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Reliable link quality estimation in low-power wireless networks and its impact on tree-routing

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ABSTRACT

Radio link quality estimation is essential for protocols and mechanisms such as routing, mobility management and localization, particularly for low-power wireless networks such as wireless sensor networks. Commodity Link Quality Estimators (LQEs), e.g. PRR, RNP, ETX, four-bit and RSSI, can only provide a partial characterization of links as they ignore several link properties such as channel quality and stability. In this paper, we propose F-LQE (Fuzzy Link Quality Estimator, a holistic metric that estimates link quality on the basis of four link quality properties—packet delivery, asymmetry, stability, and channel quality—that are expressed and combined using Fuzzy Logic. We demonstrate through an extensive experimental analysis that F-LQE is more reliable than existing estimators (e.g., PRR, WMEWMA, ETX, RNP, and four-bit) as it provides a finer grain link classification. It is also more stable as it has lower coefficient of variation of link estimates. Importantly, we evaluate the impact of F-LQE on the performance of tree routing, specifically the CTP (Collection Tree Protocol). For this purpose, we adapted F-LQE to build a new routing metric for CTP, which we dubbed as F-LQE/RM. Extensive experimental results obtained with state-of-the-art widely used test-beds show that F-LQE/RM improves significantly CTP routing performance over four-bit (the default LQE of CTP) and ETX (another popular LQE). F-LQE/RM improves the end-to-end packet delivery by up to 16%, reduces the number of packet retransmissions by up to 32%, reduces the Hop count by up to 4%, and improves the topology stability by up to 47%.

1. Introduction

Typically, radio transceivers used in Wireless Sensor Networks (WSNs) are low-cost and low-power, due to scalability and lifetime requirements. This fact makes radiated signals very prone to noise, interference, and multi-path distortion. Furthermore, these radio transceivers rely on antennas with non-ideal radiation patterns leading to anisotropic connectivity. Consequently, radio links in WSNs are extremely unreliable and often unpredictable. They experience quality fluctuation over time [1,2] and space [3,4], and their connectivity is typically asymmetric [3,5]. The unreliability of WSN links greatly affects the network performance. This raised the need for link quality estimation as a fundamental building block for the design of network protocols and mechanisms, including medium-access control (MAC), routing, mobility management, localization, and topology control.

Link quality estimation enables network protocols to mitigate and to overcome link unreliability. For instance, link quality estimation is instrumental for routing protocols

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to maintain correct network operation [6–13]. Delivering data over high quality links (i) improves the network delivery by limiting packet loss and (ii) maximizes its lifetime by minimizing the number of retransmissions, and avoiding route reselection triggered by link failures.

Basically, link quality estimation consists of evaluating a metric, 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). Existing LQEs can be classified as either hardware-based or software-based. Hardware-based LQEs such as the Received Signal Strength Indicator (RSSI) are directly read from the radio transceiver, i.e., they do not require any additional computation. Software-based LQEs are derived based on collected packet statistics e.g., packet sequence number. Some of them either count or approximate the packet reception ratio or the average number of packet transmissions/ retransmissions, and some others provide a score that identify the link state.

Existing LQEs (hardware or software) are not sufficiently accurate because they assess some link properties and ignore others, which provide a partial characterization of the link [14,15]. For example, the Packet Reception Ratio (PRR) can only capture link delivery property. It ignores other important properties that impact the link quality, such as asymmetry or stability. A link may have a good PRR and thus appears as a "good quality link", whereas the link involves several MAC retransmissions due to its high asymmetry (some acknowledgements are not delivered). Hence, the link state characterized on the basis of PRR alone can be misleading. A link that has a good delivery but has also high asymmetry is not a good quality link. Therefore, the main question investigated in this paper is the following:

Is it possible to design an LQE that provides a holistic characterization of low-power links, by combining several aspects/properties that impact overall link quality (e.g., asymmetry, stability, channel quality), so that to improve the performance of higher layer mechanisms/protocols such as routing?

We believe that such holistic link quality estimation can be achieved through a composite LQE that combines several link metrics. Each metric captures a particular link property. However, four main challenges should be addressed:

- The first challenge is **which link properties to consider** and what metrics to use for their assessment. A vast array of research works tackled the empirical characterization of low-power links through real-world measurements with different platforms, under different experimental conditions, assumptions, and scenarios (e.g., [1,2,4,16–20]). Therefore, there is the need to thoroughly analyze their outcomes, and identify the most relevant key observations. Such observations would be helpful to determine the most important properties that impact the quality of low-power links.
- The second challenge is **how to combine selected metrics**, given that they do not have necessarily the same nature. This challenge should be carefully addressed as a LQE can involve appropriate link metrics but the resulting link quality estimate may not be effective due to the inadequacy of the combination technique. For example, Rondinone et al. [21] suggest combining PRR and RSSI metrics through the multiplication of PRR by the normalized average RSSI. Another alternative would be a combination through a weighted sum.
- The third challenge is **how to validate this composite LQE**. The performance evaluation of LQEs is not a trivial task. One of the reasons is the impossibility, or at least the difficulty, to provide a quantitative evaluation of the accuracy of LQEs. In fact, there is no objective link quality metric to which a given link quality estimate can be compared. Furthermore, there are LQEs that are based on the packet reception ratio, some others are based on packet retransmission count, while others are hybrid and more complex. Thus, comparing their performance becomes challenging as they have different natures.
- The fourth challenge is **how can a particular LQE be used to boost the performance of higher layer protocols** e.g., tree-routing protocols, the most widely used for data collection wireless sensor networks.

This paper makes three main contributions. First, we propose F-LQE [22] (Section 3), a novel LQE for wireless sensor networks. In contrast to existing LQEs (Section 2), which assess link quality based on one or two link properties, F-LQE combines multiple metrics using Fuzzy Logic. Fuzzy logic provides a rigourous algebra to describe and combine different and imprecise metrics. The overall quality of the link is a result of the evaluation of a Fuzzy IF-THEN rule, which combines the different metrics, viewed as linguistic variables. The evaluation of the fuzzy rule returns the membership of the link in the fuzzy subset of good links. Second, we conduct a comparative performance study of LQEs, including F-LQE, PRR, WMEWMA, ETX, and four-bit (Section 4), based on a thorough experimental evaluation. This comparative study allowed us to show that F-LQE is more reliable and more stable than existing LQEs. Third, we investigate the use of F-LQE for improving collection tree routing, specifically the Collection Tree Protocol (CTP). Hence, we first design a routing metric based on F-LQE called F-LQE/RM (Section 5); then, we compare its impact on the performance of CTP with that of representative routing metrics (Section 6). Experimental results show that F-LQE/RM outperforms these routing metrics: it improves the end-to-end-delivery, reduces the number of packet retransmissions, reduces the hop count, and improves the topology stability. We conclude the paper by presenting some lessons learned throughout our experience on link quality estimation in WSNs, for the readers' convenience (Section 7). Table 1 outlines the organization of this paper.

2. Related work

In this section, we position our work, especially our introduced LQE, within the related literature.

2.1. Short-term link quality estimators

Few recent research works, such as [23–25] argue that intermediate-quality links, also referred as bursty links,

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Structure of the paper.

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can be exploited for data delivery (routing process) during their temporary reliability. Short-term link quality estimation allows a fine grain capture of link dynamics and then identify the periods when bursty links become temporarily reliable. Transmitting data over such bursty links is commonly referred to as opportunistic transmission/routing. Our design is fundamentally different from the opportunistic transmission and short-term link quality estimation as we try to capture good-quality links based on long-term observation. It is important to point out that long-term LQEs are mandatory to have a stable network topology. Nevertheless, the use of both short-term and long-term LQEs via an adaptive and opportunistic routing strategy can improve the overall network performance [23,25]. Generally, opportunistic routing uses reliable links for transmissions, based on long-term LQEs such as F-LQE, four-bit and ETX. However, when bursty links exhibit transient reliability, it takes advantage of them as well.

2.2. Hardware-based link quality estimators

Hardware-based LQEs such as LQI (Link Quality Indicator), RSSI (Received Signal Strength Indicator), and SNR (Signal-to- Noise Ratio), are directly read from the radio transceiver[1] (e.g., the CC2420). Their advantage is that they do not require any additional computation. However, as reported in previous studies [2,26–29], hardware based estimators do not provide accurate assessment of link quality, mainly for the following reasons: 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 quality into good, intermediate, and bad, they are incapable of providing a fine grain estimation of link quality [30,31]. For example, they can determine whether the link is in the transition region (i.e., of intermediate quality) or not but they cannot determine where in the transition region the link is.

2.3. Software-based link quality estimators

Software-based LQEs can be classified into three categories: (i) PRR-based, which either count or approximate the PRR (Packet Reception Ratio), (ii) RNP-based, which either count or approximate the RNP (Required Number of Packet retransmissions), and (iii) Score-based, which provide a score identifying the link quality. Next, we recall some of the most widely adopted software-based LQEs (refer to [32] for an exhaustive survey).

PRR-based: PRR is a receiver side estimator that is simple to measure and was widely used in routing protocols [6,33]. 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. The efficiency of PRR depends on the adjustment of the time window size. In [5], Cerpa et al. 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 Window Mean with Exponentially Weighted Moving Average (WMEWMA) [7], the Kalman filter based LQE [34] and the Holistic Packet Statistics (HoPS) [35] approximate the PRR. WMEWMA applies EWMA filter on the PRR metric to smooth it, thus providing a metric that resists to transient PRR fluctuations, yet it is responsive to major link quality changes. The Kalman filter based LQE [34] approximates the PRR based on RSSI and a pre-calibrated PRR/SNR curve. The HoPS considers four metrics separately, i.e., without combining them into a single value, namely Short-term, Long-term, Absolute Deviation, and Trend estimation. These metrics apply EWMA filter and statistical functions on PRR to capture link dynamics and provide a reliable link quality assessment.

RNP-based: RNP [1] counts the average number of packet transmissions/re-transmissions, required before successful reception. It is important to point out that the authors in [1] did not provide any particular expression for RNP nor how it can be implemented on WSN platforms. A first implementation of RNP was given by Liu et al. in [36]. In our work, we have borrowed the definition of RNP from TinyOS implementation [37]—especially data-driven link quality estimation. In this implementation, RNP is considered as a sender-side estimator, 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 [38] at the link-layer level, i.e.,

[1] Some radio transceivers do not provide LQI.

a node will repeat the transmission of a packet until it is correctly received. Note that a metric similar to 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. Cerpa et al. argued that RNP provides a better link quality characterization than PRR [1]. 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 [14].

The Expected Transmission Count (ETX) [33], and four-Bit [30] approximate the RNP. 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. Four-bit assesses link quality by combining two metrics through the EWMA filter. According the implementation of four-bit in TinyOS, combines beacon-driven estimate (estETX) and data-driven estimate (RNP), using the EWMA filter. RNP is computed based on *DLQ* transmitted/retransmitted data packets; and estETX is the inverse of smoothed PRR, minus 1. It is computed based on *BLQ* received beacons. 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.

Score-based: Some LQEs such as [21,39–42], provide a link estimate that does not refer to a physical phenomena (like packet reception or packet retransmission); rather, they provide a score or a label that is defined within a certain range. Examples of score-based LQEs are given next.

The Weighted Regression Estimator (WRE) is proposed in [39]. The authors derive a complex regression function that returns the link quality, giving the corresponding neighbor location. The DoUble Cost Field HYbrid (DUCHY) [40] 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 called *Channel State Information*(CSI). It 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. The Link Quality Ranking (LQR) is another score-based LQE [42] that allows to rank links based on PRR, SNR and LQI information and select the best one for data delivery. F-LQE, our introduced LQE, is score-based as it combines four metrics into a single score, ranging in [1...100], where 100 is the best link quality and 0 is the worst.

All the LQEs described above are either based on a single metric (e.g., PRR, RNP, WMEWMA, WRE and LQI), or combine several metrics (e.g., four-bit)—we call them composite LQEs. Single-metric LQEs are definitely inaccurate because they can only assess a particular link property and thus provide a partial characterization of the link [14,15]. Composite LQEs provide a more holistic link quality estimation by combining several link metrics. Each metric captures a particular link property.

2.4. Composite link quality estimators

The design of composite LQEs that combine several metrics encompassing different link aspects is a relatively recent concept. Two major design challenges arise: The first is how to derive appropriate metrics that capture important link properties. The second challenge is how to combine these metrics, giving that they do not necessarily have the same nature. Few research works addressed this problem [30,21,41,42].

The four-bit estimator combines RNP and the inverse of WMEWMA through EWMA filter [30]. However, it has the limitation of evaluating a single link aspect: the number of packet retransmissions. Further, four-bit relies on EWMA filter to combine two metrics that have different nature. Although filtering has been shown to be efficient in smoothing the link quality estimates and provides a metric that resists to transient link quality changes [43], exploiting it for combining different metrics can lead to unstable link quality estimation [14].

