synthetic ones (i.e., generated analytically).

The Kalman-filter-based link quality estimator (KLE) [Senel et al. 2007] was proposed to overcome the poor reactivity of average-based LQEs, including PRR. In fact, the objective of KLE is to provide a link quality estimate based on a single received packet rather than waiting for the reception of a certain number of packets within the estimation window and then compute the average. Upon packet reception, RSS (Received Signal Strength) is extracted and injected to a Kalman filter, which produces an estimation of the RSS. Then, an approximation of the SNR is gathered by subtracting the noise floor estimate from the estimated RSS. Using a precalibrated PRR-SNR curve at the receiver, the approximated SNR is mapped to an approximated PRR, which represents the KLE link quality estimate.

Discussion. Through experiments using a WSN platform of two nodes (a sender and a receiver), Senel et al. [2007] proved that KER is able to detect link quality changes faster (i.e., it is more reactive) than PRR. However, the accuracy of KER was not examined. This accuracy is typically related to the accuracy of the PRR-SNR curve, which was considered as constant over time. According to empirical observations on low-power links, this curve varies over time (in dynamic environments) and also from one node to another. Further, it seems that the positive results found by Senel et al. [2007] related to the reactivity of KER are due to the steady environment in the experimental evaluation, so that the PRR-SNR curve is constant over time.

5.2.2. RNP Based. *The Required Number of Packet Transmissions* (RNP) [Cerpa et al. 2005b] is a sender-side estimator that counts the average number of packet transmissions/retransmissions required before successful reception. It can be computed as the number of transmitted and retransmitted packets during an estimation window, divided by the number of successfully received packets, minus 1 (to exclude the first packet transmission). RNP assumes an ARQ (Automatic Repeat Request) protocol [Fairhurst and Wood 2002] at the link-layer level, that is, a node will repeat the transmission of a packet until it is correctly received. Note that a similar metric to the RNP is the Acknowledgment Reception Ratio (ARR). It is computed as the ratio of the number of acknowledged packets to the total number of transmitted packets during a predefined time window.

Discussion. Cerpa et al. [2005b] argued that RNP is better than PRR for characterizing the link quality. In fact, as opposed to RNP, PRR provides a coarse-grain estimation of link quality since it does not take into account the underlying distribution of losses. However, RNP has the disadvantage of being very unstable and cannot reliably estimate the link packet delivery, mainly due to link asymmetry [Baccour et al. 2009].

In the following, we review the most relevant LQEs that approximate the RNP using several techniques.

The Expected Transmission Count (ETX) [Couto et al. 2003] is a receiver-side estimator that uses active monitoring. ETX is the inverse of the product of the forward delivery ratio, d_f and the backward delivery ratio, d_b, which takes into account link asymmetry. d_b refers to the PRR (computed based on received packets), while d_f refers to the ARR (computed based on received ACKs). However, when active monitoring is based on broadcast probe packets, d_f can also refer to the PRR of the forward link as probe packets are not acknowledged.

Discussion. Couto et al. [2003] showed that routing protocols based on the ETX metric provide high-throughput routes on multihop wireless networks, since ETX minimizes the expected total number of packet transmissions required to successfully deliver a packet to the destination. Wang et al. [2007] found that ETX based on passive monitoring fails in overloaded (congested) networks. Indeed, a high traffic load (4 packets/s) leads to a congested network so that packets experience many losses. Consequently, a large number of nodes are not able to compute the ETX because they do not receive packets. Hence, routing is interrupted due to a lack of link quality information. This phenomenon leads to a degradation in the network throughput.

The Link Inefficiency (LI) proposed by Lal et al. [2003], as an approximation of the RNP, is based on passive monitoring and defined as the inverse of the Packet Success Probability (PSP). PSP is an approximated PRR. Lal et al. [2003] introduced the PSP metric instead of considering directly the PRR because they assume that accurate PRR measurement requires the reception of several packets, that is, a large estimation window. This imposes that sensor nodes operate under high duty cycles, which is undesirable for energy-constrained WSNs. PSP is derived by an analytical expression that maps the average SNR to PSP.

Discussion. It was shown [Aguayo et al. 2004; Yunqian 2005; Senel et al. 2007] even by Lal et al. [2003] that mapping from average SNR to an approximation of PRR may lead to erratic estimation. Hence, using PSP instead of PRR might be unsuitable for link quality estimation.

Four-bit is not only a metric for link quality estimation [Fonseca et al. 2007]. It is designed to be used by routing protocols and provides four bits of information, compiled from different layers: the *white bit* is from the physical layer and allows to quickly identify good quality links, based on one packet reading. The *ack bit* is from the link layer and indicates whether an acknowledgment is received for a sent packet. The *pin bit* and the *compare bit* are from the network layer and are used for the neighbor table replacement policy. Four-bit assesses link quality as an approximation of the packet retransmissions count by combining two metrics, through the EWMA filter. The first metric is RNP, computed based on the transmitted data packets and it assesses the quality of the forward link. The second metric is the inverse of WMEWMA minus 1. It is computed based on received beacons and it assesses the quality of the backward link. Four-bit is then both a sender- and received-side LQE and it takes into account link asymmetry. Further, it uses both passive (data packet traffic) and active (beacons traffic) monitoring.

