# F-LQE: A Fuzzy Link Quality Estimator for Wireless Sensor Networks

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**Abstract.** Radio Link Quality Estimation (LQE) is a fundamental building block for Wireless Sensor Networks, namely for a reliable deployment, resource management and routing. Existing LQEs (e.g. *PRR*, *ETX*, *Four-bit*, and *LQI*) are based on a single link property, thus leading to inaccurate estimation. In this paper, we propose *F-LQE*, that estimates link quality on the basis of four link quality properties: packet delivery, asymmetry, stability, and channel quality. Each of these properties is defined in linguistic terms, the natural language of Fuzzy Logic. The overall quality of the link is specified as a fuzzy rule whose evaluation returns the membership of the link in the fuzzy subset of good links. Values of the membership function are smoothed using EWMA filter to improve stability. An extensive experimental analysis shows that *F-LQE* outperforms existing estimators.

## 1 Introduction

In wireless sensor networks (WSNs), communication links are known to be extremely unreliable as they often experience significant quality fluctuations and weak connectivity. Link unreliability is partially due to the use of low-power radios, which are shown to be very sensitive to noise, interference, and multipath distortion.

Link quality estimation is a fundamental building block in the design of higher layer protocols, namely topology control, routing, and mobility management protocols. For instance, routing protocols rely on link quality estimation as a support mechanism to select the most stable routes for data delivery [1, 2]. Stable routes are built by selecting links with the highest quality. Building such routes will improve the network throughput and maximize its lifetime, namely

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(*i.*) increasing the end-to-end probability of message delivery, (*ii.*) avoiding excessive re-transmissions over low quality links and (*iii.*) minimizing the route re-selection operation triggered by links failure.

Several link quality estimators (LQEs) have been reported in the literature [3–7]. They can be classified as either hardware-based or software-based. Existing LQEs (hardware or software) base their estimation on a single link property. However, other properties contribute to link quality, e.g. stability and channel quality. We alert the reader that 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 the *SNR* (Signal-to-Noise Ratio). 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.

In order to better estimate link quality, we advocate combining several important link properties, to get a holistic characterization of the link. In this paper, we propose a LQE that combines multiple metrics in order to achieve this goal. Link quality is affected by several aspects that are usually *imprecisely* measured. Fuzzy logic provides a convenient language to express and combine such imprecise knowledge. Thus in this work, we resort to fuzzy logic to estimate link quality. Individual link properties are stated in linguistic terms and combined in a fuzzy rule whose evaluation gives the degree of membership of the link in the fuzzy subset of good quality links.

The rest of this paper is organized as follows: in Section 2, we discuss the limitations of existing LQEs. In Section 3, we justify the use of Fuzzy Logic for link quality estimation. Then, we introduce our Fuzzy-link quality estimator (F-LQE) in section 4. Our experimental methodology for the performance evaluation of *F-LQE* is presented in Section 5 and experimental results are given in Section 6. We conclude in Section 7. We would like to mention here that the experimental results reported in section 6 confirm extensive simulation results obtained using TOSSIM. Details of the Simulation scenarios and results are omitted due to lack of space.

## 2 Limitation of existing link quality estimators

### 2.1 Hardware-based link quality estimators

Three LQEs belong to the family of hardware-based LQEs: *LQI* (Link Quality Indicator), *RSSI* (Received Signal Strength Indicator), and *SNR* (Signal-to-Noise Ratio). These estimators are directly read from the radio transceiver (e.g. the CC2420). Their advantage is that they do not require any additional computation. However, as reported in previous studies, hardware-based estimators do not provide accurate estimates [8–10, 4], mainly for the following reasons: First, these metrics are measured based on the sample of the first 8 symbols of a received packet and not the whole packet. Second, these metrics are only measured for successfully received packets; therefore, when a radio link suffers from excessive packet losses, they may overestimate the link quality by not considering the information of lost packets. Third, despite the fact that hardware metrics provide a fast and inexpensive way to classify links as either good or bad, they are incapable of providing a fine grain estimation of link quality [5].