Rondinone et al. [21] suggest combining PRR and RSSI metrics in order to overcome the shortcomings of single metric LQEs, especially in what concern accuracy and stability. The combination is performed through the multiplication of PRR by the normalized average RSSI. The introduced LQE has two limitations: First, its accuracy and stability are conditioned by a large estimation window (250 packets), which means that it cannot quickly react to link quality changes. This observation has been partially confirmed by the authors. Second, the estimator does not provide a holistic characterization of the link as it ignores important link properties such as link asymmetry.

Boano et al. [41] propose the Triangle Metric that combines geometrically PRR, LQI, and SNR. The authors argued that each single metric has its own limitations and strengths. For example, Boano et al. observed that LQI is useful to estimate bad links but does not perform well for other kinds of links. The PRR is good for intermediate links, while it often misclassifies good links as intermediate. Hence, the Triangle Metric merges the strength of each individual metric into a more accurate metric. The idea behind the Triangle Metric seems promising but again, this LQE does not provide a holistic characterization of the link as it ignores important link properties such as link stability.

2.5. Discussion

In summary, existing LQEs can be classified as either hardware-based or software-based.

Hardware-based LQEs have been shown not sufficiently accurate (as discussed in Section 2.2). However, this does not mean that this category of LQEs is not useful. In fact, each of these LQEs provides a particular information of the link state, but none of them is able to provide a holistic characterization of the link quality. The combination of hardware metrics with software metrics can improve the accuracy of the link quality estimation [21,30,31,41,42]. For example, Fonseca et al. use LQI as a hardware metric to quickly decide whether the link is of good quality [30]. 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. confirm that LQI can accurately identify high quality links, but it fails to accurately classify intermediate links due to its high variance [31]. They exploited this observation to design LETX (LQI-based ETX), a link estimator that is customized for routing. Rondinone et al. also suggest combining hardware and software metrics though a multiplicative metric between PRR and RSSI [21], and Boano et al. propose a fast estimator suitable for mobile environments by combining geometrically PRR, SNR, and LQI [41]. F-LQE, the link estimator we propose combines SNR as a hardware-based metric with three other software-based metrics, as will be described next.

Software-based LQEs (PRR, RNP, or Score-based) can be either simple, i.e., based on a single metric, or composite, i.e., combines several metrics. Currently, there is a growing awareness that accurate link quality estimation cannot be achieved only through a composite LQE. Single-metric LQEs assess a particular link property and thus provide a partial characterization of the link. On the other hand, composite LQEs provide a holistic link characterization by combining several metrics; each metric captures a particular link property. Unfortunately, as discussed in Section 2.4, each of existing composite LQEs ignores a particular but important link property (e.g., stability or asymmetry), which leads to inaccurate link quality estimation.

The design of efficient LQEs requires a deep and clear understanding of low-power links, in order to identify the aspects that impact their quality [32]. Hence, we propose F-LQE, a composite LQE that considers four important link properties. Each of these properties is assessed by a convenient metric. The four different metrics are combined using Fuzzy Logic.

3. F-LQE: a fuzzy link quality estimator

3.1. Fuzzy logic for link quality estimation

The assessment of the quality of a radio link is a function of a number of metrics that are usually imprecisely estimated. Fuzzy logic provides a rigorous algebra for dealing with imprecise information. It is a mathematical discipline invented to express human reasoning in a rigorous mathematical notation. Unlike classical logic where a proposition is either true or false, fuzzy logic establishes the approximate truth value of a proposition based on linguistic variables and inference rules. Furthermore, fuzzy logic is a convenient method of combining conflicting objectives and expert human knowledge.

A linguistic variable is a variable whose values are words or sentences in natural or artificial language [44]. By using hedges like 'more', 'many', and 'few', and connectors like AND, OR, and NOT with linguistic variables, an expert can form rules, which will govern the approximate reasoning. In ordinary set theory, an element is either in a set or not in a set. In contrast, in fuzzy set theory, an element may partially belong to a set. A fuzzy set is defined as a class of objects with a continuum of grades of membership [45]. Formally, a fuzzy set A of a universe of discourse $X = \{x\}$ is defined as $A = \{x;\ \mu_A(x) | \forall x \in X\}$, where X is a space of points and $\mu_A(x)$ is a membership function of $x \in X$ being an element of A. In general, the membership function $\mu_A(.)$ is a mapping from X to the interval $[0,1]$. If $\mu_A(x) = 1$ or 0, $\forall x \in X$, then the fuzzy set A becomes an ordinary set [45].

Example: Packet delivery is an important link property whose goodness is highly correlated with the overall goodness of the link. It can be evaluated by the PRR link quality metric. Let PRR be the Packet Reception Ratio across a given link. According to classical logic, a link is declared good when its PRR is greater than a given threshold, say 0.95, and bad otherwise. For instance, given two different links, the first has a PRR equal to 95% and the second has a PRR equal to 94%. Classical logic declares only the first link as good. This example illustrates how PRR can only be imprecisely evaluated and classical reasoning fails to deal with such knowledge. Fuzzy Logic has been developed to handle this type of imprecise knowledge.

Let $x \in [0 \ldots 1]$ be a particular value of PRR and H be the fuzzy subset of links with high PRR. Then, for each x in the interval $[0 \ldots 1]$, $\mu_H(x)$ indicates the extent to which the link is considered having a high PRR, and $\mu_H(.)$ is the membership function of the fuzzy subset of links with high PRR. Packet delivery is considered as a fuzzy variable, which is expressed in linguistic terms such as low packet delivery and high packet delivery. The membership of the link in the Fuzzy set of high packet delivery links, is a matter of degree rather than a yes–no situation. It ranges in the interval $[0 \ldots 1]$. By recalling the previous example, the first link with PRR equal to 95%, can have a degree of membership in the fuzzy subset of high delivery links, equal to 1, whereas the second link with PRR equal to 94%, can have a degree of membership of 0.9. A possible membership function of high packet delivery links is illustrated in Fig. 2 (refer to $\mu_{SPRR}(.)$).

During the lifetime of a WSN, the quality of a wireless channel is usually a function of several imprecisely measured channel properties, as packet delivery, asymmetry, and stability. Because of their imprecise nature, each such property can be conveniently expressed in linguistic terms. E.g., a channel can be unstable, stable, and highly stable. Each such term is a linguistic value for the linguistic variable channel stability. The numerical interpretation of each linguistic value is defined in the form of a fuzzy subset, characterized by a particular fuzzy membership function. Now, suppose that we want to combine multiple link properties to properly assess the link quality, each such combination is performed by a Fuzzy IF-THEN Rule. A fuzzy rule combines the linguistic variables using connectors (operators) such as AND and OR. The evaluation of the rule using a fuzzy operator (e.g. Yager operator [46]) returns a membership degree that represents the link quality estimate.

We resort to Fuzzy Logic to estimate link quality and we propose F-LQE, which stands for Fuzzy logic-Link Quality Estimator. The goodness of the link depends on the goodness of its individual properties. Thus, the proposed LQE combines important link properties, expressed in linguistic terms, in a fuzzy rule. The evaluation of the fuzzy rule returns the degree of membership of the link in the fuzzy subset of good quality links. Next, we first identify the most important properties that greatly impact the overall quality of the link. Then, we present a Fuzzy Rule that combines these properties to better estimate link quality.

3.2. Link quality metrics

In this section, we identify four link quality metrics to be considered in the design of F-LQE [22]. Each metric describes an important link property. Selected link properties will be used in the next section to express the goodness of a given link.

Empirical studies such as [4,47–49] have shown that the transmission range is defined by three regions:

- The connected region, where links are often (1) of high packet delivery, i.e., PRR is greater than 90%, (2) stable, and (3) symmetric.
- The transitional region, where links are (1) of moderate packet delivery, i.e., PRR (in long-term assessment, e.g., based on 200 packets) is between 10% and 90%, (2) unstable, i.e. PRR (in short-term assessment e.g., based 5 packets) fluctuates between 0% and 100%, and (3) often asymmetric.
- The disconnected region, where links (1) have low packet delivery, i.e. PRR is less than 10%, and (2) are overall inadequate for communication.

From these observations, it can be easily inferred that three main properties characterize a link in WSNs: *Packet Delivery*, *Asymmetry*, and *Stability*. These properties can be assessed by software-based metrics such as PRR. On the other hand, *Channel Quality* is another important link property that is complementary to previous ones. It is assessed by hardware-based metrics and impacted by channel characteristics (interference, multi-path effects, etc.). Here, we make a difference between "channel quality" and "link quality". We define channel quality as a particular property of the communication link, which can be assessed by hardware-based metrics such as LQI and SNR. Link quality represents the overall quality of the communication link, as it takes into account all (or a set of) link properties, including channel quality property.

Next, we derive four link quality metrics for the evaluation of selected link properties, namely packet delivery, asymmetry, stability, and channel quality.

3.2.1. Packet delivery

Link packet delivery represents the capacity of the link to successfully deliver data. This property is captured by some existing LQEs such as PRR, WMEWMA, and ETX, but not by others, such as RNP. F-LQE accounts for the packet delivery of the link by a measure of SPRR, which stands for Smoothed PRR. Like WMEWMA, SPRR applies EWMA filter on PRR to smooth it, thus providing a metric that resists to transient fluctuation of PRRs, yet is responsive to major link quality changes. SPRR is then given by the following expression:

$$SPRR(\alpha, w) = \alpha \times SPRR + (1 - \alpha) \times PRR \tag{1}$$

where $\alpha \in [0 \ldots 1]$ controls the smoothness and w is the estimation window. We chose $\alpha = 0.6$ and $w = 5$, as suggested in [43]. Especially, the authors in [43] argue that the suggested value of α leads to a good balance between stability and reactivity to link quality fluctuations.

Although SPRR can accurately assess the link packet delivery property, it is not able to differentiate between a high delivery stable link, and a high delivery unstable link. Both links may have the same high delivery value, say 100%, but the first should be significantly better than the second. The first link is resilient to external effects and it typically belongs to the connected region. On the other hand, the second might be within the transitional region, where the received signal strength is weak so that any minor environmental change such as shadowing or interference can significantly change the link packet delivery. This example shows how it is important to assess link stability besides link packet delivery, in order to provide a more accurate link quality estimation. Next, we introduce the metric considered by F-LQE, for the assessment of link stability.

Note that playing on the value of α is not sufficient for SPRR to reflect the stability of the link. The reason is that SPRR is an average quantity. We need to make use of a metric that takes into account the variability in the data through its standard deviation.

3.2.2. Stability

Link stability (or variability) is of a paramount importance for network protocols that preferably forward data over stable links in order to minimize retransmissions and topological changes. F-LQE assesses the stability of the link by the measure of the coefficient-of-variation of PRR, noted as SF (Stability Factor):

$$SF = \frac{\sigma_{PRR}}{\mu_{PRR}} \tag{2}$$

where σ_{PRR} is the standard deviation of n measured $PRRs$, and μ_{PRR} is the mean of n measured $PRRs$.

SF is basically computed based on a history of 30 *PRRs*. We choose 30 as the history length to ensure a certain confidence for the computation of the coefficient of variation.[2] Nevertheless, at network startup, we anticipate the computation of SF by considering only a history of 5 *PRRs*. As long as packets are received, the PRRs history is fed back at every new measure of PRR, until collecting the 30 PRRs values. Once, a history of 30 *PRRs* is collected, we adopt the concept of "sliding window", for the update of the PRR history vector at each new measure of PRR.

The combination of SF and SPRR allows to assess the link packet delivery while taking into account its stability level. Now, let us consider two links, both having high delivery and high stability level. Further, the first link has

[2] For example, we observed that the magnitude of 95% confidence interval around estimated μ_{PRR} was around 4% of PRR, which is a good precision.

low asymmetry level while the second has high asymmetry level which makes some acknowledgment packets not reaching the transmitter. Consequently, the second link involves more MAC retransmissions for packet delivery. Hence, it is clear that although both links have high delivery and high stability, the second link appears better than the second due to its low asymmetry. This example illustrates how packet delivery and stability are not sufficient to accurately identify good links. Next, we introduce the metric considered by F-LQE, for the assessment of link asymmetry level.

3.2.3. Asymmetry

Link asymmetry is the difference in connectivity between the forward link and the backward link. Communication between sensor nodes is usually bidirectional. Empirical studies such as [4] have shown that links asymmetry is due to the discrepancy in terms of hardware calibration, i.e. nodes do not have the same effective transmission power, reception sensitivity and noise floor. Therefore, it is not sufficient to estimate the link quality as the quality of the link in one direction. While some LQEs, such as ETX and four-bit, take into account link asymmetry, other estimators including PRR, *WMAWMA* and RNP, do not. F-LQE takes into account link asymmetry by measuring the difference between PRR of the forward link ($PRR_{forward}$) and the PRR of backward link ($PRR_{backward}$), noted as ASL (ASymmetry Level):

$$ASL(w) = |PRR_{forward} - PRR_{backward}| \tag{3}$$

$PRR_{forward}$ is gathered from each received packet and stored in the neighbor table, with respect to each neighbor node. Based on w received packets, the node computes $PRR_{backward}$, gets $PRR_{forward}$ from the neighbor table, and then computes ASL according to Eq. (3). The ASL metric gives an idea on whether a transmitted packet can be acknowledged or not. In fact, for a given sender, when the forward is of high PRR and the backward is of bad PRR, a correctly received packet would not be acknowledged or at least acknowledged after a certain number of retransmissions. The ASL captures this effect, which cannot be detected by the PRR or SPRR alone.