Discussion. To evaluate the performance of four-bit, Fonseca et al. [2007] considered the CTP routing protocol [Gnawali et al. 2009]. In CTP, routing consists in building and maintaining a tree towards the sink node, based on link quality estimation. Then, the authors compared the original version of CTP that uses ETX as LQE, against a modified version of CTP that uses four-bit as LQE. They also involved another routing protocol called MultiHopLQI [TinyOS MultiHopLQI routing algorithm 2004], which also builds and maintains a tree toward the sink node, but LQI is used as LQE. Performance comparison was performed using three metrics: (i) cost, which accounts for the total number of transmissions in the network for each unique delivered packet,

(ii) average depth of the routing tree, and (iii) delivery rate, which is the fraction of unique messages received at the root. Fonseca et al. [2007] found that CTP based on four-bit provides better performance (e.g., packet delivery) than the original version of CTP and MultiHopLQI.

The L-NT and L-ETX are two sender-side LQEs that approximate the *RNP* [Zhang et al. 2010]. They are referred as data-driven LQEs because they are based on feedback from unicast data packets. L-NT counts the number of transmissions to successfully deliver a packet then applies the EWMA filter. On the other hand, L-ETX first computes the ratio of the number of acknowledged packets to the total number of transmitted packets based on a certain estimation window. Then, it applies the EWMA filter and inverts the result.

Discussion. Through mathematical analysis and experimental measurements, Zhang et al. [2010] demonstrated that L-ETX is more accurate in estimating ETX than L-NT. It is also more stable. However, this result does not mean that L-ETX is accurate at estimating link quality because ETX is not a reference/objective metric. The authors also showed through an experimental study that L-NT, when used as a routing metric, achieves better routing performance than L-ETX, namely a higher data delivery ratio and energy efficiency. This result might be more convincing than the first as it indeed shows that L-ETX is an accurate LQE. Such routing performances can be explained by the fact that L-ETX allows to select stable routes with high quality links.

5.2.3. Score Based. Some LQEs provide a link estimate that does not refer to a physical phenomen (like packet reception or packet retransmission); rather, they provide a score or a label that is defined within a certain range. In the following, we present an overview on four score-based LQEs: MetricMap [Wang et al. 2007], WRE [Xu and Lee 2006], F-LQE [Baccour et al. 2010] and CSI [Puccinelli and Haenggi 2008].

MetricMap is proposed by Wang et al. [2007] as an alternative LQE for MintRoute, a hierarchical routing protocol, when the original LQE ETX fails to select routes [Woo et al. 2003]. Such failure occurs when a node cannot find a route, that is, a node that cannot find a parent (an orphan node) in MintRoute. Wang et al. [2007] identified link quality estimation as a classification problem. MetricMap uses a classification algorithm to classify the link among a set of classes (e.g., “Good”, “Bad”). This algorithm has as input a feature vector, which consists of a set of metrics that impact link quality, including RSSI, channel load assessment, and node depth. This classification algorithm relies on a training phase, which is performed using a database of training samples. Each sample consists of a feature vector and a corresponding class label.

Discussion. Wang et al. [2007] showed that MetricMap combined with ETX improves the network performance in terms of packet delivery rate and fairness. This measures the variability of the delivery rate across all source nodes. However, MetricMap can be used as a back-off metric but not as a sole metric for link quality estimation. This fact is due to the use of learning algorithms, which are greedy algorithms and might be unsuitable to be executed by sensor nodes.

The *Weighted Regression Estimator* (WRE) is proposed by Xu and Lee [2006]. Xu and Lee [2006] argued that the received signal strength is correlated with distance. This observation was generalized to the fact that a node can determine the quality of the link to its neighbor giving the location of this neighbor. Hence, WRE derives a complex regression function based on an input vector that contains a set of node locations together with their link quality known in advance. This function is continuously refined and updated by the knowledge of a new input, that is, node location and the corresponding link quality. Once derived, this function returns an estimation of the link quality giving the neighbour location.

Discussion. The performance of WRE is evaluated by comparing it to WMEWMA using the same evaluation methodology as that of Woo et al. [2003], where PRR is considered as the objective metric. Xu and Lee [2006] found that WRE is more accurate than WMEWMA. However, we believe that the introduced estimator is complex and involves computation overhead and high memory storage (due to regression weights determination). Moreover, WRE assumes that link quality is correlated with distance, which is not always true, as proved by several empirical studies on low-power links [Zhao and Govindan 2003; Zuniga and Krishnamachari 2004; Cerpa et al. 2003; Reijers et al. 2004].

The Fuzzy Link Quality Estimator (F-LQE) [Baccour et al. 2010] is a receiver-side estimator. In contrast to existing LQEs, which only assess one single link property thus providing a partial view of the link, F-LQE estimates link quality on the basis of four link properties in order to provide a holistic characterization of the link, namely Smoothed Packet Reception Ratio (SPRR), link stability factor (SF), link Asymmetry Level (ASL), and channel Average-Signal-to-Noise Ratio (ASNR). These desirable properties are defined in linguistic terms (e.g., high SF, low ASL)—the natural language of fuzzy logic, and combined into a fuzzy rule to express link quality. For a particular link, the fuzzy logic interpretation of the rule gives an estimation of its quality as a membership score in the fuzzy subset of good quality links. Scores near 1/0 are synonym of good/poor quality links. Membership scores are smoothed using the EWMA filter to provide stable link quality estimates.