The above limitations of hardware-based LQEs do not mean that this category of LQEs is useless. In fact, each of these LQEs (*SNR*, *LQI* and *RSSI*) provides a particular information on the link state, but none of them is able to provide a holistic information on the link quality. For instance, in [9], it has been reported that *RSSI* can provide a quick and accurate estimate of whether an incoming link is in or out of the grey area, whereas *LQI* can provide an estimate of where in the gray area a link is.

### 2.2 Software-based link quality estimators

Software-based LQEs enable to either count or approximate the reception ratio or the average number of packet transmissions/re-transmissions. Next, we recall some of the most widely adopted software-based LQEs.

The *PRR* counts the Packet Reception Ratio. It is computed as the ratio of the number of successfully received packets to the number of transmitted packets, for each window of $w$ received packets. The Required Number of Packet retransmissions (RNP) [6] counts the average number of packet retransmissions required before a successful reception. It is computed as the ratio of the number of transmitted and retransmitted packets to the number of successfully received packets, minus 1 to exclude the first packet transmission. This metric is evaluated at the sender side for each $w$ retransmitted packets.

The Window Mean with Exponentially Weighted Moving Average (WMEWMA) [3] and the Kalman filter based LQE [7] approximate the *PRR*. *WMEWMA* applies filtering on the *PRR* metric to smooth it, thus providing a metric that resists to transient fluctuation of *PRRs*, yet is responsive to major link quality changes. *WMEWMA* is then given by the following:

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

where $\alpha \, \epsilon \, [0..1]$ controls the smoothness. This factor enables to give more importance, to the current *PRR* value (with $\alpha < 0.5$) or to the last *SPRR* value (with $\alpha > 0.5$). The Kalman filter based LQE [7] approximates the packet reception ratio based on *RSSI* and a pre-calibrated *PRR*/*SNR* curve.

On the other hand, the Expected Transmission Count (ETX) [11], and *four-Bit* [5] approximate the *RNP*. *ETX* is the inverse of the product of *PRR* of the forward link and the *PRR* of the backward link, which takes into account link asymmetry property. *Four-bit* is a sender-initiated estimator, already implemented in TinyOS. Like *ETX*, *four-bit* considers link asymmetry property. It combines two metrics (*i.*) $estETX_{up}$, as the quality of the unidirectional link from sender to receiver, and (*ii.*) $estETX_{down}$, as the quality of the unidirectional link from receiver to sender. The $estETX_{up}$ is exactly the *RNP* metric and $estETX_{down}$ approximates *RNP* as the inverse of *WMEWMA*, minus 1. The combination of the two metrics is performed through the EWMA filter as follow:

$$\textit{four-bit}(w_a, w_b, \alpha) = \alpha \times \textit{four-bit} + (1 - \alpha) \times estETX \tag{2}$$

*estETX* corresponds to $estETX_{up}$ or $estETX_{down}$: given $w_a$ the beacon-driven estimation window and $w_p$ the data-driven estimation window; at $w_a$ received packets, the sender derives the *four-bit* estimate by replacing *estETX* for $estETX_{down}$ in Eq.2. At $w_p$ transmitted/re-transmitted data packets, the sender derives the *four-bit* estimate by replacing *estETX* for $estETX_{up}$ in Eq.2.

Except of *four-bit*, these aforementioned LQEs rely on a single link quality metric, e.g. *PRR*, *SNR* or *RSSI*, to approximate either the reception ratio or the average number of packet transmissions/re-transmissions. However, as it has been shown [8, 4, 9], a single link quality metric assesses a particular link property and thus provides a partial characterization of the link. On the other hand, *four-bit* integrates two link quality metrics, namely *PRR* and *RNP*. However, it has the limitation of evaluating a single link aspect: the number of packet retransmissions, and does not take into account other important aspects, such as link stability level or channel quality. Further, *four-bit* combines two metrics having different nature, using the filter EWMA. Although filtering has been shown to be efficient to smooth the link quality estimates and provides a metric that resists to transient link quality changes [3], exploiting it for combining different metrics would lead to unstable link quality estimation [8].