ASL, SF, and SPRR represent software-based metrics. Several studies such as [50,28], argued that hardware-based

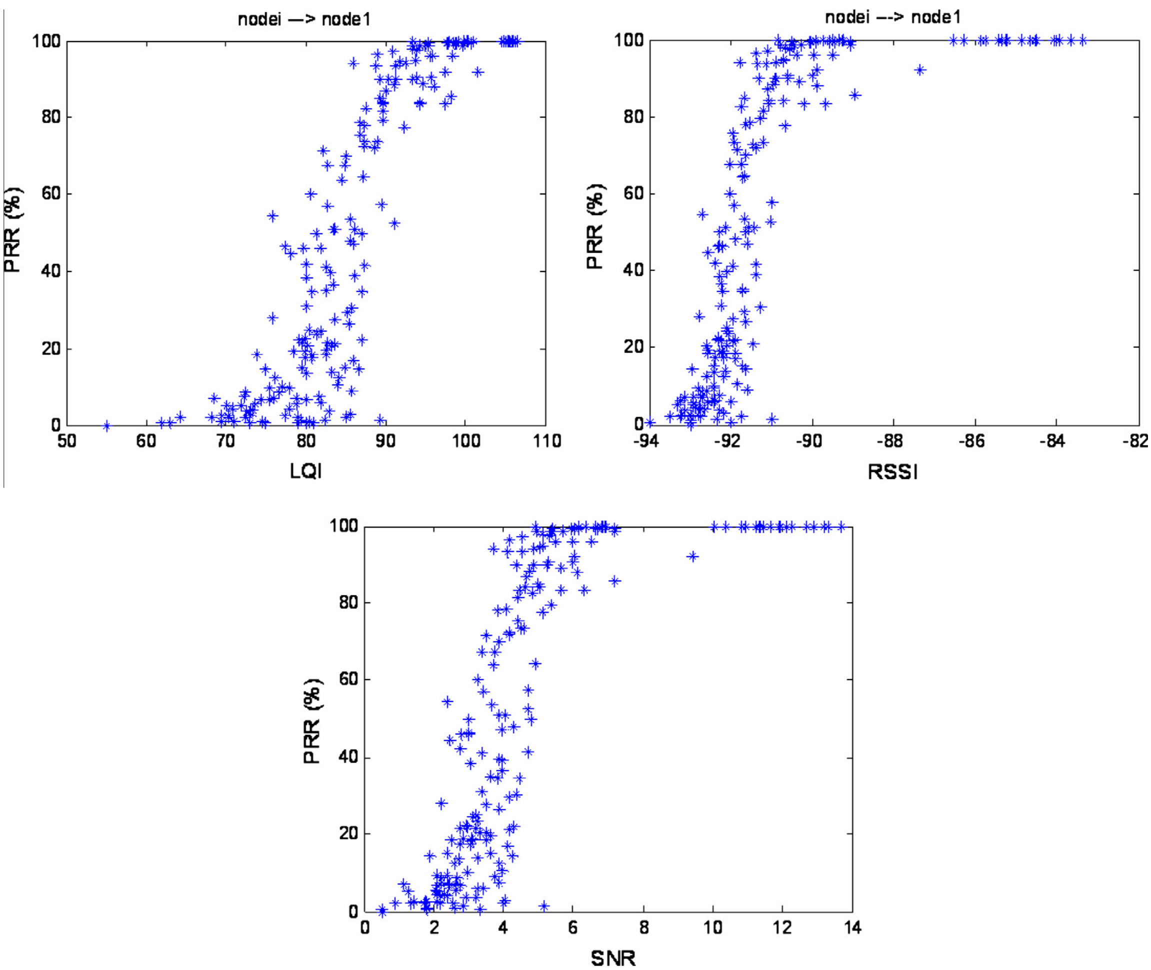


Fig. 1. Hardware-based metrics as a function of PRR. These curves are obtained from real experimentation (Experiment settings can be found in Table 2 – Default Setting). PRR metric cannot differentiate between "very good" and "good" links, while hardware-based metrics can differentiate between "very good" links and the rest of links.

metrics, such as SNR, RSSI, and LQI, are inaccurate when used individually, but their integration to software-based metrics improve their accuracy. In other words, hardware-based and software-based metrics are complementary. Particularly, hardware-based metrics are convenient to evaluate the channel quality.

To illustrate this fact, we have analyzed the curves in Fig. 1. These curves illustrate hardware-based metrics, namely LQI, RSSI, and SNR as a function of PRR. Each measure of LQI, RSSI, or SNR is an average over w values, where w is also the estimation window of PRR, set to 200 packets. Fig. 1 shows that PRR metric cannot differentiate between "good" and "very good" links as both have high PRR (e.g., 100%). On the other hand, hardware-based metrics (e.g., SNR) can only differentiate between "very good" links and the rest (due to different values of SNR). For example, consider two links having perfect packet delivery, i.e., PRR equal to 100%. The first link has SNR equal to 13 dB and the second has SNR equal to 6 dB. According to PRR, both links are of "very good" quality. This classification is not correct if we take into consideration the SNR: The first link should be of "very good" quality as it belongs to the connected region, while the second link is of "good" quality as it is in the border of the transitional region. A link in the transitional region is susceptible to drop considerably with a small change in the noise floor.

3.2.4. Channel quality

F-LQE assesses channel quality based on either SNR or LQI, averaged over w received packets to get ASNR (Average SNR) or ALQI (Average LQI) respectively. SNR and LQI are better than RSSI as reported in several studies such as [32]. SNR is better than LQI because (i) it does not have a maximum value, which permits a finer grained classification of links and (ii) it can better identify very good quality links as depicted in Fig. 1. However, SNR involves additional delay as it is computed in three steps: (i) sampling the RSSI at packet reception to get the received signal (S), (ii) sampling the RSSI just after packet reception to get the noise floor (N), and (iii) subtracting N from S to get SNR. On the other hand, LQI is computed in one operation, just by sampling the LQI at packet reception. In the first experimental study (refer to Section 4), this limitation of SNR does not matter as LQEs (including SNR) are computed off-line, after the experiment finishes, based on collected link measurements. Thus, in this study, we choose ASNR for channel quality assessment. In the second experimental study (refer to Section 5), LQEs are derived by the routing protocol during network runtime to make quick decision about link quality. Consequently, ALQI is better than ASNR in this context as it provides a more quick decision about the channel link quality.

For the remainder of this section, we choose ASNR as link quality metric for the channel assessment.

3.3. Combination of link quality metrics

3.3.1. Fuzzy rule

F-LQE considers each of the link properties mentioned in the previous section as a different fuzzy variable. The goodness (i.e. high quality) of a link is characterized by the following rule:

IF the link has *high packet delivery* AND *low asymmetry* AND *high stability* AND *high channel quality* **THEN** it has *high quality*.

Here, *high packet delivery*, *low asymmetry*, *high stability*, *high channel quality*, and *high quality* are linguistic values for the fuzzy variables packet delivery, asymmetry level, stability, channel quality, and quality (refers to link quality).

In order to produce a numerical value of the link quality, the above rule should be translated to a mathematical expression. This is done according to a fuzzy algebraic interpretation of the fuzzy logic operator (AND and OR). Instead of using the min–max logic of Lotfi Sadeh [44], where the AND (OR) is interpreted as a min (max) operator, we used the Yager AND-like and OR-like operators [46]. The reason is that the original min–max operators are non-compensatory, where only a fuzzy subset dominates (the smallest for AND, and largest for the OR fuzzy operator). On the other hand, the Yager AND-like and OR-like operators are compensatory, where in the resulting translated expression, all the fuzzy subsets are accounted for, according to a weight factor β. Hence, using and-like compensatory operator of Yager, the above rule translates to the following equation of the fuzzy measure of the link i high quality.

$$\mu(i) = \beta \cdot min(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) + (1 - \beta) \cdot mean(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) \quad (4)$$

The parameter β is a constant in [0...1]. Recommended values for β are in the range [0.5...0.8] where 0.6 usually gives the best results [51].

3.3.2. Membership functions

All membership functions have piecewise linear forms and then have low computation complexity. They are determined by two thresholds, as it is shown by Fig. 2.

The choice of the two thresholds, for the membership functions μ_{SPRR} and μ_{ASL} can be tuned according the application requirements. We have chosen reasonable values of these thresholds, with respect to each membership function. For μ_{SPRR}, for values of SPRR below 25%, the link is considered totally out of the fuzzy subset of links with high packet delivery. Starting from 95%, the membership to the fuzzy subset of links with high packet delivery is of 1. For values of SPRR between 25% and 95%, the membership increases linearly from 0 to 1. The same reasoning holds for μ_{ASL}.

The membership function μ_{SF} differs slightly from the other ones as the two thresholds are superposed. A link has 1 as membership to the fuzzy subset of links with high stability, only when the measured SF is equal to 0. For SF values greater than 0, the link membership decreases linearly to achieves 0 when SF is equal to 0.7. The value 0.7 has been chosen by analyzing the SF of all experienced links in our experimental study. Experiments were conducted under different network conditions (refer to Table 2). We generate the curves SF/*Distance* and the empirical CDF of SF, for each network setting. Fig. 3 shows these curves

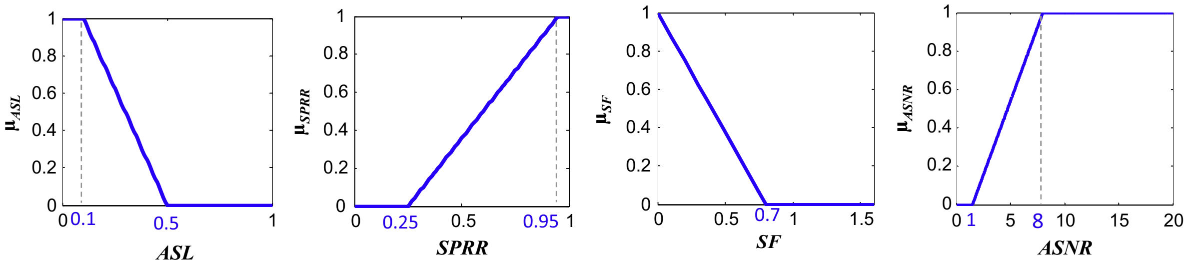


Fig. 2. Definition of membership functions.

Table 2
Experiment scenarios. Burst(N, IPI, P) and Synch(W, IPI); N: Number of packets per burst, IPI: inter-packets interval, P: number of bursts, W: total number of packets.

	Traffic Type	Pkt size	Channel	Rtx count
Scenario 1: Impact of Traffic	{Burst(100, 100, 10), Burst(200, 500, 4), Burst(100, 1000, 2), Synch(200, 1000)}	28	26	6
Scenario 2: Impact of Pkt Size	Burst(100, 100, 10)	{28, 114}	26	6
Scenario 3: Impact of Channel	Burst(100, 100, 10)	28	{20, 26}	6
Default Settings	Burst(100, 100, 10)	28	26	6

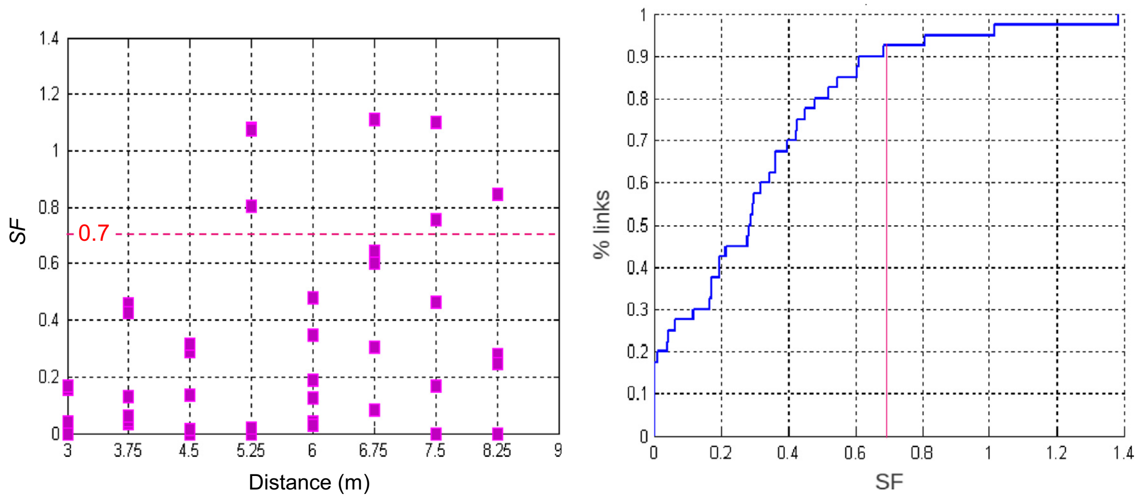


Fig. 3. SF threshold determination based on curves obtained from real experimentation (Experiment settings can be found in Table 2 – Default Setting)). Most of links (92%) have SF less than 0.7. Hence, a link that has SF superior or equal to 0.7 is considered as instable.

for the default setting. We have noticed that most of links (92%) have SF less than 0.7. In other words, a link that has SF superior or equal to 0.7 is considered as unstable (i.e., the membership level of the link in the fuzzy subset of stable links is equal to 0).

