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A Study on Hardware and Software Link Quality Metrics for Wireless Multimedia Sensor Networks

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ABSTRACT

Due to the lack of accurate evaluation of the transmission characteristics of the wireless communication links, routing algorithms in wireless sensor networks may result in poor network performance. In order to avoid sending packets over the unstable link, routing protocol has to rely on noble metrics to choose better routing path. Better estimation of link reliability between neighboring nodes could permit the selection of a more reliable route. Since the routing metrics play an important role as they have a direct impact on the efficiency and robustness of routing protocols. Different routing metrics will provide different performances to routing protocols when used to compute weight of paths. This paper presents a study on various hardware and software link quality metrics that help network protocol designers can choose an efficient Link Quality Estimator to develop reliable routing techniques for WMSNs. Additionally a classification tree of different routing metrics is presented which helps in understanding the strengths and weaknesses of these LQ metrics, thus enabling the designer of the routing protocol to make an informed choice.

Keywords— **Link Quality, routing protocol, sensor networks, need for link quality analysis, LQI, PRR, RNP.**

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I. INTRODUCTION

In Wireless Sensor Networks (WSNs), link quality estimation is more challenging than in the other traditional wireless mesh and ad-hoc networks[1], because sensor nodes are densely deployed and basically use low-power radios. It has been experimentally shown that low-power radios are more prone to noise, interference, and multipath distortion [2]. The propagation of wireless signals with low-power radios is affected by several factors that contribute to the degradation of its quality. Consequently, radio links in WSNs are often unpredictable. In fact, their quality fluctuates over time and space. As a result, communication links in WSNs exhibit more unreliability.

Generally Routing in networks addresses the problem of finding efficient paths for data forwarding between source and destination nodes. Most of the routing protocols typically rely on metrics such as hop-count or end-to-end delay [3], which do not explicitly reflect link quality. This can result in poor path selection, since the routing protocol is not aware of reliability of the links. These conditions can make communication inefficient, resulting in communication loss and frequent packet retransmissions. In addition to using the traditional metrics, routing techniques can infer more knowledge on the forwarding path with the help of Link quality estimation, is the process through which many routing techniques designed for wireless networks can be able to know the quality of the link after analysing its dynamic behaviour so as to select the suitable path for packet the help of t transmission. Now a day many sophisticated routing protocols aim to overcome link unreliability in order to efficiently maintain network connectivity. With the aim of achieving this, they over sees the link quality estimation (LQE) as a support mechanism to select the most stable routes for data. Stable routes are built by selecting links with the highest quality and discarding those of bad quality. Building such routes will definitely improve the network throughput and maximize its lifetime.

The link quality estimation process comprises of link monitoring, link measurements, and metric evaluation. Link monitoring involves three kinds .they are (i) active link monitoring,(ii.) passive link monitoring, and (iii.) hybrid link monitoring. Passive monitoring involves evaluating data from received packets during communication while active monitoring entails sending probe packets and evaluating data from response packets. Passive link monitoring has been widely used in WSNs due to its energy-efficiency compared to active 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 [4]. In general, the quality of a link is estimated as a proportion of successfully received packets. Hence, the goodness of a link is linear to the proportion of received packets. Thus, a generic observation is that each link may belong to one of the following zones: high link quality, transitional ('gray zones') for intermediate link quality, and low link quality.

Efficient link quality estimation has several requirements such as Energy efficiency, Accuracy, Reactivity and Stability etc. in order to minimize high communication overhead, to correctly characterize the link state, to quickly react to persistent changes in link quality and to tolerate transient (short-term) variations in link quality.

II. CATEGORY OF LINKQUALITY ESTIMATORS

Link quality estimators in wireless sensor networks can roughly be classified in two categories such as hardware-based estimators and software-based estimators. Hardware-based estimators include Link Quality Indicator (LQI) Received Signal Strength Indicator (RSSI) and Signal to- Noise Ratio (SNR). These estimators are directly obtained from the hardware for example CC2420 radio transceiver [5]. Their advantage is that they do not require any computation overhead as they are built-in directly on the hardware. However, as it was observed and reported in pervious experimental studies, hardware-based estimators do not provide accurate estimate. These metrics are measured based on 8 symbols of a received packet and not the whole packet. Second, these metrics are only measured for successfully received packets. Therefore, when a radio link suffers from excessive packet loss, they could overestimate the transmission performance by not considering the information of lost packets. They are also dependant on the transceiver model, as LQI, for instance, might not be available on all radio transceivers. Figure 1 represents the association different link quality metrics based on their estimation type.