Discussion. To validate their estimator, Baccour et al. [2010] analyzed the statistical properties of F-LQE, independently of higher-layer protocols such as MAC collisions and routing. These statistical properties impact its performance, in terms of *reliability* and *stability*. The performance of F-LQE was compared in terms of reliability and stability with five existing LQEs: PRR, WMEWMA, ETX, RNP, and four-bit. It was found that F-LQE outperforms all these LQEs because they are only able to assess a single link property. However, F-LQE might involve higher memory footprint and computation complexity as it combines four different metrics capturing four different link properties.

The DoUble Cost Field HYbrid (DUCHY) [Puccinelli and Haenggi 2008] is a routing metric that allows to select routes with short hops and high quality links. DUCHY is based on two LQEs. The first is receiver-side and uses active monitoring (based on beacon traffic). It is called *Channel State Information* (CSI). CSI is computed by normalizing RSSI and LQI, which are gathered from received beacons and combining the two normalized values into a weighted sum. The second estimator is the RNP. This estimator is used to refine CSI measurements supposed to be inaccurate since they are based on beacon traffic.

Discussion. DUCHY was integrated in Arbutus, a hierarchical routing protocol based on link quality estimation [Puccinelli and Haenggi 2010]. Arbutus is then compared to MultiHopLQI, another hierarchical routing protocol that is based on LQI as LQE [TinyOS MultiHopLQI routing algorithm 2004]. Performance metrics include packet delivery ratio and the average number of transmissions needed for delivery. Puccinelli and Haenggi [2008] found that Arbutus outperforms MultiHopLQI and deduce that DUCHY is better than LQI. However, this deduction might be unfair as the two LQEs were compared in different contexts. It would be more reasonable, for example, to integrate LQI in Arbutus and compare DUCHY-based Arbutus to LQI-based Arbutus.

Furthermore, it is obvious that DUCHY is better than LQI because DUCHY integrates LQI and other metrics. Hence, it would be interesting to compare DUCHY to other software LQEs to demonstrate its performance.

6. PERFORMANCE OF LINK QUALITY ESTIMATORS

The performance evaluation of LQEs is a challenging problem. One of the reasons is the difficulty in providing a quantitative evaluation of the accuracy of LQEs. In fact, there is no objective link quality metric to which the link quality estimate can be compared. Furthermore, LQEs may be heterogeneous: there are LQEs that are based on PRR, others that are based on RNP, and others that provide a score. Thus, the comparison of their performance becomes challenging as it requires a holistic evaluation methodology that can be used regardless of the nature of the LQE under consideration.

Few works addressed the performance evaluation of LQEs [Cerpa et al. 2005b; Baccour et al. 2009, 2011; Zhang et al. 2010]. Two evaluation methodologies were adopted. The first methodology consists in analyzing the impact of LQEs on routing [Zhang et al. 2010; Baccour et al. 2009]. For instance, stable LQEs are those that yield less parent changes in hierarchical routing protocols. The second methodology consists in analyzing the statistical properties of LQEs [Cerpa et al. 2005b; Baccour et al. 2011]. For instance, stable LQEs are those that have low coefficient of variation.

In the following, we give key observations made by previous studies on LQE performance. Such observations are very useful for network designers to choose the most appropriate LQE. They are also useful for the design of new LQEs.

Observation 1. RNP is better than PRR and PRR overestimates link quality. Cerpa et al. [2005b] observed different links during several hours, by measuring PRR and RNP every one minute. They found that for good-quality and bad-quality links, that is, according to their definition links having high ($>90\%$) and low reception rates ($<50\%$) respectively, PRR follows the same behavior as RNP. However, for intermediate quality links, PRR *overestimates* the link quality because it does not take into account the underlying distribution of packet losses. When the link exhibits short periods during which packets are not received, the PRR can still have high value but the RNP is high so that it indicates the real link state. As a matter of fact, a packet that cannot be delivered may be retransmitted several times before aborting transmission. Baccour et al. [2011] conducted a comparative study of several LQEs through simulation and real experimentation and concluded that LQEs that are based on PRR in their computation (including WMEWMA and ETX) overestimate link quality.

Observation 2. RNP is more reactive than PRR but it can underestimate link quality. In fact, RNP is a sender-side LQE, that is, it is computed based on transmitted packets. Consequently, RNP is able to provide link quality estimates as long as there is traffic generated from the sender. On the other hand, PRR is receiver-side, that is, it is computed based on received packets. Consequently, when the link is of poor quality, packets are not delivered and PRR cannot be computed. On the other hand, RNP can be computed even if no packet is received. However, RNP can underestimate link quality in particular situations, as sometimes packets are retransmitted many times before being successfully received. This situation yields to good PRR but bad RNP. Baccour et al. [2011] generalized this observation to LQEs that are based on RNP in their computation.

Observation 3. ETX, RNP and four-bit are unstable, contrary to PRR, WMEWMA and F-LQE. Baccour et al. [2011] studied the coefficient of variation of link quality estimates, with respect to each LQE, including PRR, WMEWMA, ETX, RNP, four-bit, and F-LQE. Three observations were found: First, generally, F-LQE is the most stable

LQE. Second, WMEWMA is more stable than PRR, and four-bit is more stable than RNP. The reason is that WMEWMA and four-bit use an EWMA filter to smooth PRR and RNP respectively. Third, except ETX, receiver-side LQEs (i.e., PRR and WMEWMA) are generally more stable than sender-side LQEs (i.e., RNP and four-bit). ETX is receiver-side, yet it is shown as unstable. The reason is that when the PRR tends to 0 (very bad link) the ETX will tend to infinity, which increases the standard deviation of ETX link estimates.