The choice of the two thresholds for the membership function μ_{ASNR} depends on the environment and the hardware characteristics. In what follow, we present a detailed analysis for an efficient determination of these two thresholds.

In previous empirical studies, such as [28], based on the PRR/SNR curve, the existence of two SNR thresholds has been proven. When SNR is larger than the first threshold, the PRR is greater than 95% almost all the time, which implies good channel quality. If SNR is less than the second threshold, the PRR is lower than 25% most of the time and the channel quality is bad. These thresholds are determined from the PRR/SNR curve, which is in turn determined experimentally. In fact, each measure of SNR in the PRR/SNR curve is an average over w values, where w is also the estimation window of PRR. In the rest of this section we note this SNR measure as ASNR. In order to gather this curve, we carried out a set of experiments. Experiments were conducted under different network conditions (refer to Table 2). We generate the PRR/SNR curve for each network setting and we set w to 200 packets.

Fig. 4 depicts the PRR/SNR curve for the default setting. The convenient choice of the two ASNR thresholds can be

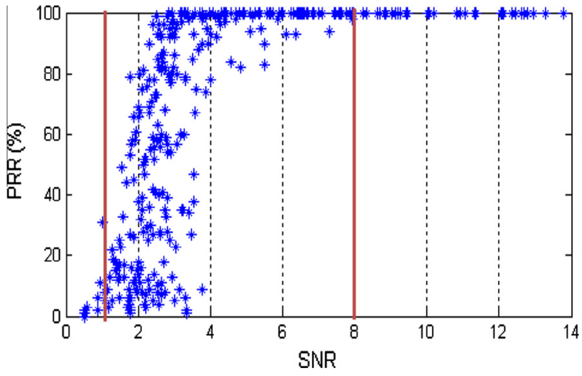


Fig. 4. PRR/SNR curve obtained from experimentation with RadiaLE testbed [15] (Experiment settings can be found in Table 2 – Default Setting)). For ASNR greater than 8dBm, the PRR is equal to 100%, and for ASNR less than 1 dBm, the PRR is less than 25%. In between, a small variation in the ASNR can cause a big difference in the PRR; links are typically in the transitional region.

easily inferred from this curve (1 dBm and 8 dBm). Notice that these thresholds are the same for all PRR/SNR curves (settings), as we found that the curves have similar shapes.

3.3.3. F-LQE expression

The final step toward F-LQE computation is detailed in this section. We consider the following link quality metric (LQ):

$$LQ(w) = 100 \cdot \mu(i) \tag{5}$$

LQ combines SPRR, ASL, SF and ASL to provide a comprehensive assessment of the link. It attributes a score to the link, ranging in [0...100], where 100 is the best link quality and 0 is the worst. Using EWMA filter, we smooth *LQ*to get the F-LQE metric:

$$FLQE(\alpha, w) = \alpha \cdot FLQE + (1 - \alpha) \cdot LQ \tag{6}$$

where $\alpha = 0.9$, to provide stable link quality estimates. Notice that w is the estimation window, meaning that a node estimates link quality, i.e. computes F-LQE, based on each w received packets.

Eq. (5) assumes that the mote has available data to compute the SF and the ASL. However, SF can be computed only when the mote has at least 5 measures of PRR and ASL can be computed only when the mote has both forward and backward *PRRs* (refer to Eq. (4)). Therefore, we introduced a simple mechanism that consists in the following: a node wishes to estimate link quality by considering different link properties, evaluated by the SPRR, ASNR, ASL, and SF. When one or both ASL and SF cannot be computed due to the lack of some data (this occurs at the startup of the network only), the node ignores the corresponding metric(s) in the computation of the membership function $\mu(i)$ in Eq. (5). For instance, when the node is not able to compute both ASL and SF, $\mu(i)$ in Eq. (5) becomes:

$$\mu(i) = \beta \cdot min(\mu_{SPRR}(i), \mu_{ASNR}(i)) + (1 - \beta) \cdot mean(\mu_{SPRR}(i), \mu_{ASNR}(i)) \tag{7}$$

Notice that four-bit LQE considers packet delivery and asymmetry properties like F-LQE. However, asymmetry is evaluated differently by the two LQEs: four-bit dos not explicitly evaluate link asymmetry through a given metric. Rather, it considers link asymmetry property by combining outbound link information (i.e., RNP) and inbound link information (i.e., inverse of smoothed PRR) through EWMA filter. On the other hand, F-LQE explicitly evaluates link asymmetry through ASL metric. Also link properties are combined differently: F-LQE combines them based on a rigorous algebra, namely Fuzzy Logic, whereas four-bit relies on EWMA filter to combine two metrics that have different nature. Exploiting EWMA filtering for combining different metrics can lead to unstable link quality estimation [14].

Also note that four-bit metric does not consider channel quality property in its computation. Nevertheless, as it is designed to be used by routing protocols, it provides four bits of information, compiled from different layers. Especially, the white bit from the physical layer allows to quickly identify good quality links, based on channel quality assessment (through LQI measurement).

4. Performance analysis of F-LQE

In this section, we demonstrate the effectiveness of F-LQE by comparing its performance in terms of *reliability* and *stability*, with a set of well-known LQEs, namely PRR, WMEWMA, ETX, RNP, and four-bit, based on real experimentation. We would like to mention here that the experimental results reported in this section confirm extensive simulation results obtained using TOSSIM.[3]

4.1. Evaluation methodology

In link quality estimation, there is a lack of a real metric of reference based on which the accuracy of LQEs can be assessed. In fact, in classical estimation theory an estimated process is typically compared to a real known process using a certain statistical tool (e.g. least mean square error or regression analysis). However, such comparison is not possible in link quality estimation, since: (1) there is no metric that is considered as the "real" one to represent link quality; and (2) link quality is represented by quantities with different natures, since some estimators are based on the computation of PRR, some others are based on RNP and some others would be hybrid and more complex. Therefore, it turns out that the performance evaluation of LQEs is not a trivial problem.

The evaluation methodology that we propose consists in analyzing the statistical properties of LQEs, independently of any external factor, such as collisions (each node transmits its data in an exclusive time slot) and routing (a single-hop network). These statistical properties impact the performance of LQEs, in terms of:

- **Reliability**: It refers to the ability of the LQE to correctly characterize the link state. The reliability of LQEs is assessed *qualitatively*, by analyzing (i) their temporal

[3] Details of the simulation scenarios and results are omitted for space limitations and because the simulation results match pretty well the experimental results, as reported in [15].

behavior, and (ii) the distribution of their link quality estimates, illustrated by the scatter plot and the empirical cumulative distribution function (CDF).

- **Stability**: It refers to the ability to resist to transient (short-term) variations (also called fluctuations) in link quality. The stability of LQEs is assessed *quantitatively*, by computing the coefficient of variation (CV) of the link quality estimates. It is important to note that stability does not mean that the LQE is not reactive to persistent changes in link quality. Indeed, these changes should be captured by the LQE. Only transient link fluctuations are tolerated by a stable LQE.

4.2. Experiments description

In our experiments, we have deployed a single-hop network with 49 TelosB motes [27], $N_1, \ldots, N_{49}$, positioned in an outdoor environment (a garden at the university). The motes are distributed in a radial topology (refer to Fig. 5). In this topology, 48 motes are divided in 8 sets with different radius. Each set contains 6 nodes, all placed in a circle around the central node N_1. The distance between two consecutive sets is equal to Y, where Y is set to 0.75 m. The first set, i.e. the nearest circle to N_1, has a radius of X meters, where X varies in $\{2,3\}$.

In this study, we propose to estimate the quality of the unidirectional links $N_1 \leftarrow N_i$. Since distance and direction are fundamental factors that affect link quality, we argue that by placing the nodes $N_2 \ldots, N_{49}$ at different distances and directions from the central node N_1, the underlying links, $N_1 \leftarrow N_i$, exhibit different qualities. Particularly, we choose convenient X and Y values so that the links have diverse qualities to better explore the performance of *F-LQE* as well as the other LQEs under evaluation. By observing all the links we have 47% of links of intermediate quality (i.e., the average PRR is between 10% and 90%); 32% of links of high quality (i.e., the average PRR is greater than 90%); and 21% of links of poor quality (i.e., the average PRR is less than 10%).

After receiving the token, each couple of nodes (N_1, N_i), exchanges a certain number of data packets then passes the token to the next couple, (N_1,N_{i+1}). We considered two traffic patterns: *Bursty traffic* and *synchronized traffic*: For the Bursty traffic, after receiving a command from the PC, N_1 sends a first burst of packets to N_i. When it finishes, it sends a notification to the PC, which in turn sends a command to N_i requesting it to send its burst of packets to N_1. When N_i finishes sending, it notifies the PC. This operation is repeated for a certain number of bursts. As for the synchronized traffic, N_1 and N_i are synchronized to exchange packets (one packet a time). The PC sends a command to each mote to indicate the beginning of transmission time so that the mote sends its data in an exclusive time slot (to avoid collisions).

Based on exchanged data, the quality of links $N_1 \leftarrow N_i$ has been estimated using F-LQE, as well as PRR, WMEWMA, ETX, RNP, and four-bit. We subject LQEs to different network conditions. In fact, we performed extensive experimentations through different experiments sets. In each experiments set we varied a certain parameter to study its impact, and for each parameter modification the experiment was repeated. Parameters under consideration were traffic type (3 sorts of burst and 1 synch), packet size (28/114), and channel (20/26). The duration of each experiment was approximately 8 h. Table II depicts the different settings for each experiments set. The transmission power was set to the minimum, -25 dBm, in order to reach the transitional region at shorter distances.

Like F-LQE, four-bit and WMEWMA use EWMA filter, which has an important parameter: the history control factor α. We chose $\alpha = 0.9$ for *four-bit*, as in [30], and $\alpha = 0.6$ for *WMEWMA*, as suggested in [43]. The estimation window w is a common parameter for all LQEs. In our study, we chose a small window, equal to 5 packets, for short-term link quality estimation. The same value of w is adopted in [30]. Further, in [52], it has been argued that short-time link quality estimation captures link dynamics at a high resolution in time.

4.3. Experimental results

In this section, we present the experimental results related to the performance comparison of F-LQE with State-Of-the-Aart LQEs, namely PRR, WMEWMA, ETX, RNP, four-bit and F-LQE, in terms of reliability and stability.

We point out that we collected empirical data from the 48 links of our Radial topology. Furthermore, we repeated the experiments twice; for $x = 2$ and $x = 3$. In total, we obtained empirical data from $48 * 2 = 96$ bidirectional links.

4.3.1. Reliability

The reliability of F-LQE is tested by studying (i) the distribution of link quality estimates (Fig. 6 and (ii) the temporal behavior (Fig. 7).

Link quality estimates distribution: Recall that in our experiments, we set the links to have diverse qualities (see Section 4.2 for more details). Fig. 6 presents link quality estimates distribution (represented by the global empirical CDF), with respect to each LQE. We do not know the actual distribution of links. However, we can affirm that a LQE that considers most of the links of high quality or of poor quality is unreliable because this is in contradiction with the experimental scenario that set 32% of the links of high quality and 21% of the links of poor quality. A good LQE should classify the links close to the proportions set in the experimental scenario.

Fig. 6 shows that PRR, WMEWMA, and ETX, which are PRR-based LQEs,[4] overestimate the link quality. For instance, this figure shows that almost 80% of links in the network have a PRR and WMEWMA greater than 84% (which is considered a high quality value). Also 75% of the links have ETX equal to 1, (i.e. 0 retransmissions, which also means high quality). The reason of this overestimation is the fact that PRR-based LQEs are only able to evaluate the link delivery, and they are not aware of the number of retransmissions made to deliver a packet. A packet that is lost after

[4] Here, PRR-based means that the computation of these LQEs is based on a single metric, the PRR.