## 3 Fuzzy logic for link quality estimation

The assessment of the quality of a wireless channel 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 [12]. By using hedges like 'more', 'many', 'few', etc., 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 [13]. Formally, a fuzzy set A of a universe of discourse X = {x} is defined as A={x; $\mu_A$(x) | ∀ x $\epsilon$ X}, where X is a space of points and $\mu_A$(x) is a membership function of x $\epsilon$ 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, ∀ x $\epsilon$ X, then the fuzzy set A becomes an ordinary set [13].

**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 $\epsilon$ [0..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..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..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 [14]) returns a membership degree that represents the link quality estimate.

## 4 *F-LQE* : a Fuzzy Link Quality Estimator

### 4.1 Link quality metrics

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

**Packet delivery** is related to the capacity of the link to successfully deliver data. It 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*. The *SPRR* is exactly the *WMEWMA*[3], described in section 2.

**Asymmetry** is the difference in connectivity between the uplink and the downlink. Communication between sensor nodes is usually bidirectional. Empirical studies such as [15] 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 the uplink *PRR* ($PRR_{up}$) and the downlink *PRR* ($PRR_{down}$), noted as *ASL* (ASymmetry Level):

$$ASL(w) = |PRR_{up} - PRR_{down}| \tag{3}$$

The *ASL* metric gives an idea on whether a transmitted packet can be acknowledged or not. In fact, for a given sender, when the downlink is of high quality and the uplink is of bad quality, 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* alone.

**Stability** is the variability level of the link. Link stability is of a paramount importance for network protocols that preferably forward data over stable links in order to minimize retransmissions and topological changes. To the best of our knowledge, none of the existing LQEs takes into account this property. *F-LQE* assesses the stability of the link by the measure of the stability factor (SF), defined as the coefficient-of-variation of *PRR*. The *SF* metric is basically computed based on a history of 30 *PRRs*. We adopt the idea of "sliding window", for the update of the *PRRs* history at a new measure of *PRR*. We choose 30 as the history length to ensure a certain confidence for the computation of the coefficient of variation. Nevertheless, at network startup, we anticipate the computation of *SF* by considering only a history of 5 *PRRs* and as long as packets are received, the *PRRs* history is feeded back at every new measure of *PRR*, until collecting the 30 *PRRs* values.

**Channel quality** can be evaluated through the measure of the Signal-to Noise-Ratio (SNR). It has been shown in previous studies, such as [16] and [4] that although *SNR* alone is not able to give a holistic characterization of the link, it helps to enhance the accuracy of the link quality estimation. For example, a link that has a *PRR* near to 1 and a high *SNR*, e.g. 10 dBm (refer to Fig. 1), is significantly better than another link that has the same *PRR* but low *SNR*, e.g. 4 dBm, because the link quality of the second link is susceptible to drop considerably with a small change in the noise floor [4]. This observation can be clearly understood from Fig. 1.

The *SNR* metric can be derived by subtracting the noise floor ($N$) from the received signal ($S$), both in dBm. The $S$ can be deduced by sampling the *RSSI* at the packet reception, and $N$ can be derived from the *RSSI* sample just after

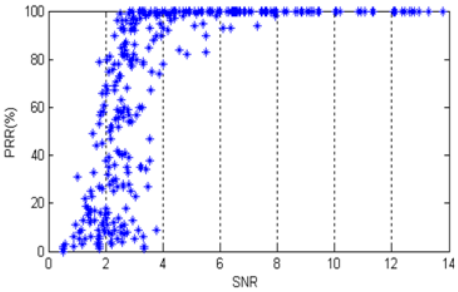


**Fig. 1.** *PRR/SNR*. For *ASNR* greater than 8dBm, the *PRR* is equal to 100%, and for *ASNR* less than 1 dBm, the *PRR* is less than 25%. In between, a small variation in the *ASNR* can cause a big difference in the *PRR*; links are typically in the transitional region.

the packet reception. In our proposed LQE, we average *SNR*, over $w$ received packets to get *ASNR*: the link quality metric for the channel assessment.