Observation 4. L-ETX is more accurate and more stable than L-NT. Zhang et al. [2010] studied the impact of L-ETX and L-NT on a geographic and distance vector routing protocol called NADV. They found that L-ETX achieves a higher packet delivery rate and lower average number of transmissions per packet than L-NT. Further, routing using L-NT leads to unstable routes compared to using L-ETX. Route stability is measured by comparing the route taken by every two consecutive packets.

7. CONCLUSION AND FUTURE DIRECTIONS

Link quality estimation has been attracting a lot of attention in the WSN community as it emerges as a fundamental building block for several protocols such as MAC, routing, mobility management, and localization. This article fills a gap by presenting the first attempt to survey and understand the fundamental concepts related to link quality estimation in WSNs.

In the first part of this article, we synthesized the vast array of empirical studies on low-power links into a set of high-level observations, some of which are contradictory. This is mainly due to the discrepancies in experimental conditions between empirical studies, that is, they do not have the same environment characteristics, neither the same WSN platform nor the same experiment settings. Apart from these contradicting observations, we identified a set of observations showing how low-power links experience a complex and dynamic behavior. In fact, low-power links are extremely unreliable due to the low-power and low-cost radio hardware typically employed in WSN nodes.

The second part of this article was devoted to link quality estimation, where we described the main related aspects and provided a first taxonomy of LQEs. This part demonstrates that research on link quality estimation is challenging and far from being completed. Efficient link quality estimation that provides a fine-grain classification of links, especially intermediate links, should be based on several link quality metrics, each metric capturing a particular link property such as link asymmetry or stability. In fact, a single metric (e.g., RSSI, PRR, RNP, ETX) can only assess a particular link property and thus provides just a partial characterization of the link. In other words, estimators that combine several link properties (e.g., four-bit [Fonseca et al. 2007], F-LQE [Baccour et al. 2010], and the Triangle metric [Boano et al. 2010c]) seem to be promising, but their overhead (memory footprint, computation time) must be assessed, as well as their ability to tackle network dynamics (e.g., mobility). Overall, efficient LQEs must be reactive to persistent changes in link quality, yet stable by ignoring transient (short-term) variations in link quality.

The design of LQEs that provide a holistic view on the radio link quality is a relatively new research area, thus, several research challenges still remain open. One challenging problem is to select representative link quality metrics for the specification of a holistic link quality estimation. For instance, a big emphasis has been made in the literature about the goodness of hardware metrics, namely RSSI, LQI, and SNR in quantifying some properties of the link. Another problem that is worth investigating is devising new methodologies for combining these metrics and producing a single LQE. The fuzzy logic was one interesting approach that led to combining heterogeneous metrics resulting in the F-LQE estimator, but others should also be investigated.

Another open issue is how to validate LQEs and tune them to be optimally used by higher-layer protocols or mechanisms such as routing, mobility management, or fault tolerance. For instance, recent research work on routing and mobility management tend to integrate link quality estimation in the decision process. The design of a link-quality-based routing metric is a crucial and challenging problem. The effectiveness of a routing protocol depends not only on the link quality estimation process, but also on how to use the estimate as a routing metric for path selection. This was addressed in the widely used Collection Tree Protocol [Gnawali et al. 2009], but is still to be resolved for the Routing Protocol for Low-power and Lossy Networks (RPL) [Goyal 2010] specified for 6LowPAN networks [Kim et al. 2009]. The design of reliable hand-off techniques for supporting physical mobility in WSNs may also build upon efficient link quality estimation. One of the main challenges here is to find an optimal trade-off between the stability of the LQE and the ability to cope with link quality dynamics, since the estimation must be computed fast and have sufficient sensitivity to detect link quality changes resulting from physical mobility.

REFERENCES

AGUAYO, D., BICKET, J., BISWAS, S., JUDD, G., AND MORRIS, R. 2004. Link-level measurements from an 802.11b mesh network. *SIGCOMM Comput. Comm. Rev. 34,* 4, 121–132.

BACCOUR, N., KOUBÂA, A., BEN JAMAA, M., YOUSSEF, H., ZUNIGA, M., AND ALVES, M. 2009. A comparative simulation study of link quality estimators in wireless sensor networks. In *Proceedings of the 17th IEEE/ACM International Symposium on Modelling, Analysis and Simulation of Computer and Telecommunication Systems (MASCOTS '09)*. IEEE, 301–310.

BACCOUR, N., KOUBÂA, A., JAMAA, M. B., DO ROSÁRIO, D., YOUSSEF, H., ALVES, M., AND BECKER, L. B. 2011. Radiale: A framework for designing and assessing link quality estimators in wireless sensor networks. *Ad Hoc Netw. 9,* 7, 1165–1185.

BACCOUR, N., KOUBÂA, A., YOUSSEF, H., BEN JAMAA, M., DO ROSÁRIO, D., ALVES, M., AND B. BECKER, L. 2010. F-LQE: A fuzzy link quality estimator for wireless sensor networks. In *Proceedings of the 7th European Conference on Wireless Sensor Networks (EWSN'10)*. Springer, 240–255.

BANNISTER, K., GIORGETTI, G., AND GUPTA, S. K. 2008. Wireless sensor networking for hot applications: Effects of temperature on signal strength, data collection and localization. In *Proceedings of the 5th Workshop on Embedded Networked Sensors (HotEmNets'08)*.