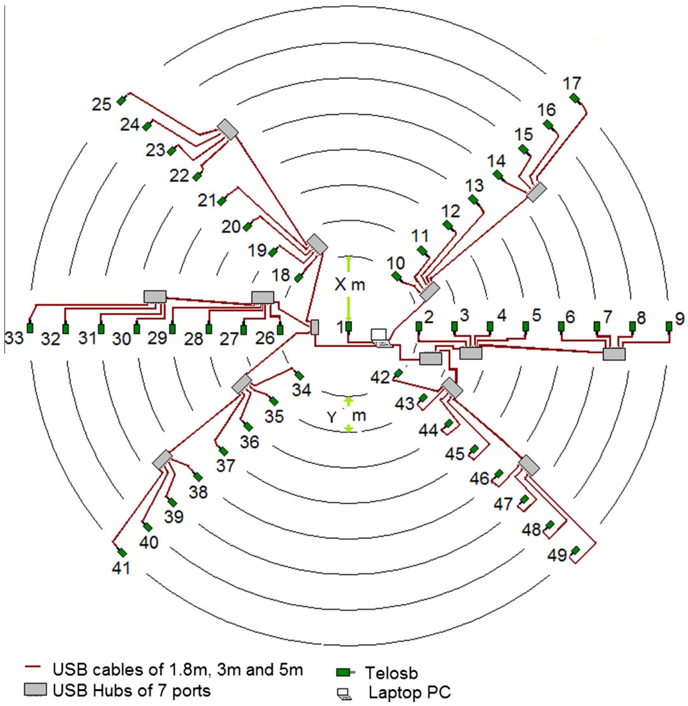


Fig. 5. Experimental test-bed for the performance evaluation of F-LQE - nodes forming a radial topology.

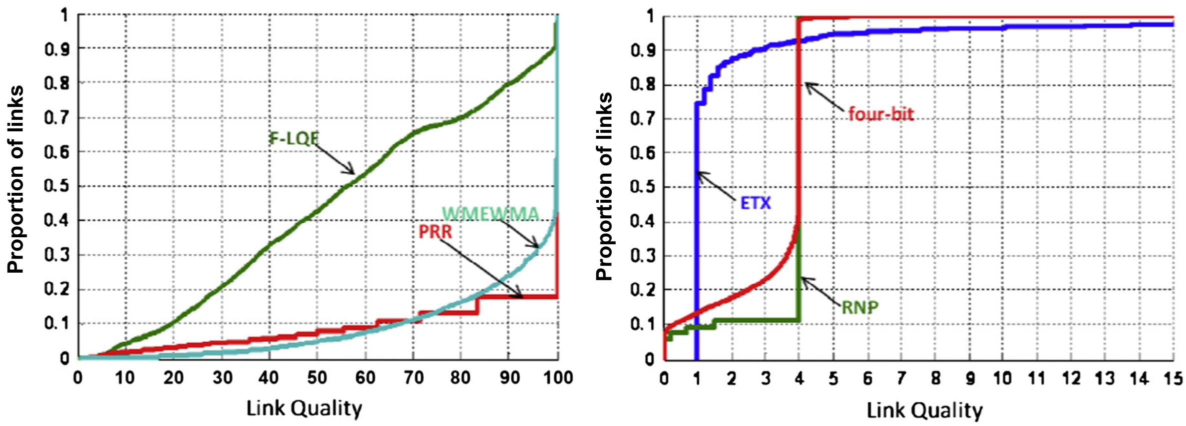
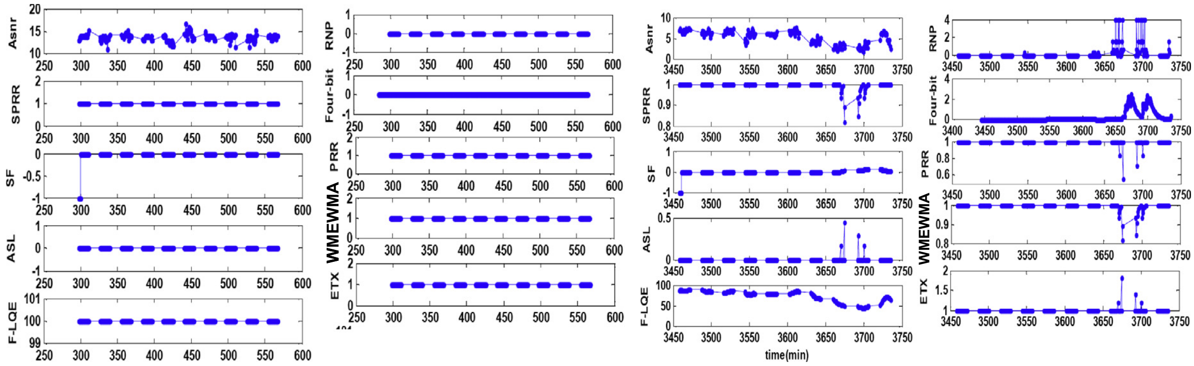


Fig. 6. Empirical CDFs of LQEs (Default Setting). In contrast to traditional LQEs, the distribution of F-LQE estimates is near to uniform distribution, which means that F-LQE is able to distinguish between links having different link qualities.

one retransmission or after n retransmissions will produce the same estimate. Fig. 6 also shows that four-bit and RNP, which are RNP-based, underestimate the link quality. For example, almost 90% of the links have RNP equal to 4 retransmissions (maximum value for RNP), which means that the link is of very bad quality. We observe that Four-bit provides a more balanced characterization of the link quality than RNP, since its computation also accounts for PRR. This underestimation of RNP and four-bit is due to the fact that they are not able to determine if these packets are received after these retransmissions or not. This discrepancy between PRR-based and RNP-based link quality estimates is justified by the fact that most of the packets transmitted over the link are correctly received (high PRR) but after a certain number of retransmissions (high RNP). More importantly, each of these LQEs assess a single and different link property (either packet reception or number of packet retransmission). For example, they ignore other important properties such as link stability or channel quality.

As a conclusion, conventional LQEs are not sufficiently reliable as they consider most of the links either of high quality (overestimation) or of poor quality (underestimation). On the other hand, Fig. 6 shows that the distribution of link quality estimates for F-LQE is nearly a uniform distribution. This means that F-LQE estimated equally well



(a) Very Good Link (b) Good Link

Fig. 7. Temporal behavior of LQEs when faced with links with different qualities (Default Setting). All LQEs estimate the link in Fig.8(a) as of very good quality. However, only F-LQE can distinguish between a good link (Fig.8(b)) and a very good link (Fig.8(a)).

link quality for all link quality ranges. The reason is that F-LQE takes into account different properties of radio links, namely reception ratio, stability, asymmetry, and channel quality, which provides a more holistic characterization of the link.

Temporal Behavior: Fig. 7 shows how F-LQE outperforms existing LQEs because they are not able to distinguish between links, especially good links and very good links. Let us observe the temporal behavior of the link in Fig. 7, until the time 3660 min (just before the link quality fluctuation). PRR, WMEWMA, and ETX are based on PRR in their computation. They account for only one property: link delivery for PRR and WMEWMA; and packet retransmissions for ETX. These LQEs declare the link as of very good quality (i.e., 100% of packet delivery and 0 retransmissions). The same link quality state is declared by RNP and four-bit, which also account for a unique link property: packet retransmissions. However, our link should not have a very good quality due to the low ASNR values. In fact, the measured ASNR values are close to the receiver sensitivity, which means that the link is in the transitional region and thus should not be of very good quality as suggested by these LQEs. The good properties of the link that have been captured by these LQEs (i.e., 100% of packet delivery and 0 retransmissions), are due to the constructive interference effect.

F-LQE detects the real link state by combining different link properties, especially ASNR which is responsible of preventing the link from being declared as "very good". Hence, F-LQE provides a high but not a maximum score. Indeed, the link shown in Fig. 7 has some very good properties, including the delivery, the asymmetry and the stability, yet it has a moderate channel quality which make of it a good link but not a very good link.

In summary, we have shown that traditional LQEs, including PRR, WMEWMA, ETX, RNP and four-bit are not sufficiently reliable, as they either overestimate or underestimate link quality. On the other hand, F-LQE, is more reliable as it provides a fine grain classification of links.

4.3.2. Stability

A link may show transient link quality fluctuations due to many factors mainly related to the environment, and also to the nature of low-power radios, which have been shown to be very prone to noise. LQEs should be robust against these fluctuations and provide stable link quality estimates. This property is of a paramount importance in WSNs. 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.

To reason about this issue, we measured the sensitivity of the LQEs to transient fluctuations through the coefficient of variation of their estimates. Fig. 8 compares the sensitivity (stability) of LQEs, with respect to different settings (refer to Table 2). According to this figure, we retain the following observations. 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 filtering to smooth PRR and RNP respectively. Third, except ETX, PRR-based LQEs, i.e. PRR and WMEWMA, are generally more stable than RNP-based LQEs, i.e. RNP and four-bit. ETX is PRR-based, 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.

5. On the use of F-LQE for improving collection tree routing

Improved link quality estimation in WSNs should result in a more optimized network operation. In this section, we demonstrate the applicability and usefulness of F-LQE by assessing its impact on the performance of the Collection Tree Protocol (CTP) [8]. We propose a routing metric based on F-LQE, which we call F-LQE/RM. F-LQE/RM uses link quality estimates provided by F-LQE to select the best path in terms of global quality as well as length, i.e. hop-count. Then, in Section 6, we investigate the impact of F-LQE/RM on the performance of CTP, based on an extensive set of experiments performed over two widely used WSN testbeds. Further, we compare the impact of F-LQE/RM to that of four-bit, the default metric of CTP, as well as ETX [33]. Both four-bit and ETX are considered by the WSN community as representative and reference metrics.

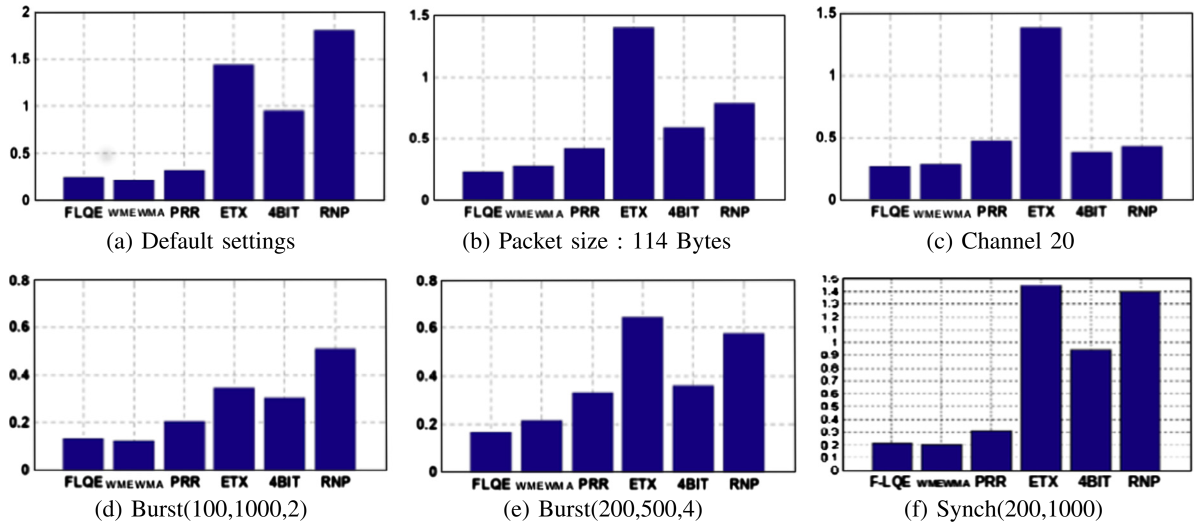


Fig. 8. Sensitivity to transient fluctuation in link quality, for different network settings. Generally, F-LQE is more stable than traditional LQEs.

5.1. F-LQE/RM: Fuzzy Link Quality Estimator-based Routing Metric

Routing metrics design is critical for the performance of routing protocols. Our goal is to design a routing metric based on F-LQE. Such design has three main requirements:

- First, the routing metric should correctly evaluate the path cost based on individual link costs, i.e., F-LQE link quality estimates. This requirement should be carefully addressed as F-LQE is a link based metric whereas route selection needs a path based metric.
- Second, path cost evaluation should carefully trade-off both path length (number of hops) as well as the quality of individual links composing the path. A long path composed of good quality links may be better than a much shorter path with a low quality link. Short paths reduce the number of transmissions but low quality links increase packet retransmissions and tree instability.

In order to fulfill the above requirements, we define F-LQE/RM as follows:

$$FLQE/RM(Path) = \sum_{i \in Path} \frac{1}{FLQE_i} \tag{8}$$

$\frac{1}{FLQE_i}$ is the cost of link *i*. Thus F-LQE/RM defines the path cost as the sum of the link costs. The path having minimal cost is selected. F-LQE/RM takes into account the path global quality and implicitly favors the selection of short paths. Indeed, by defining the link cost as $\frac{1}{FLQE_i}$ instead of $FLQE_i$, the longer the path (more hops), the more costly it becomes and the lower the chances of being selected. The link cost definition also improves the effectiveness of the F-LQE/RM by avoiding paths having low quality links: the poorer the link quality, the more costly it becomes, which impacts the overall path cost and reduces the probability of that path being selected.

5.2. Integration of F-LQE/RM in CTP

CTP is the network layer reference protocol of TinyOS 2.x. [8]. Due to its modularity, and also the fact that it relies on a link quality based routing metric, we use it as a benchmark for analyzing the impact of different link quality based routing metrics on routing performance.