### 4.2 Combination of link quality metrics

*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 goodness* are linguistic values for the fuzzy variables packet delivery, asymmetry level, stability, channel quality, and quality (refers to link quality). Using and-like compensatory operator of [14], the above rule translates to the following equation of the fuzzy measure of the link $i$ high quality.

$$\begin{aligned}\mu(i) = \beta.min(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) + \\ (1-\beta).mean(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i))\end{aligned} \tag{4}$$

$\mu(i)$ is the membership in the fuzzy subset of high quality links. The parameter $\beta$ is a constant in [0..1]. Recommended values for $\beta$ are in the range [0.5..0.8] where 0.6 usually gives the best results [20], which is also confirmed in this work (see Section 6.1). $\mu_{SPRR}$, $\mu_{ASL}$, $\mu_{SF}$, and $\mu_{ASNR}$ represent membership functions in the fuzzy subsets of high packet delivery, low asymmetry, low stability, and high channel quality, respectively. 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 $\mu_{SPRR}$, $\mu_{ASL}$, and $\mu_{SF}$, can be tuned according the application requirements. In our study, we

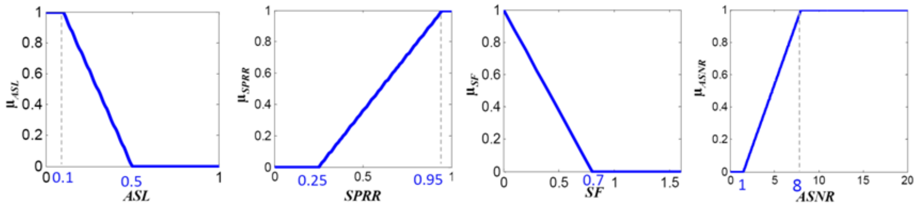


**Fig. 2.** Definition of membership functions $\mu_{SPRR}$, $\mu_{ASL}$, $\mu_{SF}$, and $\mu_{ASNR}$

have chosen reasonable values of these thresholds, with respect to each membership function. For instance, for $\mu_{SPRR}$, for values of *SPRR* below 25%, the link is considered totally out of the fuzzy subset of links with high *PRR*. Starting from 95%, the membership to the fuzzy subset of links with high *PRR* is of 1. For values of *SPRR* between 25% and 95%, the membership increases linearly from 0 to 1. The same reasoning holds for $\mu_{ASL}$. The membership function $\mu_{SF}$ differs slightly to the other ones as the two thresholds are superposed. In fact, a link has 1 as membership to the fuzzy subset of links with high stability, only when the measured *SF* is equal to 1. Otherwise, its 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.

The choice of the two thresholds for the membership function $\mu_{ASNR}$ depends on the environment and the hardware characteristics. Next, we present a detailed analysis for an efficient determination of these two thresholds.

In previous empirical studies, such as [4], based on the *PRR*/*ASNR* curve, the existence of two *ASNR* thresholds has been proven. When *ASNR* is larger than the first threshold, the *PRR* is greater than 95% almost all the time, which implies good channel. If *ASNR* is less than the second threshold, the *PRR* is lower than 25 % most of the time and the channel is bad. These thresholds are determined from the *PRR*/*ASNR* curve, which is in turn determined experimentally. In order to gather the *PRR*/*ASNR* curve, we carried out a set of experiments, using our testbed (refer to section V). Experiments were conducted under different network conditions (refer to TABLE 1). We generate the *PRR*/*ASNR* curve for each network setting. Fig. 1 depicts the *PRR*/*ASNR* curve for the default setting. The convenient choice of the two *ASNR* thresholds can be easily inferred from this curve. Notice that these thresholds are the same for all *PRR*/*ASNR* curves (settings), as we found that the curves have similar shapes.