BOANO, C. A., BROWN, J., TSIFTES, N., ROEDIG, U., AND VOIGT, T. 2010a. The impact of temperature on outdoor industrial sensornet applications. *IEEE Trans. Industr. Inf. 6,* 3, 451–459.

BOANO, C. A., VOIGT, T., DUNKELS, A., OSTERLIND, F., TSIFTES, N., MOTTOLA, L., AND SUAREZ, P. 2009. Poster abstract: Exploiting the LQI variance for rapid channel quality assessment. In *Proceedings of the International Conference on Information Processing in Sensor Networks (IPSN '09)*. IEEE Computer Society, 369–370.

BOANO, C. A., VOIGT, T., NODA, C., RÖMER, K., AND ZÚÑIGA, M. A. 2011. JamLab: Augmenting sensornet testbeds with realistic and controlled interference generation. In *Proceedings of the 10th International Conference on Information Processing in Sensor Networks (IPSN '11)*. ACM Press, 175–186.

BOANO, C. A., VOIGT, T., TSIFTES, N., MOTTOLA, L., RÖMER, K., AND ZÚÑIGA, M. A. 2010b. Making sensornet MAC protocols robust against interference. In *Proceedings of the 7th European Conference on Wireless Sensor Networks (EWSN '10)*. Springer, 272–288.

BOANO, C. A., ZUNIGA, M., VOIGT, T., WILLIG, A., AND RÖMER, K. 2010c. The triangle metric: Fast link quality estimation for mobile wireless sensor networks. In *Proceedings of the 19th International Conference on Computer Communications and Networks (ICCCN '10)*. IEEE, 1–7.

BROWN, J., MCCARTHY, B., ROEDIG, U., VOIGT, T., AND SREENAN, C. J. 2011. Burstprobe: Debugging time-critical data delivery in wireless sensor networks. In *Proceedings of the 8th European Conference on Wireless Sensor Networks (EWSN '11)*. Springer, 195–210.

BTNODE. www.btnode.ethz.ch.

CERPA, A., BUSEK, N., AND ESTRIN, D. 2003. Scale: A tool for simple connectivity assessment in lossy environments. Tech. rep.

CERPA, A. AND ESTRIN, D. 2004. ASCENT: Adaptive self-configuring sensor networks topologies. *IEEE Trans. Mobile Comput. 3,* 3, 272–285.

CERPA, A., WONG, J. L., KUANG, L., POTKONJAK, M., AND ESTRIN, D. 2005a. Statistical model of lossy links in wireless sensor networks. In *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks (IPSN '05)*. IEEE Press, 81–88.

CERPA, A., WONG, J. L., POTKONJAK, M., AND ESTRIN, D. 2005b. Temporal properties of low power wireless links: Modeling and implications on multihop routing. In *Proceedings of the 6th International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc '05)*. ACM, 414–425.

CHIPCON AS. 2007. CC2420 datasheet - 2.4 GHz IEEE 802.15.4/ZigBee-Ready RF Transceiver (Rev. B). Chipcon AS.

CHOWDHURY, K. R. AND AKYILDIZ, I. F. 2009. Interferer classification, channel selection and transmission adaptation for wireless sensor networks. In *Proceedings of the International Conference on Communication (ICC '09)*. IEEE, 1–5.

COUTO, D. S. J. D., AGUAYO, D., BICKET, J., AND MORRIS, R. 2003. A high-throughput path metric for multihop wireless routing. In *Proceedings of the 9th Annual International Conference on Mobile Computing and Networking (MobiCom '03)*. ACM, 134–146.

DUTTA, P., DAWSON-HAGGERTY, S., CHEN, Y., LIANG, C.-J. M., AND TERZIS, A. 2010. Design and evaluation of a versatile and efficient receiver-initiated link layer for low-power wireless. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys '10)*. ACM, 1–14.

DYER, M., BEUTEL, J., THIELE, L., KALT, T., OEHEN, P., MARTIN, K., AND BLUM, P. 2007. Deployment support network—A toolkit for the development of WSNs. In *Proceedings of the 4th European Conference on Wireless Sensor Networks (EWSN '07)*. Springer, 195–211.

FAIRHURST, G. AND WOOD, L. 2002. Rfc 3366 : Advice to link designers on link automatic repeat request (arq). Tech. rep.

FONSECA, R., GNAWALI, O., JAMIESON, K., AND LEVIS, P. 2007. Four bit wireless link estimation. In *Proceedings of the 6th International Workshop on Hot Topics in Networks (HotNets VI)*. ACM SIGCOMM.

GANESAN, D., KRISHNAMACHARI, B., WOO, A., CULLER, D., ESTRIN, D., AND WICKER, S. 2002. Complex behavior at scale: An experimental study of low-power wireless sensor networks. Tech. rep.

GNAWALI, O., FONSECA, R., JAMIESON, K., MOSS, D., AND LEVIS, P. 2009. Collection tree protocol. In *Proceedings of the 7th ACM Conference on Embedded Networked Sensor Systems (SenSys '09)*. ACM, 90–100.

GOLDSMITH, A. 2005. *Wireless Communications*. Cambridge University Press.

GOMEZ, C., BOIX, A., AND PARADELLS, J. 2010. Impact of LQI-based routing metrics on the performance of a one-to-one routing protocol for IEEE 802.15.4 multihop networks. *EURASIP J. Wirel. Comm. Netw. 2010*, 6:1–6:20.

GOYAL, M. 2010. Mechanisms to support point-to-point routing in low power and lossy networks. Tech. rep.