On the other hand Software based LQEs are computed by the number of received and sent packets and different strategies are adopted to calculate these software based link quality estimators. Some software based link quality estimators are calculated at the sender node side, while others are calculated at the receiver node side [6]. These estimators enable to count or approximate either the reception rate or the average number of packet transmissions/re-transmissions, required before its successful reception. Based on that Software-based LQEs can be classified into three categories, such as (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. Some of the software LQEs are Packet Reception Rate (PRR), Acquitted Reception Rate (ARR) count the reception rate and ETX - based metrics will account for expected number of retransmission for the successful reception of data. These link quality estimators are simple, yet they have been widely used in routing protocols. The main difference between hardware and software based estimators is the fact that hardware based estimators only rely on received packet information, they do not account for packet loss. Software based estimators account for packet loss by incorporating data collected from the data link layer, such as packet retransmissions.

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. The above limitations of hardware-based LQEs do not mean that this category of LQEs is not useful. In fact, each of these LQEs provides 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.

III. NEED FOR LINK QUALITY ESTIMATION

Link quality estimation is a fundamental problem in wireless networks, and in particular sensor and mobile ad hoc networks, due to the fact that the accuracy of link quality estimation has a fundamental impact on the efficiency of networking protocols. In Wireless SENSOR Networks (WSN) routes towards sinks are evaluated using link cost metrics also known as link estimators.

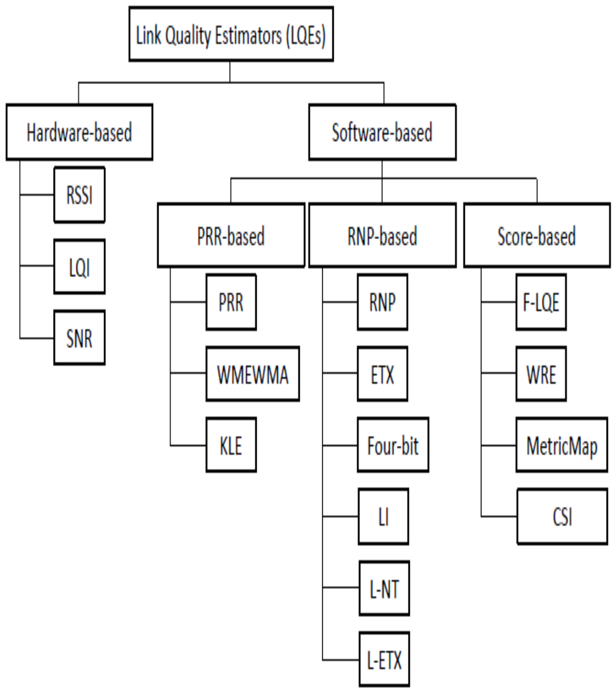

Figure 1: Organization of different LQEs

Link estimators can play an important role in a route algorithm to choose the "best" route towards the sink using different properties of the links. A link estimator chooses one of the neighbouring nodes as a parent node and transmits data towards the sink using that node. The node that a link estimator chooses as a parent is considered as the "best" in terms of a cost function. Poor link estimation may lead to a less stable network with higher packet loss and/or higher delays. Ideally, a routing protocol for a wireless multihop network should favour the use of good

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quality links.The problem is particularly critical in multihop routing when link-quality-aware metrics [7] (e.g., expected transmission count (ETX), expected transmission time are used to select the best neighbour to relay a message. The availability of robust link quality estimates is even more critical when routing needs to support quality-of-service provisioning (e.g. in the case of voice or video data transmissions). Other important applications that can benefit from the availability of accurate link estimation models include, among others: sensor placement, topology control, and load-balancing, relay node placement, network failure diagnosis, coordination in sensor-actor networks. Accurate and reliable link quality estimation is a challenging task in wireless networks. In fact, the effective quality of Link assessment is required for a better comprehension of the environments we cope with. More specifically, a good perception on the link behaviour helps to design robust link quality estimators (LQEs). In fact, a good LQE for routing has to guarantee low energy consumption, stable topology, a high throughput, a low end-to-end delay, reliable paths when retransmissions are present, and low churn (neighbour changes). On the other hand, it should be reactive, able to predict short and long term link fluctuations, stable in time, to accurately discriminate link quality, should rely on simple computation (light memory footprint), or to have accurate predefined thresholds to Discriminate unreliable neighbours (blacklist mechanism).