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

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

*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

**Fig. 3.** Nodes distribution according the circular topology, at an outdoor environment

the *F-LQE* metric:

$$FLQE(\alpha, w) = \alpha.FLQE + (1 - \alpha).LQ \qquad (6)$$

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.4 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 uplink and downlink *PRRs* (refer to Eq.3). Thereby, we introduced a simple mechanism that consists to 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* can not be computed due to the lack of some data, the node ignores the corresponding metric(s) in the computation of the membership function $\mu(i)$ in Eq. 4. For instance, when the node is not able to compute both *ASL* and *SF*, $\mu(i)$ in Eq. 4 becomes:

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

## 5 Experimental Methodology

Our experimental study aims at analyzing and understanding the statistical properties of *F-LQE*, independently of any external factor, such as collisions and routing. These statistical properties impact its performance, in terms of *reliability* and *stability*. Reliability refers to the ability of the LQE to correctly characterize the link state. Stability refers to the ability to resist to transient (short-term) variations, also called fluctuations, in link quality. We compare the performance of *F-LQE* in terms of reliability and stability, with a set of well-known LQEs, namely *PRR*, *SPRR*, *ETX*, *RNP*, and *four-bit*.

**Table 1.** Experiment sets. Burst(X, Y, Z) and Synch(W, Y); X: Number of packets per burst, Y: inter-packets interval, Z: number of bursts, W: total number of packets.

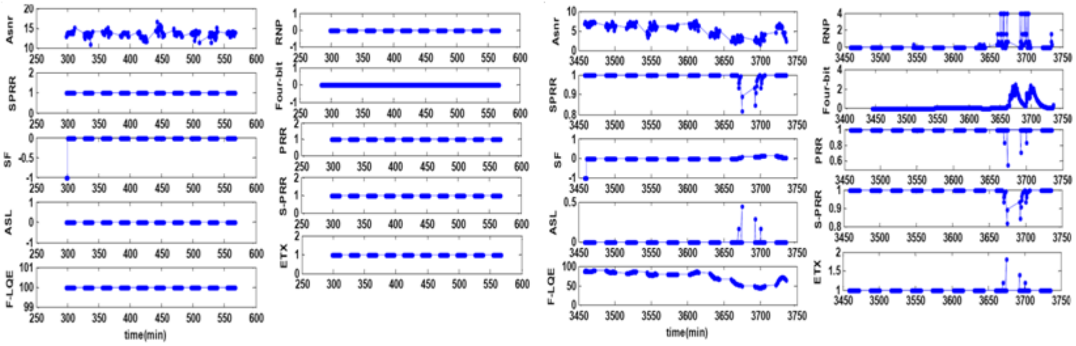
| | **Traffic Type** | **Packet Size** | **channel** |
|---|---|---|---|
| **Impact of the Traffic Type** | {Burst(100,100,10), Burst(200,500,4), Burst(100,1000,2), Synch(200,1000)} | 28 | 26 |
| **Impact of the Packet Size** | Burst(100,100,10) | {28, 114} | 26 |
| **Impact of the Channel** | Burst(100,100,10) | 28 | {20, 26} |
| **Default Setting** | Burst(100,100,10) | 28 | 26 |

Our testbed consists of a single-hop network with 49 TelosB motes [10], $N_1 \ldots N_{49}$, positioned in an outdoor environment (a garden at the university). The motes are distributed in a circular topology, as shown in Fig. 3. 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 0.75 meter. The first set, i.e. the nearest circle to $N_1$, has a radius of $X$ meters, where $X$ varies in $\{2, 3\}$. All TelosB motes are connected to a laptop PC using a combination of USB (Universal Serial Bus) cables and active USB hubs. We developed a software tool that runs on the PC to control and analyze the experiments. The control part, developed in Java, allows (*i.*) motes programming and control, (*ii.*) network configuration, and (*iii.*) data logging into a MySQL database. The data analysis (including graph generation) is performed in Matlab, allowing to work off-line. The motes are programmed in nesC [19] over TinyOS2.x environment.