HUANG, G. J., XING, G., ZHOU, G., AND ZHOU, R. 2010. Beyond co-existence: Exploiting WiFi white space for Zigbee performance assurance. In *Proceedings of the 18th IEEE International Conference on Network Protocols (ICNP '10)*. IEEE, 305–314.

IEEE 802.15.4 STANDARD. 2003. http://standards.ieee.org/getieee802/download/802.15.4-2003.pdf.

INCEL, O. D., DULMAN, S., JANSEN, P., AND MULLENDER, S. 2006. MultiChannel interference measurements for wireless sensor networks. In *Proceedings of the 31th International Conference on Communications*. IEEE, 694–701.

IYER, V., WOEHRLE, M., AND LANGENDOEN, K. Chrysso: A multichannel approach to mitigate external interference 2011. In *Proceedings of the 8th Communication Society Conference on Sensor, Mesh, and Ad Hoc Communications and Networks (SECON '11)*.

JIANG, P., HUANG, Q., WANG, J., DAI, X., AND LIN, R. 2006. Research on wireless sensor networks routing protocol for wetland water environment monitoring. In *Proceedings of the 1st International Conference on Innovative Computing, Information and Control (ICICIC '06)*. IEEE, 251–254.

KIM, E., KASPAR, D., GOMEZ, C., AND BORMANN, C. 2009. Problem statement and requirements for 6lowpan routing. Tech. rep. draft-ietf-6lowpan-routing-requirements-04.

KIM, K.-H. AND SHIN, K. G. 2006. On accurate measurement of link quality in multihop wireless mesh networks. In *Proceedings of the 12th Annual International Conference on Mobile Computing and Networking (MobiCom '06)*. ACM, 38–49.

KIM, M. AND NOBLE, B. 2001. Mobile network estimation. In *Proceedings of the 7th Annual International Conference on Mobile Computing and Networking (MobiCom '01)*. ACM, 298–309.

KOKSAL, C. AND BALAKRISHNAN, H. 2006. Quality-aware routing in time-varying wireless networks. *IEEE J. Select. Areas Comm. 24,* 11, 1984–1994.

KOTZ, D., NEWPORT, C., AND ELLIOTT, C. 2003. The mistaken axioms of wireless-network research. Tech. rep., Dartmouth College.

LAL, D., MANJESHWAR, A., AND HERRMANN, F. 2003. Measurement and characterization of link quality metrics in energy constrained wireless sensor networks. In *Proceedings of the IEEE Global Telecommunications Conference (Globecom '03)*. IEEE, 446–452.

LEE, H., CERPA, A., AND LEVIS, P. 2007. Improving wireless simulation through noise modeling. In *Proceedings of the 6th International Conference on Information Processing in Sensor Networks (IPSN '07)*. ACM, 21–30.

LI, Y., CHEN, J., LIN, R., AND WANG, Z. 2005. A reliable routing protocol design for wireless sensor networks. In *Proceedings of the IEEE International Conference on Mobile Adhoc and Sensor Systems (MASS '05)*. IEEE, 61–65.

LIANG, C.-J. M., PRIYANTHA, N. B., LIU, J., AND TERZIS, A. 2010. Surviving wi-fi interference in low power zigbee networks. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems (SenSys'10)*. ACM, 309–322.

LIM, G. 2002. Link stability and route lifetime in ad-hoc wireless networks. In *Proceedings of the International Conference on Parallel Processing Workshops (ICPPW '02)*. IEEE, 116.

LIN, S., ZHANG, J., ZHOU, G., GU, L., STANKOVIC, J. A., AND HE, T. 2006. Atpc: Adaptive transmission power control for wireless sensor networks. In *Proceedings of the 4th International Conference on Embedded Networked Sensor Systems (SenSys '06)*. ACM, 223–236.

LIN, S., ZHOU, G., WHITEHOUSE, K., WU, Y., STANKOVIC, J. A., AND HE, T. 2009. Towards stable network performance in wireless sensor networks (RTSS '09). In *Proceedings of the 30th IEEE Real-Time Systems Symposium*. IEEE, 227–237.

LIU, H., LI, J., XIE, Z., LIN, S., WHITEHOUSE, K., STANKOVIC, J. A., AND SIU, D. 2010. Automatic and robust breadcrumb system deployment for indoor firefighter applications. In *Proceedings of the 8th International Conference on Mobile Systems, Applications, and Services (MobiSys '10)*. ACM, 21–34.

LYMBEROPOULOS, D., LINDSEY, Q., AND SAVVIDES, A. 2006. A.: An empirical characterization of radio signal strength variability in 3-d ieee 802.15.4 networks using monopole antennas. In *Proceedings of the 7th European Conference on Wireless Sensor Networks (EWSN' 10)*. Springer, 326–341.

MOTTOLA, L., PICCO, G. P., CERIOTTI, M., GUNĂ, C., AND MURPHY, A. L. 2010. Not all wireless sensor networks are created equal: A comparative study on tunnels. *ACM Trans. Sen. Netw. 7*, 15:1–15:33.

MUNIR, S., LIN, S., HOQUE, E., NIRJON, S. M. S., STANKOVIC, J. A., AND WHITEHOUSE, K. 2010. Locationing burstiness for reliable communication and latency bound generation in wireless sensor networks. In *Proceedings of the 9th ACM/IEEE International Conference on Information Processing in Sensor Networks (IPSN '10)*. ACM, 303–314.