CTP establishes and maintains a routing tree, where the tree root is the ultimate sink node of the collected data. CTP implementation contains three basic components: (i) link estimator, which is based on the Link Estimation Exchange Protocol (LEEP) [37] and four-bit [30], (ii) routing engine, which is responsible for the establishment and maintenance of the routing tree for data collection, and (iii) forwarding engine, which is responsible for queueing and scheduling outgoing data packets.

To integrate F-LQE/RM in CTP, we have implemented F-LQE in the Link Estimator component, as a replacement of the four-bit estimator.

ALQI for channel quality assessment: As reported in Section 3.2, two metrics are feasible for the assessment of channel quality in F-LQE, namely ASNR and ALQI. Based on our experiments, we confirm that ALQI is better than ASNR in the context of routing. For example, based on experiments with MoteLab testbed, we found that ALQI based F-LQE leads to significantly better routing performance than ASNR based F-LQE (e.g., in terms of end-to-end packet delivery: 0.95 vs. 0.84). Therefore, we consider ALQI for channel quality assessment in F-LQE integration for CTP.

Beacon-driven link quality estimation: F-LQE combines four metrics, SPRR, ASL, SF, and ASNR, which are computed at the receiver side, i.e., based on received traffic. Our implementation of F-LQE leverages on broadcast control traffic (i.e., beacons), which is initiated by CTP routing engine for the topology control. F-LQE can be also implemented based on data traffic, which requires the overhearing of incoming packets.

CTP uses an adaptive beaconing rate that changes according to the topology consistency. We disabled this mechanism and we used a constant beaconing rate of 1 beacon/s, so that beacon-driven LQEs such as F-LQE, ETX and partially four-bit, can be updated periodically.

Link direction: In CTP tree routing, data travel from child to parent. In order to select their parents, child nodes need to assess forward links, i.e., $child \rightarrow parent$ links. Although F-LQE takes into consideration link asymmetry through ASL metric, it evaluates the reverse link, i.e., $parent \rightarrow child$ link (because each of SPRR, SF, and ASNR provide reverse link estimate). Considering the reverse link estimate to decide about the forward link for parent selection leads to misleading routing decisions. Therefore, we define two F-LQE estimates: F-LQE$_{in}$ and F-LQE$_{out}$. F-LQE$_{in}$ is the F-LQE for the reverse link, (i.e., inbound link). It is computed by each node, based on incoming beacons. F-LQE$_{out}$ is the F-LQE for the forward link, (i.e., outbound link) and it is gathered from received packets. F-LQE$_{in}$ and F-LQE$_{out}$ are stored in the neighbor table, with respect to each neighbor node. CTP defines a list of neighbor entries, that is included in the footer of each sent packet. In our implementation, a neighbor entry is composed of the neighbor address, PRR$_{in}$, and F-LQE$_{in}$. When a node receives a packet, it extracts PRR$_{in}$, and F-LQE$_{in}$ and stores them in its neighbor table, specifically in PRR$_{out}$, and the F-LQE$_{out}$ fields.

Link Estimator component is used by the Routing engine to get the link cost. For F-LQE/RM, the link cost is $\frac{1}{F-LQE_{out}}$.

Parent update: Nodes update their parents, when the new parent is better than the current one by *ParentChThresh*. This constant parameter depends on the routing metric. We set it to 4 for F-LQE/RM based on several experiments with different ParentChThresh values. We retained the value that led to the best routing performances. Note that the *ParentChThresh* for four-it is equal to 1.5.

Routing engine: Like four-bit, F-LQE/RM selects parents that lead to minimal path costs, where a path cost is the sum of its link costs. Hence, the implementation of F-LQE/RM does not require major modifications in the Routing Engine component.

6. Experimental evaluation of F-LQE/RM in CTP

6.1. Evaluation methodology

The goal of our experimental study was to investigate the impact of F-LQE/RM on the performance of CTP using real WSN platforms. Further, we compare the impact of F-LQE/RM to that of four-bit, the default metric of CTP, as well as ETX [33]. Both four-bit and ETX are considered by the WSN community as representative and reference routing metrics.[5] Hence, we implemented two versions of CTP; in each version, we replaced the default four-bit based routing metric by F-LQE/RM or ETX. Then, we conducted different experiments with each of the three CTP versions (including the original version with four-bit). In each experiment we assessed several performance metrics that allow to compare the contribution of each routing metric, i.e., four-bit, F-LQE/RM, and ETX in enhancing CTP routing. The considered performance metrics are the following:

- **Packet Delivery Ratio** (PDR). It is computed as the total number of delivered packets (at the sink node, i.e., the root) over the total number of sent packets (by all source nodes). This metric indicates the end-to-end reliability of routing protocols.
- **Average number of re-transmissions** in the network for each delivered data packet (RTX). Efficient routing protocols try to minimize packet retransmissions by delivering data over high quality links.
- **Average number of parent changes per node** (ParentCh). This metric is an indicator of topology stability. The number of parent changes depends on two factors: the *ParentChThresh* parameter of CTP, and also the agility of the LQE allowing for detecting link quality changes. Too many parent changes lead to instable topology, but improves the quality of routes and thus improves routing performance (e.g., PDR and RTX). On the other hand, few parent changes leads to stable topology but also worse quality routes. Hence, an agile LQE, along with a good *ParentChThresh* choice would lead to a good tradeoff between topology stability and route qualities.
- **Average hop count** (Hop Count). It is important that link quality-aware routing protocols minimize route lengths in order to reduce (i) the number of packet transmissions to deliver a packet, (ii) the number of nodes involved in data delivery, and possibly (iii) the end-to-end latency (in case the involved nodes are not overloaded).

In our experimental study, we resort to remote test-beds, namely MoteLab [53] and Indriya [54]. MoteLab consists of 190 TMote Sky motes, deployed over 3 floors of the Harvard university building, and Indriya consists of 127 TelosB motes, deployed over 3 floors of the National University of Singapore building. In both test-beds, node placement is very irregular and nodes programming is performed under TinyOS.

In contrast to Indriya, which is a recently released testbed, MoteLab has been serving the WSN community for six years. Hence, around 100 nodes in MoteLab are not working mostly due to aged hardware. Further, the number of working nodes in both testbeds varies according to time due to many reasons such as hardware failure and human activity. The major part of our experiments was carried out between April and July 2011, where 72 nodes from Motelab and 121 nodes from Indriya were available.

Using low transmission powers for sensor nodes allows to have more intermediate quality links, and thus better evaluate link quality based routing metrics. However, this may lead to a partitioned network, as some of the nodes will not be able to join the network due to poor connectivity. Hence, the transmission power should be correctly set to have as much as possible a rich set of links (i.e., having

[5] Basically, four-bit and ETX are LQEs, but they have been extensively used as routing metrics, where the path cost is simply the sum of link estimates.

different qualities), while preserving the network connectivity. To this end, we set the transmission power to −25 dBm for Indriya experiments and to 0 dBm for MoteLab experiments. These values were determined through several experiments. In each experiment, we set the transmission power to arbitrary values and check the connectivity of the network through the graphical interface provided by the test-bed software.

6.2. Experiments description

Our experiments consist of a many-to-one application scenario where nodes generate traffic at a fixed rate, destined to the sink node. Data collection is performed using CTP, with a fixed beacon rate (1 pkt/s). Nodes use the default MAC protocol in TinyOS, B-MAC (the maximum number of retries is kept to default value, set to 30 by CTP-forwarding engine component). Recall that we set the transmit power to −25 dBm for Indriya experiments and to 0 dBm for MoteLab experiments. The radio channel is set to 26 to minimize interference with co-existing networks such as Wi-Fi. Most experiments were conducted with Indriya as it provided more active nodes (121 nodes) than MoteLab (72 nodes). Each experiment lasted 60 min. Nodes began their transmission after a delay of 10 min to enable the topology establishment.

Experiments were divided into different sets. In each experiment set, we varied a certain parameter to study its impact, and the experiment was repeated for each parameter modification. Considered parameters were the test-bed under use, traffic load, topology, and number of source nodes (Table 3).

6.3. Experimental results

6.3.1. Performance analysis for different test-beds

We begin by assessing the overall impact of F-LQE/RM, four-bit and ETX on CTP routing performance, using Indriya test-bed (refer to Table 3 – Set 1 of experiments). Each experiment is repeated 5 times. Experimental results are illustrated in Fig. 9.

Fig. 9 shows that F-LQE/RM provides better routing performance, compared to four-bit and ETX as it is capable of delivering more packets (Fig. 9(a)), with less retransmissions (Fig. 9(b)), less parent changes (Fig. 9(d)), and through shorter routes (Fig. 9(c)).

Fig. 9(a) shows that ETX presents very low PDR compared with F-LQE/RM and four-bit. This can be interpreted by the fact that ETX is not able to identify high quality routes for data delivery. One of the reasons is the unreliability of ETX as an LQE, i.e., ETX is not an accurate metric for link quality estimation. Further, ETX is unstable as it leads to frequent parent changes (Fig. 9(d)). Parent changes may lead to packet loss. The unreliability and unstability of ETX was confirmed in Section 4, when we analyzed the statistical properties of different LQEs, including ETX, independently of higher layer protocols, especially routing.

Network conditions, especially the nature of the surrounding environment (e.g., indoor/outdoor, static/mobile obstacles, the geography of the environment), the type of WSN platform, and even the climate conditions (e.g., temperature, humidity), affects the quality of the underlying links, and thus impacts the network performance. For this reason, we have investigated the performance of F-LQE/RM, four-bit, and ETX, using another test-bed (besides Indriya)—MoteLab.

Experimental results carried out with MoteLab (refer to Table 3 – Set 1 of experiments) are depicted in Fig. 10. From this figure, two main observations can be made: First, by examining the PDR in Fig. 10(a), it can be inferred that links in MoteLab have worse quality than those in Indriya, as the maximum achieved PDR (by F-LQE/RM) is equal to 75%. Second, MoteLab experimental results confirm that F-LQE/RM leads to the best routing performance and ETX leads to the worst. This is a consequence of the better F-LQE reliability compared to other LQEs. Indeed, we have shown in Section 4 that F-LQE provides a fine grain classification of links, especially intermediate links, better than four-bit and ETX.

Note that while improvements achieved by F-LQE compared four-bit on Indriya testbed are fairly considerable, performance differences on Motelab are not significant. In fact, we have observed that when the links (or a large proportion of them) are of good or bad quality, it is hard to compare two concurrent LQEs such as F-LQE and four-bit, because such links are easy to assess (even PRR can do that). The strength of F-LQE is better visualized when the links exhibit intermediate quality. Such links are for example instable, asymmetric or have low channel quality. These properties are captured by F-LQE and not by the others LQEs, which leads to better routing performances.

6.3.2. Performance analysis as a function of the traffic load

We have assessed the impact of F-LQE/RM, four-bit and ETX on CTP routing performance for different traffic loads. Experiment settings are presented in Table 3 – Set 2 and Fig. 11 illustrates the results. With the increase in traffic load, the congestion level of the network increases, which leads to packet loss induced by buffer overflow as well as MAC collisions.

For traffic load smaller or equal to 1 pkt/s, Fig. 11 shows that F-LQE/RM performs better than four-bit and ETX: It

Table 3
Experiment sets.

	Test-bed	Traffic load (in pkts/s)	Num. of source nodes	Topology (root ID)
Set 1: Impact of test-bed	{Indriya, MoteLab}	0.125	120	1
Set 2: Impact of traffic load	Indriya	{0.125, 0.25, 0.5, 1, 2}	120	1
Set 3: Impact of source nodes	Indriya	0.125	{120, 84, 60, 42, 29}	1
Set 4: Impact of topology	Indriya	0.125	120	{1, 15, 58, 113}

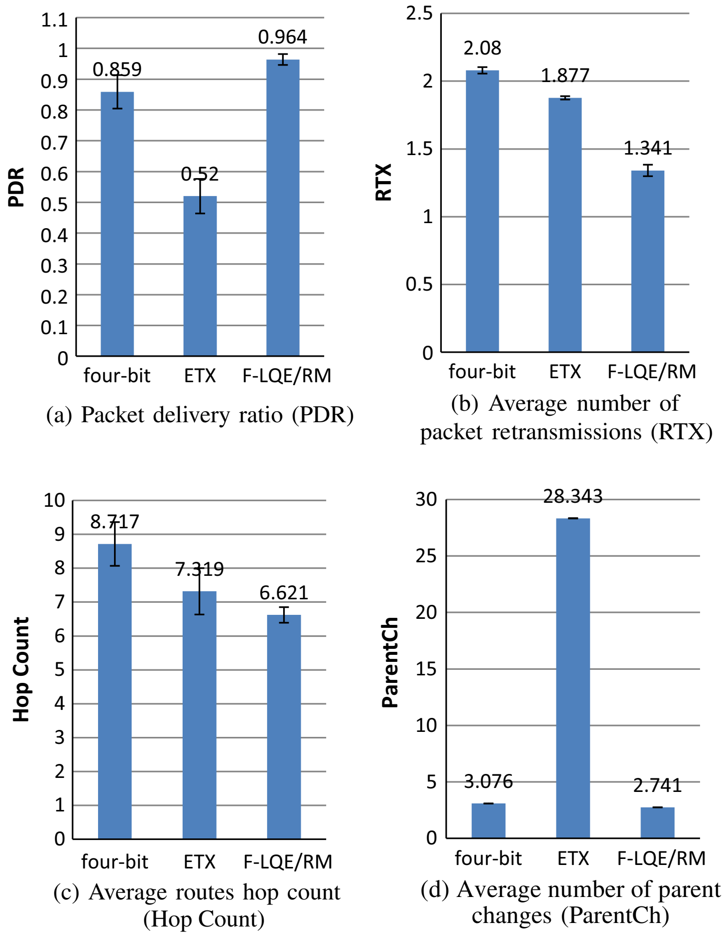


Fig. 9. Impact of F-LQE/RM, four-bit, and ETX on CTP performance, using Indriya test-bed (refer to Table 3 – Set 1). F-LQE is capable to deliver more packets, with less retransmissions, less parent changes, and through shorter routes.

improves the PDR and reduces the number of parent changes. If we observe RTX and Hop count together, it can be inferred that F-LQE/RM reduces the global number of packet transmissions (i.e., Hop count) and retransmissions (i.e., RTX), compared with ETX and four-bit. For example, for traffic load equal to 1 pkt/s, F-LQE/RM has RTX equal to 1.27 and Hop count equal to 4.56, while ETX has RTX equal to 1.123 and Hop count equal to 4.86. Thus, overall, F-LQE/RM reduces the number of packet transmissions and retransmissions (5.83) compared with ETX (5.98).