In this study, we propose to estimate the quality of the unidirectional links $N_1 \longleftarrow N_i$. 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, $N_1 \longleftarrow N_i$, exhibit different qualities. Particularly, we choose a convenient $X$ value so that most of the links are of intermediate qualities (belong to the transitional region) to better explore the performance of *F-LQE* as well as the other LQEs under evaluation.

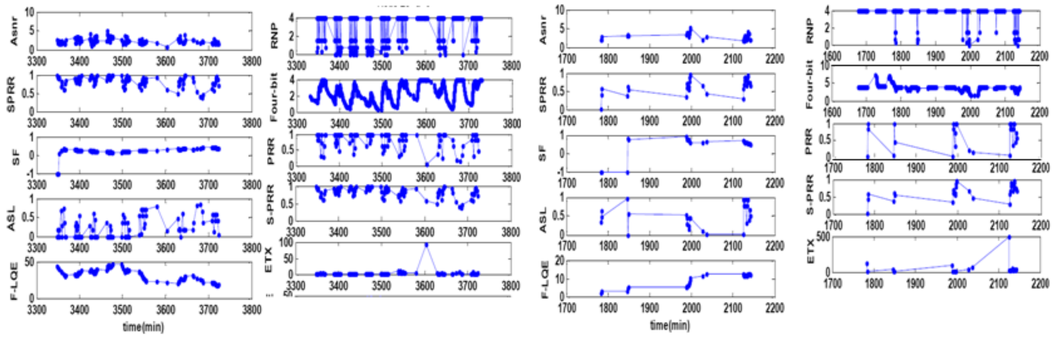
After receiving the token, each couple of nodes ($N_1$, $N_i$), exchanges a certain number of data packets then passes the token to the next couple, ($N_1$, $N_{i+1}$). We considered two traffic patterns: *Bursty traffic* and *synchronized traffic*: For the Bursty traffic, $N_1$ sends a first burst of packets to $N_i$. When it finishes, it sends a notification to the PC, to allow $N_i$ sending its burst of packets to $N_1$. When $N_1$ 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 $N_1 \longleftarrow N_i$ has been estimated using *F-LQE*, as well as *PRR*, *SPRR*, *ETX*, *RNP*, and *four-bit*. We subject LQEs to different network conditions. In fact, we performed extensive experimentations



(a) Very Good Link

(b) Good Link



(c) Moderate Link

(d) Bad Link

**Fig. 4.** Temporal behaviour of LQEs when faced with links with different qualities (Default Setting)

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 8hs. TABLE 1 depicts the different settings for each experiments set. The transmission power was set to -25 dBm.

Like *F-LQE*, *four-bit* and *SPRR* use EWMA filter, which has an important parameter: the history control factor $\alpha$. We chose $\alpha = 0.9$ for *four-bit*, as in [17], and $\alpha = 0.6$ for *SPRR*, as suggested in [3]. 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 [17]. Further, in [18], it has been argued that short-time link quality estimation captures link dynamics at a high resolution in time.