To overcome the energy waste, LQEs should properly foresee the quality of the link over few samples. Since a wrong decision leads to packet loss and neighbour changes, which are costly. More exactly, when routing relies on bad links, retransmissions at the MAC layer increase, which causes energy waste. If the metric fails choosing an unreliable neighbour, interferences through concurrent transmissions are introduced. Interference that affects the quality of neighbouring links. Therefore, the main requirements related to forwarding data over dynamic wireless links are designing good link estimators.

IV. HARDWARE METRICS

Many radio chips that implement proprietary radio technologies provide the received signal strength indicator (RSSI), which is the strength of a received radiofrequency (RF) signal, researchers considered the use of PHY parameters from off-the-shelf radio hardware [8]. Furthermore, IEEE 802.15.4-compliant radio chips, like the widely used Chipcon CC2420, also offer the LQI. As defined by the standard, measurement of the LQI may be implemented by means of receiver energy detection, signal to-noise ratio estimation, or a combination of these methods.

1. Received Signal Strength Indicator (RSSI)

In the newer radios such as CC2420, the RSSI is an 8-bit integer value. It is read from the RSSI register (in case of the signal absence, the value indicates the noise). RSSI for CC2420 radio chip is computed over the eight symbol period (128μs) using equation (1).

$$RSSI\ [dBm] = RSSI\ VAL\ +\ RSSIOFFSET --- \quad (1)$$

where The RSSI VAL is a 12 bit register and the RSSI OFFSET is equal to -45dBm. RSSI ranges from -28dBm to -127dBm. RSSI can provide a quick and accurate estimate of whether a link is of very good quality. The empirical studies proved the existence of a RSSI value (-87 dBm) above which the PRR is consistently high (99%) i.e., belong 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. Second, RSSI is 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.

2. Signal to- Noise Ratio (SNR)

Another measure extensively used to quantify link behaviour is SNR that denotes the strength of the signal. It is defined as the ratio of the received signal strength and the strength of the background noise. To estimate SNR, the receiver records at first the RSSI of the received packet, and then it has to measure the background noise. RSSI of a signal is defined as:

- RSSI [dBm] = 10log10 (Power received packet + Background noise),
- RSSI of the ambient noise is estimated as 10log10 (Background noise):
- SNR [dBm] = RSSI [dBm] − Background noise [dBm] (2.9)

3. Link Quality Indicator (LQI)

The Link Quality Indicator (LQI) is a metric that estimates the current quality of the received information. For CC1101, LQI gives an estimate of how easily a received signal can be demodulated by accumulating the magnitude of the error between ideal constellations and the received signal over the 64 symbols immediately following the sync word [76] .It ranges between [0...127]. A low value indicates a good link quality. Thus, its values depend on the used modulation (2-SK/GFSK/MSK/OOK).Many Simulation results show that our adaptation of the LQI metric is among the best route selection criteria regardless of the performance criterion under consideration, and that the load balancing significantly improves the routing efficiency by lengthening the network lifetime while minimizing packet losses[9],[10][11]. The CC2420 chip provides a correlation value that is based on the first eight symbols of the incoming packet. This correlation value is in the range of 50 to 110, where 50 correspond to the lowest quality frames detectable by the chip and 110

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indicates a maximum quality frame. According to the standard, the LQI value is represented by one byte. For this reason, Chipcon suggested the use of a linear conversion of the correlation values into a range of 0 to 255, using empirical methods based on Packet Error Rate (PER) measurements. In addition, the LQI value may be obtained by combining the correlation and RSSI values. However, the LQI values have been assumed to be the correlation values in the relevant literature, without the range conversion [12][13].One of the first attempts at a link quality estimator for a routing protocol based on the LQI was MultiHopLQI [6], which was actually an evolution of the aforementioned many-to-one scheme proposed in [5]. A path cost metric is computed as the sum of the link costs of the path. The cost of a link is inversely proportional to the LQI. It might be reasonable to use a single RSSI or LQI reading to decide if the link is of high quality or not. Such decision is based on RSSI and LQI thresholds, beyond which a link can maintain high quality, e.g., a PRR of at least 95% [18]. 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 [23].