For traffic load equal to 2 pkts/s, Fig. 11 shows that F-LQE/RM provides slightly better (or nearly equal) performance than four-bit. This is due to the fact that four-bit has more information on links status as the data rate (2 pkts/s) is the double of the beacon rate (1 pkt/s). Recall that four-bit uses both beacon traffic and data traffic for link quality estimation, while F-LQE/RM and ETX perform link quality estimation based on beacon traffic only. Fig. 11 also shows that for traffic load equal to 2 pkts/s, ETX outperforms F-LQE/RM and four-bit for all performance metrics except for the parent changes. This observation pertains to CTP, which does not employ any explicit congestion control mechanism, as it is designed for low data-rate applications.

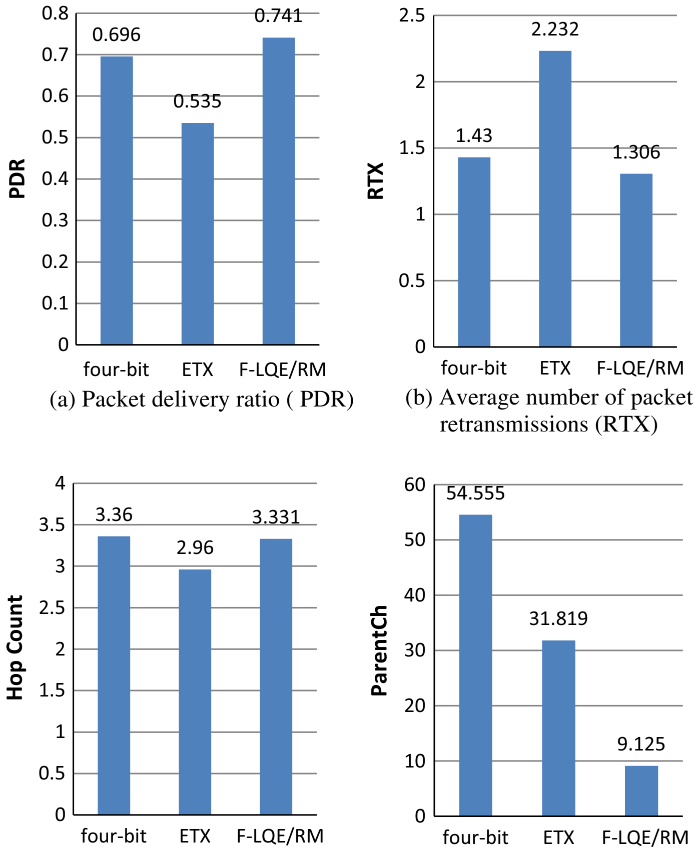
6.3.3. Performance analysis as a function of the number of source nodes

We have analyzed the impact of F-LQE/RM, four-bit and ETX on CTP routing performance while varying the number of source nodes. Experiment settings are presented in Table 3 – Set 3 and experimental results are illustrated in Fig. 12. By default, all nodes except the root node (i.e., 121 nodes) are data sources (refer to Table 3). By decreasing the number of source nodes, the congestion level of the network decreases, which reduces the number of packet losses induced by collisions or buffer overflow.

Fig. 12 shows that overall, F-LQE/RM leads to the best performance and ETX leads to the worst. By observing Figs. 12 and 11, it can be observed that generally, in terms of PDR, routing metrics are more sensitive to the traffic load variation than the number of source nodes variation. This is due to the considered data traffic rate (0.125 pkt/s), which is low enough to avoid network congestion for any number of source nodes.

6.3.4. Performance analysis as a function of the topology

The network topology has a significant impact on routing performance [55]. To examine the impact of topology on CTP tree routing, we considered different sink (Root



(a) Packet delivery ratio (PDR)

(b) Average number of packet retransmissions (RTX)

(c) Average route shop count (Hop Count)

(d) Average number of parent changes (ParentCh)

Fig. 10. Impact of F-LQE/RM, four-bit and ETX, on CTP performance, using MoteLab test-bed (refer to Table 3 – Set 1). F-LQE is capable to deliver more packets, with less retransmissions, less parent changes, and through shorter routes.

node) placements. Hence, for each CTP version, based on a particular routing metric (F-LQE/RM, four-bit or ETX), we carried out a set of experiments, while varying the sink node assignment, i.e., varying the Root ID (refer to Table 3 – Set 4).

Fig. 13 illustrates routing performance, with respect to each routing metric as a function of the root ID assignment. This figure confirms the impact of the topology on routing performance. Further, it shows that again, F-LQE/RM leads to the best performance and ETX leads to the worst, for all considered sink assignments.

6.3.5. Discussion

Tables 4–6 summarize our experimental results with the 122-node Indriya test-bed. These tables show that overall, F-LQE/RM improves the end to end packet delivery (PDR) by up to 16% over four-bit (Table 6) and up to 24% over ETX (Table 6). It also reduces the number of retransmissions per delivered packet by up to 32% over four-bit and also ETX (Table 5). The Hop count metric can be interpreted by the average route lengths as well as the average number of packet transmissions to deliver a packet. F-LQE/RM reduces the Hop count by up to 4% over four-bit (Tables 5 and 6) and up to 45% over ETX (Table 5). The ParentCh metric impacts on the topology stability. F-LQE/RM improves topology stability by up to 47% over four-bit (Table 5) and up to 92% over ETX (Table 6).

F-LQE/RM, four-bit and ETX select routing paths, which correspond to the establishment of the routing tree in the context of collection tree routing, based on link quality estimation. Our experimental study demonstrates that F-LQE/RM establishes and maintains the routing tree better than four-bit and ETX as it generally presents the highest PDR and lowest RTX, Hop count and ParentCh. The effectiveness of F-LQE/RM as a routing metric can be interpreted by (i) the accuracy of link quality estimation and (ii) a suitable path cost evaluation, that adequately trades-off link quality and path length:

- In the context of CTP routing, all routing decisions are based on link quality estimation. The more accurate the estimate is, the more correct routing decisions are. We have shown (Section 4) that F-LQE is more accurate than four-bit and ETX (viewed as LQEs) as it provides a fine grain classification of links, especially intermediate links (these are the most difficult to assess). Thus, our experimental results confirm the accuracy of F-LQE, which is traduced by the correctness of routing decisions.

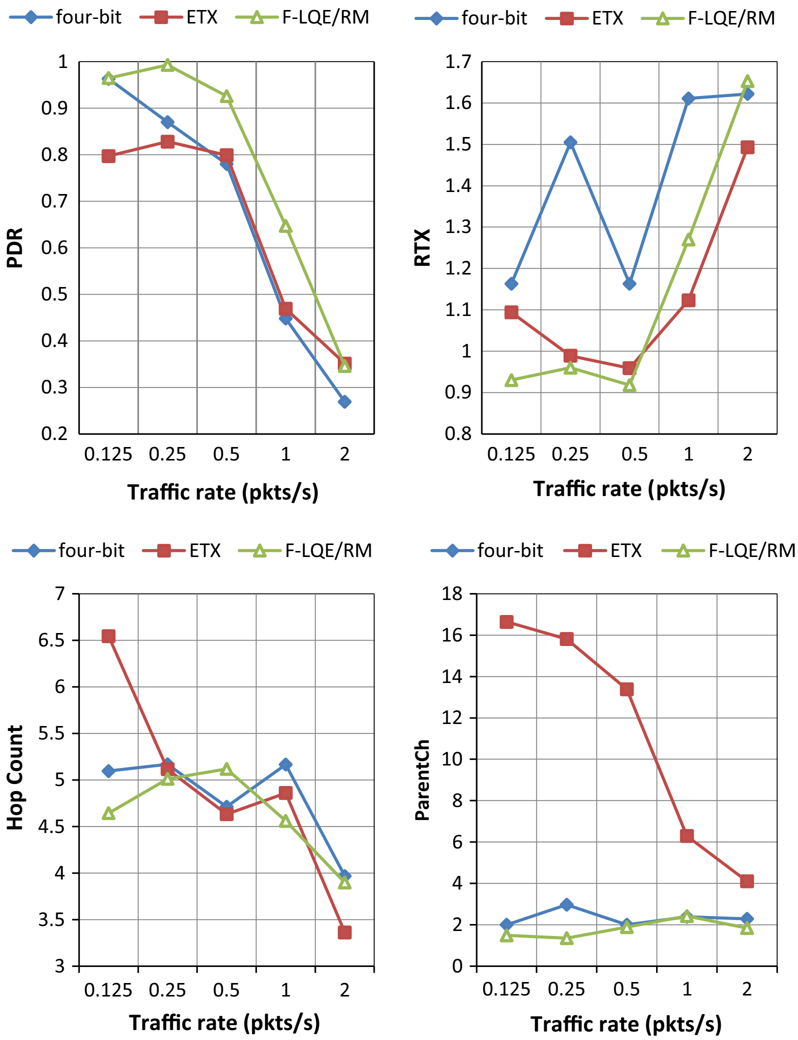


Fig. 11. Performance as a function of the traffic load (refer to Table 3 – Set 2). For traffic load smaller or equal to 1 pkt/s, F-LQE/RM performs better than four-bit and ETX. For traffic load equal to 2 pkts/s, F-LQE/RM provides slightly better performance than four-bit and ETX outperforms F-LQE/RM and four-bit.

- The effectiveness of a routing metric depends not only on the accuracy of link quality estimation, but also on how to use link estimates to evaluate the path cost. The F-LQE/RM path cost function allows to select paths composed of high quality links (in terms of F-LQE), while avoiding those having some weak links among high quality links. This path cost function also favors the selection of short paths. In fact, the path cost functions of four-bit and ETX also share these features. That is, they take into account the path global quality and implicitly favor the selection of short paths that do not have poor links. Hence, what makes F-LQE/RM more effective than four-bit and ETX seems to be the accuracy of link quality estimation through the use of F-LQE.

Our experimental results also show that four-bit performs better than ETX. Definitely, this result mainly pertains to the accuracy of link quality estimation. Four-bit takes into account more link aspects compared to ETX, as it combines RNP and estETX, which is a kind of smoothed ETX using the EWMA filter.

6.4. Memory footprint and computation overhead

The improved performance of F-LQE/RM over four-bit and ETX, which are representative and well-known metrics in the WSN community does not come without a price. We measured memory footprint and computation overhead for F-LQE/RM, four-bit, and ETX. As shown in Table 7, a sensor node (here a TelosB mote) running F-LQE/RM as routing metric consumes a total ROM footprint equal to 27.10 KB and a total RAM footprint equal to 4.47 KB, which are slightly greater than the footprints of four-bit and ETX. Nevertheless, today's sensor platforms provide higher memory than that consumed by F-LQE/RM. For example, a TelosB mote has a total ROM of 48 KB and a total RAM of 10 KB.