MUSALOIU-E., R. AND TERZIS, A. 2007. Minimising the effect of WiFi interference in 802.15.4 wireless sensor networks. *Int. J. Sensor Netw. 3,* 1, 43–54.

NODA, C., PRABH, S., BOANO, C. A., VOIGT, T., AND ALVES, M. 2011. Poster abstract: A channel quality metric for interference-aware wireless sensor networks. In *Proceedings of the International Conference on Information Processing in Sensor Networks (IPSN '11)*. IEEE, 167–168.

PETROVA, M., WU, L., MAHONEN, P., AND RIIHIJARVI, J. 2007. Interference measurements on performance degradation between colocated ieee 802.11g/n and ieee 802.15.4 networks. In *Proceedings of the 6th International Conference on Networking*. IEEE, 93–.

POLASTRE, J., SZEWCZYK, R., AND CULLER, D. 2005. Telos: Enabling ultra-low power wireless research. In *Proceedings of the 4th International Symposium on Information Processing in Sensor Networks (IPSN '05)*. IEEE Press, 364–369.

PUCCINELLI, D. AND HAENGGI, M. 2008. DUCHY: Double cost field hybrid link estimation for low-power wireless sensor networks. In *Proceedings of the 5th Workshop on Embedded Networked Sensors (Hot EmNets'08)*. ACM.

PUCCINELLI, D. AND HAENGGI, M. 2010. Reliable data delivery in large-scale low-power sensor networks. *ACM Trans. Sen. Netw. 6,* 4, 1–41.

RAMAN, B. AND CHEBROLU, K. 2008. Censor networks: A critique of "sensor networks" from a systems perspective. *SIGCOMM Comput. Comm. Rev. 38*, 75–78.

RAMAN, B., CHEBROLU, K., MADABHUSHI, N., GOKHALE, D. Y., VALIVETI, P. K., AND JAIN, D. 2006. Implications of link range and (in)stability on sensor network architecture. In *Proceedings of the 1st International Workshop on Wireless Network Ttestbeds, Experimental Evaluation & Characterization (WiNTECH '06)*. ACM, 65–72.

RAPPAPPORT, T. S. 2001. *Wireless Communications: Principles and Practice*. Prentice Hall.

REIJERS, N., HALKES, G., AND LANGENDOEN, K. 2004. Link layer measurements in sensor networks. In *Proceedings of the 1st IEEE Internationall Conference on Mobile Ad-hoc and Sensor Systems (MASS '04)*. IEEE, 24–27.

Rondinone, M., Ansari, J., Riihijärvi, J., and Mähönen, P. 2008. Designing a reliable and stable link quality metric for wireless sensor networks. In *Proceedings of the Workshop on Real-World Wireless Sensor Networks (RealWSN '08)*. 6–10.

Seada, K., Zuniga, M., Helmy, A., and Krishnamachari, B. 2004. Energy-Efficient forwarding strategies for geographic routing in lossy wireless sensor networks. In *Proceedings of the 2^{nd} International Conference on Embedded Networked Sensor Systems (SenSys '04)*. ACM, 108–121.

Senel, M., Chintalapudi, K., Lal, D., Keshavarzian, A., and Coyle, E. J. 2007. A Kalman filter based link quality estimation scheme for wireless sensor networks. In *Proceedings of the IEEE Global Telecommunications Conference (GLOBECOM '07)*. IEEE, 875–880.

Sha, M., Hackmann, G., and Lu, C. 2011. ARCH: Practical channel hopping for reliable home-area sensor networks. In *Proceedings of the 17^{th} Real-Time and Embedded Technology and Applications Symposium (RTAS '11)*. IEEE.

Sikora, A. and Groza, V. F. 2005. Coexistence of IEEE 802.15.4 with other systems in the 2.4 GHz-ISM-band. In *Proceedings of the IEEE Conference on Instrumentation and Measurement Technology*. 1786–1791.

Son, D., Krishnamachari, B., and Heidemann, J. 2006. Experimental study of concurrent transmission in wireless sensor networks. In *Proceedings of the 4^{th} International Conference on Embedded Networked Sensor Systems (SenSys '06)*. ACM, 237–250.

Srinivasan, K., Dutta, P., Tavakoli, A., and Levis, P. 2006a. Understanding the causes of packet delivery success and failure in dense wireless sensor networks. In *Proceedings of the 4^{th} International Conference on Embedded Networked Sensor Systems (SenSys '06)*. ACM, 419–420.

Srinivasan, K., Dutta, P., Tavakoli, A., and Levis, P. 2010a. An empirical study of low-power wireless. *ACM Trans. Sen. Netw. 6*, 1–49.

Srinivasan, K., Jain, M., Choi, J. I., Azim, T., Kim, E. S., Levis, P., and Krishnamachari, B. 2010b. The κ factor: Inferring protocol performance using inter-link reception correlation. In *Proceedings of the 16^{th} Annual International Conference on Mobile Computing and Networking (MobiCom '10)*. ACM, 317–328.

Srinivasan, K., Kazandjieva, M. A., Agarwal, S., and Levis, P. 2008. The β-factor: Measuring wireless link burstiness. In *Proceedings of the 6^{th} International Conference on Embedded Network Sensor Systems (SenSys '08)*. ACM, 29–42.

Srinivasan, K. and Levis, P. 2006b. Rssi is under appreciated. In *Proceedings of the 3^{rd} International Workshop on Embedded Networked Sensors (EmNets'06)*.