V. SOFTWARE-BASED LQES

Software-based LQEs can be classified into three categories, such as (i.) PRR-based (ii.) RNP-based and (iii.) Score-based.

1. PRR BASED

1.1. Packet Reception Rate (PRR)

PRR is a receiver side estimator that is simple to measure and was widely used in routing protocols [6]. This metric is computed at the receiver for each window of *w* received packets, as follows:

$$PRR = \frac{Number\ of\ received\ packets}{Number\ of\ sent\ packets} --(2)$$

The number of lost packets is determined using the sequence number of packets. The *PRR* is based on passive monitoring, which means that useful statistical data is collected from received/sent data packets over that link. 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 [14]. The main objective of approximating the PRR is to provide more efficient link quality estimates than the current PRR of a link. The efficiency of PRR depends on the adjustment of the time window size. 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 accurate link quality estimation.

1.2. The Window Mean with Exponentially Weighted Moving Average (WMEWMA)

A filter based link quality estimator which uses the EWMA filter as main estimation technique, based on link measurements, the PRR is computed and then smoothed to the previously computed PRR using EWMA filter which provides more stable but sufficiently agile estimation compared to PRR It is a receiver-side LQE based on passive monitoring. It smoothes PRR estimates using the EWMA filter, To assess the performance of WMEWMA, 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 Culler [24],[25] laid the foundation for subsequent work on filter-based LQE, although their solution required a more thorough assessment, e.g., based on real-world data traces instead of synthetic ones (i.e., generated analytically). The Kalman filter based link quality estimator (KLE) was proposed [25] to overcome the poor reactivity of average-based LQEs, including PRR.

2. RNP BASED

2.1. Requested Number of Packets (RNP)

It counts the average number of packet transmissions/re-transmissions required before a successful reception. It is introduced in [6], follow passive monitoring, this metric is evaluated at the sender side for each transmitted and re-transmitted packets as follows:

$$RNP = \frac{Number\ of\ transmitted\ \&\ retransmitted\ packets}{number\ of\ successfully\ received\ packets} - 1 \quad ---(3)$$

where the first packet transmission is excluded. Note that the number of successfully received packets is determined by the sender as the number of acknowledged packets. RNP is more reactive than PRR but it can underestimate link quality[15][16]. In fact, RNP is a sender side LQE, i.e., 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. Various authors argue that RNP is better than PRR for characterizing the link quality because PRR provides a coarse-grain estimation of the link quality since it does not take into account the underlying distribution of losses, in contrast to RNP. 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.

On the other hand, RNP can be computed even if no packet is received. RNP is not aware of the link asymmetry

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in the sense that they provide an estimate of the quality of the unidirectional link from the sender to the receiver. 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. RNP has the disadvantage of being very unstable and cannot reliably estimate the link packet delivery, mainly due to link asymmetry

2.2. The Expected Transmission Count (ETX)

A receiver-side estimator that uses active monitoring. It measures link quality by estimating the number of transmissions and retransmissions needed to send a data packet over a link. ETX is the inverse of the product of the forward delivery ratio and the backward delivery ratio, which takes into account link asymmetry.

To get the ETX value, every node broadcasts a probe packet periodically to neighbouring nodes. The formula to calculate ETX is as given as follows:

$$ETX = \frac{1}{df - dr} - - - - - - (4)$$

Where, the forward delivery ratio, df, denotes the probability that a packet will be successfully delivered in the forward direction, and the reverse delivery ratio dr denotes the probability of receiving the corresponding acknowledgement packet. Therefore, ETX involves the delivery ratio and the number of transmissions in both directions over a link. Since the two probabilities are independent, df × dr can be understood as the expected probability of a successful transmission, which includes acknowledgement. df × dr is also equal to (1- Pf) ×(1- Pr), where Pf and Pr are the forward and reverse packet loss ratios. Experiments proved that routing protocols based on the ETX metric provide high-throughput routes on multihop wireless networks. However, [17] found that ETX based on passive monitoring fails in overloaded (congested) networks, since a large number of nodes are not able to compute the ETX because they do not receive packets.