In terms of computation overhead, it can be easily inferred from Table 7 that the complexity of four-bit and ETX is O(1). As for F-LQE, the complexity is O(1) plus the

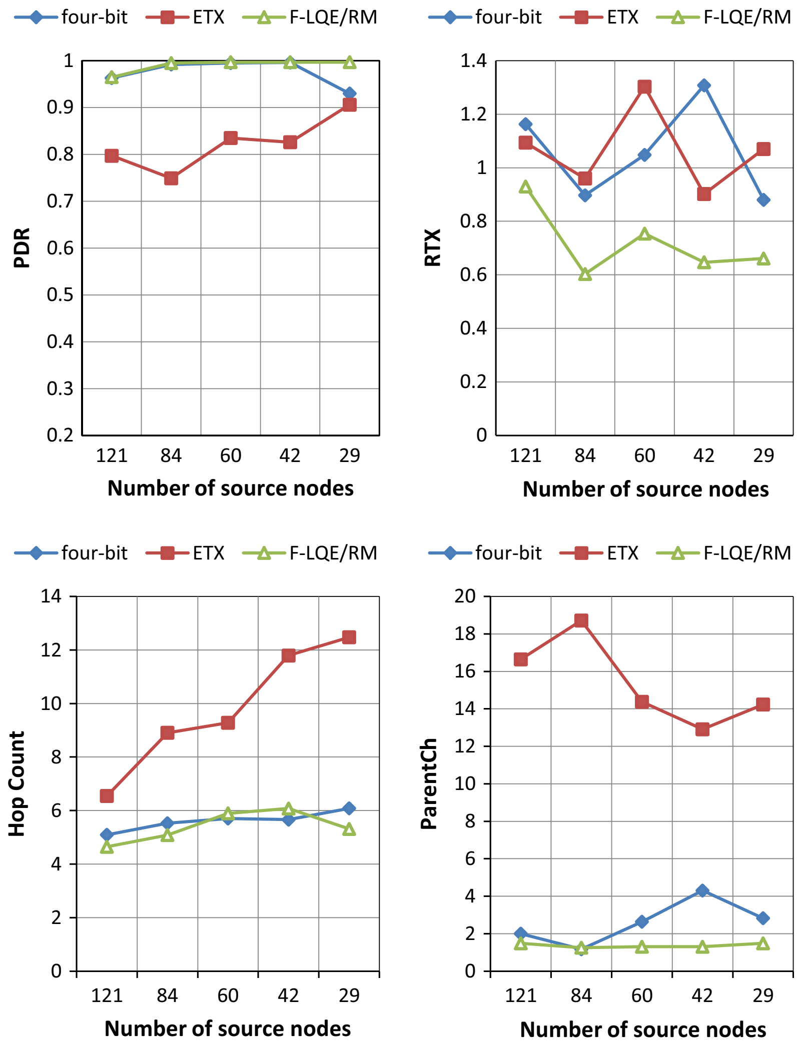


Fig. 12. Performance as a function of the number of source nodes (refer to Table 3 – Set 3). F-LQE/RM leads to the best performance and ETX leads to the worst.

complexity of the square root function in SF metric (for computing standard deviation). Note that SF can be computed incrementally in order to avoid traversing the array of PRR history every F-LQE estimate. Hence, F-LQE is slightly more complex than four-bit and ETX but still has low complexity. Recall that F-LQE computes four link quality metrics (SPRR, ASL, SF, and ALQI), applies these metrics to piecewise linear membership functions, then combines the different membership levels into a particular equation. On the other hand, four-bit combines two link quality metrics through a simple weighted sum (the EWMA filter), and ETX uses a single link quality metric.

7. Lessons learned

The extensive experimental study carried out and reported in this paper leads us to some relevant conclusions, that we summarize next as "lessons learned":

Lesson 1: We have drawn the following recommendations for the design of an efficient link quality estimator (LQE):

- An efficient LQE must be reactive to persistent changes in link quality, yet stable by ignoring transient (short-term) variations in link quality. A good balance between reactivity and stability can be obtained through the use of EWMA (Exponentially Weighted Moving Average) filtering [43]. This filter has two parameters that should be carefully tuned: the smoothing factor α and the estimation window w.
- Efficient link quality estimation that provides a fine grain classification of links, especially intermediate quality 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.
- A common error is to design a unidirectional LQE and use it for the assessment of bidirectional links, assuming that both link directions have the same quality, i.e., the link is symmetric. This misconception (typically found in mesh routing) has a negative

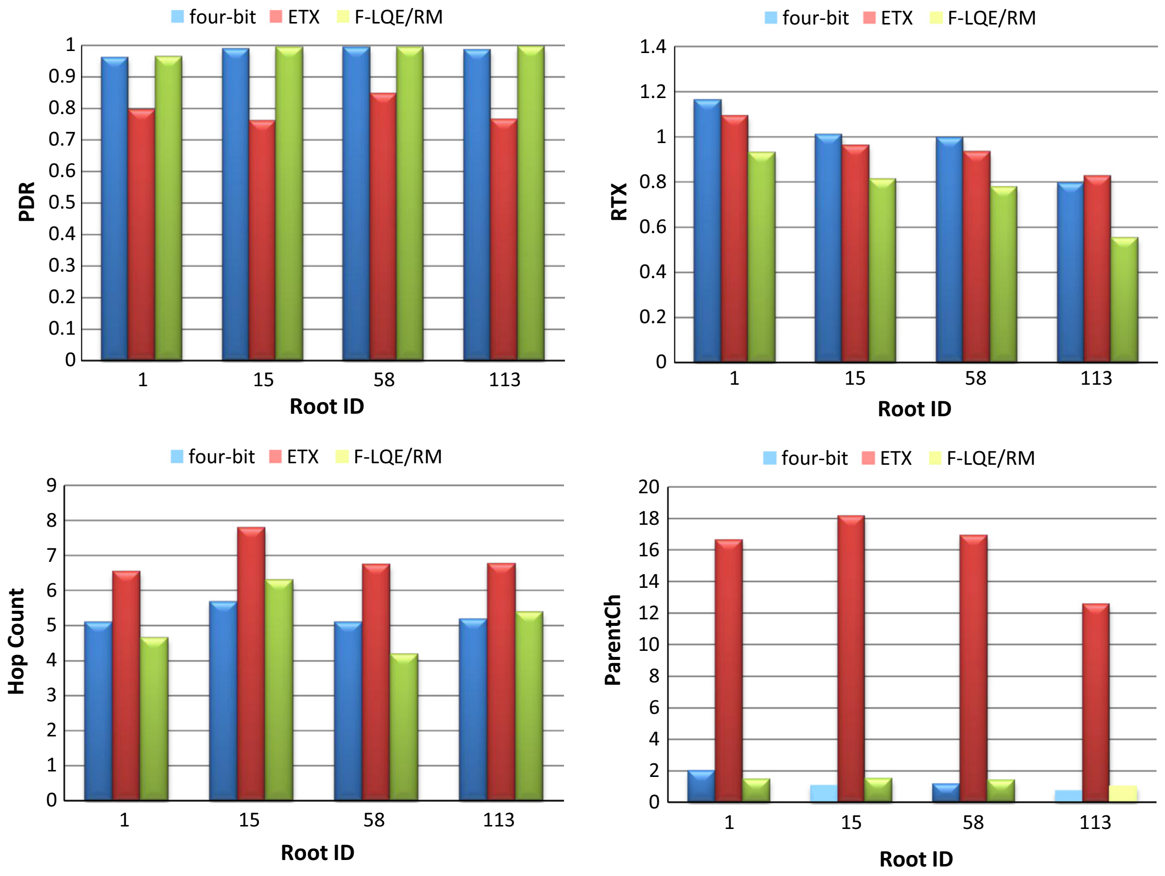


Fig. 13. Performance as a function of the topology (refer to Table 3 – Set 4).

Table 4
Overall results for Indriya experiments, where 121 nodes are data sources and the node with ID equal to 1 is selected as root, averaged over all considered traffic loads.

Performance indicator	four-bit	ETX	F-LQE/RM
Packet delivery ratio (PDR)	0.666 ± 0.26	0.647 ± 0.19	0.775 ± 0.24
Number of retransmissions for packet delivery (RTX)	1.412 ± 0.2	1.131 ± 0.19	1.146 ± 0.28
Hop count	4.821 ± 0.45	4.902 ± 1.01	4.646 ± 0.43
Number of parent changes (ParentCh)	2.326 ± 0.35	11.246 ± 5.1	1.794 ± 0.37

Table 5
Overall results for Indriya experiments, where the traffic load is fixed to 0.125 pkt/ss and the node with ID equal to 1 is selected as root, averaged over all considered number of source nodes.

Performance indicator	four-bit	ETX	F-LQE/RM
Packet delivery ratio (PDR)	0.975 ± 0.02	0.822 ± 0.05	0.99 ± 0.01
Number of retransmissions for packet delivery (RTX)	1.059 ± 0.16	1.065 ± 0.13	0.719 ± 0.11
Hop count	5.613 ± 0.31	9.8 ± 2.13	5.402 ± 0.52
Number of parent changes (ParentCh)	2.585 ± 1.03	15.374 ± 2.05	1.363 ± 0.09

impact on the performance of network protocols and can lead to dramatic performance degradation due to the prevalence of asymmetric links in WSNs. This does not mean that all LQEs should be bidirectional and unidirectional LQEs are useless. Specific applications such as data collection based on tree routing only need to assess one link direction (from child to parent). Thus, using a unidirectional LQE for these applications, specifically a sender-side LQE, is a convenient choice [14]. The design of bidirectional LQEs is not a trivial task. A bidirectional LQE should combine feedback from both link directions. The

Table 6
Overall results for Indriya experiments, where 121 nodes are data sources and the traffic load is fixed to 0.125 pkt/s, averaged over all considered Root ID assignments.

Performance indicator	four-bit	ETX	F-LQE/RM
Packet delivery ratio (PDR)	0.982 ± 0.01	0.793 ± 0.03	0.987 ± 0.01
Number of retransmissions for packet delivery (RTX)	0.991 ± 0.13	0.954 ± 0.09	0.769 ± 0.13
Hop count	5.268 ± 0.24	6.963 ± 0.48	5.129 ± 0.8
Number of parent changes (ParentCh)	1.247 ± 0.46	16.083 ± 2.1	1.354 ± 0.19

Table 7
Memory footprint and computation overhead of four-bit, ETX, and F-LQE/RM.

	Memory footprint		Computation overhead
	ROM (in Kilobytes)	RAM (in Kilobytes)	
four-bit	22.28	4.04	3 add., 3 sub., 4 mul., 3 div.
ETX	22	4.06	1 add., 3 div.
F-LQE/RM	27.10	4.47	12 add., 15 sub., 8 mul., 10 div, 1 square root

main requirement is that these feedbacks should be obtained at the same time in order to cope with link dynamics. ETX and four-bit are bidirectional LQEs, but they do not meet this challenge.

Lesson 2: PRR and RNP are two basic yet representative LQEs. They have been extensively used for routing protocols and also for the design of composite LQEs. Hence, it is important to understand their features:

- For good-quality and bad-quality links, i.e., links having high (e.g., >90%) and low reception rates (e.g., <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 remain high but the RNP will also be high, which indicates the real link state. As a matter of fact, a packet that cannot be delivered may be retransmitted several times before aborting transmission.
- RNP is more reactive than PRR but it can underestimate link quality. 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. On the other hand, PRR is receiver side, i.e., it is computed based on received packets. Consequently, when the link is of poor quality, packets are not delivered and PRR cannot be computed. However, RNP can underestimate link quality in particular situations, where packets are retransmitted many times before being successfully received. This situation yields to good PRR but bad RNP. Further, RNP is unstable compared with PRR.

Lesson 3: The design of LQEs that provide a holistic view on the link quality is relatively new research problem, 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 challenging problem is to devise convenient techniques for combining these metrics and producing a single link quality estimate. In this paper, we have addressed these challenges by introducing F-LQE. F-LQE combines four link metrics (SPRR, ASNR, ASL, and SF) using Fuzzy Logic.

We have extensively evaluated F-LQE, demonstrating improved performance over existing and representative LQEs, in terms of reliability and stability. In Section 6, we have demonstrated the usefulness and applicability of F-LQE by investigating its impact on the Collection Tree routing Protocol (CTP). We have shown through real experimentation that using F-LQE for link quality estimation boosts CTP performance by improving the end-to-end delivery, reducing the number of packet retransmissions, reducing the hop count, and improving the topology stability. Nevertheless F-LQE has the following limitation:

F-LQE is receiver-side LQE as all considered link quality metrics are computed based on received packets. Consequently, when the link is of poor quality, packets are not delivered and F-LQE estimate cannot be updated. This limitation has a negative impact on mobility management schemas, where responsiveness to link quality dynamics is a major concern. Nevertheless, F-LQE stands for the methodology of combing representative link quality metrics using Fuzzy logic, for a holistic characterization of the link. Hence, another possible version of F-LQE would be the combination of sender-side link quality metrics such as RNP, in order better cope with link dynamics.

Lesson 4: Several network protocols and mechanisms are built upon efficient link quality estimation. A LQE can be efficient on a link basis, but leads to poor performance when integrated in a particular protocol or mechanism. In Section 5, we have shown how to use F-LQE for collection tree routing. For example, using as a path cost function the sum of F-LQE estimates would lead to poor performance while the path cost function based on the sum of the inverse of F-LQE estimate would fail to correctly capture path quality. On the other hand, as we have seen, using the sum of the inverse of F-LQE estimates as a path cost function provides a good characterization of path quality.

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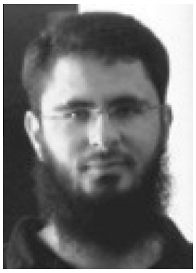

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