Tang, L., Sun, Y., Gurewitz, O., and Johnson, D. B. 2011. EM-MAC: A dynamic multichannel energy-efficient MAC protocol for wireless sensor networks. In *Proceedings of the 12^{th} ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc '11)*. ACM.

Tang, L., Wang, K.-C., Huang, Y., and Gu, F. 2007. Channel characterization and link quality assessment of ieee 802.15.4-compliant radio for factory environments. *IEEE Trans. Industr. Inf. 3,* 2, 99–110.

Thelen, J., Goense, D., and Langendoen, K. 2005. Radio wave propagation in potato fields. In *Proceedings of the 1^{st} Workshop on Wireless Network Measurements*.

TinyOS MultiHopLQI routing algorithm. 2004. http://www.tinyos.net/tinyos-1.x/tos/lib/MultiHopLQI/.

Toscano, E. and Bello, L. L. 2008. Cross-Channel interference in IEEE 802.15.4 networks. In *Proceedings of the 7^{th} International Workshop on Factory Communication Systems (WFCS '08)*. 139–148.

Wang, Y., Martonosi, M., and Peh, L.-S. 2007. Predicting link quality using supervised learning in wireless sensor networks. *ACM SIGMOBILE Mobile Comput. Comm. Rev. 11,* 3, 71–83.

Werner-Allen, G., Lorincz, K., Johnson, J., Lees, J., and Welsh, M. 2006. Fidelity and yield in a volcano monitoring sensor network. In *Proceedings of the 7^{th} Symposium on Operating Systems Design and Implementation (OSDI '06)*. USENIX Association, 381–396.

Woo, A. and Culler, D. 2003a. Evaluation of efficient link reliability estimators for low-power wireless networks. Tech. rep. UCB/CSD-03-1270, EECS Department, University of California, Berkeley.

Woo, A., Tong, T., and Culler, D. 2003. Taming the underlying challenges of reliable multihop routing in sensor networks. In *Proceedings of the 1^{st} International Conference on Embedded Networked Sensor Systems (SenSys '03)*. ACM, 14–27.

Wu, Y., Stankovic, J. A., He, T., and Lin, S. 2008. Realistic and efficient multi-channel communications in wireless sensor networks. In *Proceedings of the 27^{th} Conference on Computer Communications (INFOCOM '08)*. IEEE, 1193–1201.

Xing, G., Sha, M., Huang, J., Zhou, G., Wang, X., and Liu, S. 2009. MultiChannel interference measurement and modeling in low-power wireless networks. In *Proceedings of the 30^{th} IEEE Real-Time Systems Symposium (RTSS '09)*. IEEE, 248–257.

XU, Y. AND LEE, W.-C. 2006. Exploring spatial correlation for link quality estimation in wireless sensor networks. In *Proceedings of the 4th Annual IEEE International Conference on Pervasive Computing and Communication (PERCOM '06)*. IEEE Computer Society, 200–211.

YANG, D., XU, Y., AND GIDLUND, M. 2010. Coexistence of IEEE802.15.4 based networks a survey. In *Proceedings of the 36th Annual Conference on IEEE Industrial Electronics Society (IECON '10)*. IEEE, 2107–2113.

YUNQIAN, M. 2005. Improving wireless link delivery ratio classification with packet snr. In *Proceedings of the International Conference on Electro Information Technology*. IEEE, 6–12.

ZHANG, H., SANG, L., AND ARORA, A. 2008. Unravelling the subtleties of link estimation and routing in wireless sensor networks. Tech. rep.

ZHANG, H., SANG, L., AND ARORA, A. 2010. Comparison of data-driven link estimation methods in low-power wireless networks. *IEEE Trans. Mobile Computing 9*, 1634–1648.

ZHAO, J. AND GOVINDAN, R. 2003. Understanding packet delivery performance in dense wireless sensor networks. In *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems (SenSys '03)*. ACM, 1–13.

ZHOU, G., HE, T., KRISHNAMURTHY, S., AND STANKOVIC, J. A. 2004. Impact of radio irregularity on wireless sensor networks. In *Proceedings of the 2nd International Conference on Mobile Systems, Applications, and Services (MobiSys '04)*. ACM, 125–138.

ZHOU, G., HE, T., KRISHNAMURTHY, S., AND STANKOVIC, J. A. 2006a. Models and solutions for radio irregularity in wireless sensor networks. *ACM Trans. Sen. Netw. 2,* 2, 221–262.

ZHOU, G., HE, T., STANKOVIC, J. A., AND ABDELZAHER, T. 2005. Rid: Radio interference detection in wireless sensor networks. In *Proceedings of the 24th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM '05)*. IEEE, 891–901.

ZHOU, G., STANKOVIC, J. A., AND SON, S. H. 2006b. Crowded spectrum in wireless sensor networks. In *Proceedings of the 3rd Workshop on Embedded Networked Sensors (EmNets '06)*.

ZUNIGA, M. AND KRISHNAMACHARI, B. 2004. Analyzing the transitional region in low power wireless links. In *Proceedings of the 1st International Conference on Sensor and Ad Hoc Communications and Networks (SECON '04)*. IEEE, 517–526.

ZUNIGA, M. AND KRISHNAMACHARI, B. 2007. An analysis of unreliability and asymmetry in low-power wireless links. *ACM Trans. Sen. Netw. 3,* 2, 63–81.

Received March 2011; revised June 2011; accepted July 2011