The main disadvantages of ETX lie in the way it broadcasts small probe packets to detect data delivery ratio, and that probe packets are sent at a lower data rate. This estimation may not reflect the real packet loss ratio, because actual packets are usually larger and sent at higher data rates. Additionally, ETX does not take link data rates into account. The same packet loss ratio may be associated with different data rates and link delays. For this reason, ETX is more suitable for single-rate networks.

2.3. Four bit

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 identifying 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 neighbour table replacement policy. Four-bit assesses link quality as an approximation of the packet retransmissions count by combining two metrics (RNP and WMEWMA) 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. It is a hybrid estimator as it uses both passive and active (beacons traffic) monitoring. [18] found that CTP based on four-bit provides better performance (e.g., packet delivery) than the original version of CTP and Multi Hop. During active monitoring, nodes periodically broadcast probe packets. Based on wa received probe packets, the sender computes the WMEWMA estimate and derives an approximation of the RNP, denoted as estETXdown, as follows:

$$\text{estETXdown} = \frac{1}{\text{WMEWMA}} - 1 \text{ ----(5)}$$

This metric estimates the quality of the unidirectional link from the receiver to the sender based on active monitoring. During passive monitoring, the sender computes *RNP* based on number of transmitted/re-transmitted data packets to the receiver.Then, it uses EWMA filter to smooth *RNP* into *estETX*up, expressed as follows:

$$estETXup = \alpha \times estETXdown + (1 - \alpha) \times RNP \ - - - (6)$$

In Eq. (6), the metric *estETX*up estimates the quality of the unidirectional link from the sender to the receiver based on passive monitoring. Thus, the *four-bit* estimator combines both estETXup and estETXdown metrics via the EWMA filter, in order to obtain an estimate of the bidirectional link expressed as follows:

$$fourbit = \alpha \times fourbit + (1 - \alpha) \times estETX \ - - - (7)$$

where estETX corresponds to estETXup or estETXdown : At wa received probe packets, the sender drives the four-bit estimate according to Eq. (7) by replacing estETX by estETXdown . At wp transmitted/re-transmitted data packets, the sender drives the four-bit estimate according to Eq. (7) by replacing estETX by estETXup.

2.4. L-NT and L-ETX

The **L-NT and L-ETX** is two sender-side LQEs that approximate the RNP. 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. Through mathematical analysis and experimental measurements, 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.

3. *SCORE BASED*

Some LQEs provide a link estimate that does not refer to physical phenomena (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 score-based LQEs such as WRE, F-LQE

3.1. Fuzzy- Link Quality Estimator (F-LQE)

The Fuzzy Link Quality Estimator (F-LQE) 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).To validate their estimator, The statistical properties of F-LQE, independently of higher layer protocols [4] 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 5 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[20][21][22]. However, F-LQE might involve higher memory footprint and computation complexity as it combines four different metrics capturing four different link properties. 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.

3.2. The Weighted Regression Estimator (WRE)

It is proposed in [24] and 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 neighbour giving the location of this neighbour. Hence, WRE derives a complex regression function based on an input vector that contains a set of nodes locations together with their links quality known in advance. This function is continuously refined and updated by the knowledge of a new input, i.e., node location and the corresponding link quality. Once derived, this function returns an estimation of the link quality giving the neighbour location[23]. The performance of WRE is evaluated by comparing it to WMEWMA using the same evaluation methodology as that of used in [25], where PRR is considered as the objective metric. Existing work 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 [24],[25],[26].

VI. CONCLUSION AND FUTURE WORK

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 paper fills a gap by presenting the first attempt to survey and understand the fundamental concepts related to link quality estimation in WSNs. Further it was devoted to link quality estimation, where we described the main related aspects and provided a first taxonomy of LQEs [26]. 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. In this paper, we proposed a comparative study of a set of the well-known hardware and software based link quality estimators, namely LQI, RSSI, SNR, PRR, RNP, WMEWMA, ETX and Four-Bit etc. In future works one of the challenges is the design of estimators that make a good balance between stability and accuracy. Another challenge is design of estimators that take into account several parameters which should address the shortcomings of existing estimators.

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