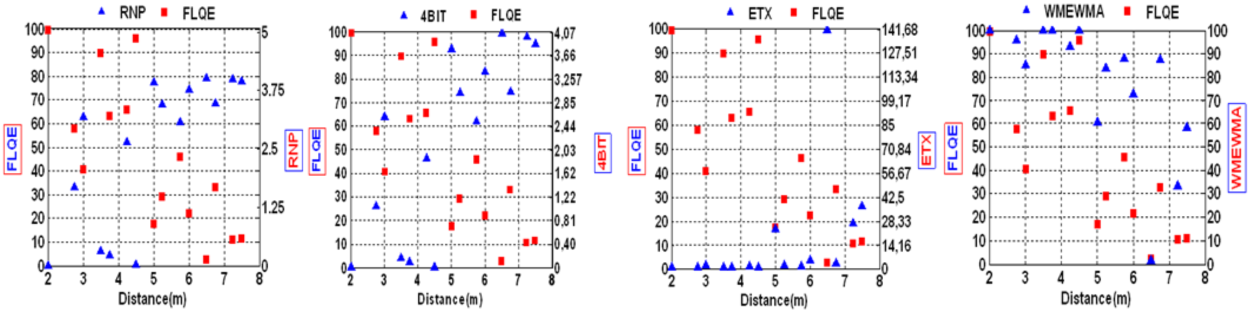


**Fig. 5.** Scatter plot of each LQE according to distance (Default Setting).

## 6 Experimental Results

### 6.1 Reliability

The reliability of *F-LQE* is tested by studying (*i.*) the temporal behavior (Fig. 4), and (*ii.*) the distribution of link quality estimates, illustrated by the a scatter plot (Fig. 5) and the empirical cumulative distribution function, CDF, (Fig. 6).

**Temporal Behavior**: Fig. 4 uses four different links to show the temporal behaviour of each individual metric that constitutes *F-LQE* and its overall behavior. It also presents the results from other existing LQEs. From this figure, it can be observed that all LQEs agree that the first link (Fig. 4(a)) is of very good quality. This is expected since links of good quality are easy to estimate as they trend to be stable and symmetric [6, 15]. On the other hand, moderate and bad links which are typically those of the transitional region and the disconnected region respectively, are more difficult to characterize.

Fig. 4(b) shows how *F-LQE* outperforms existing LQEs because they are not able to distinguish between links, especially good links and very good links. In fact, let's observe the temporal behaviour of the link in Fig. 4(b), until the time *3660 min* (just before the link quality fluctuation). *PRR*, *SPRR*, and *ETX* are based on the *PRR* metric. They account for only one property : link delivery. These PRR-based LQEs declare the link as of very good quality. The same link quality state is declared by *RNP* and *four-bit*, which are RNP-based and accounts for a unique link property. However, our link should not have a very good quality due to the low *ASNR* value. In fact, the measured *ASNR* values are close to the receiver sensitivity. Consequently, the channel is of moderate quality, which prevents the link of being declared as "very good". In addition, the good properties that the link have are likely due to the constructive interference effect. On the other hand, *F-LQE* detects the real link state by considering different link properties. Indeed the link shown in Fig. 4(b) has some very good properties, including the delivery, the asymmetry and the stability, yet it has an *ASNR* of moderate quality which make of it a good link but not a very good link. From Fig. 4(c), we can observe how PRR-based LQEs, i.e. *PRR*,

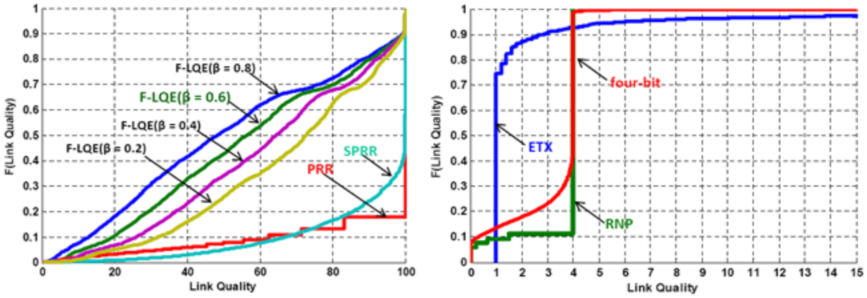
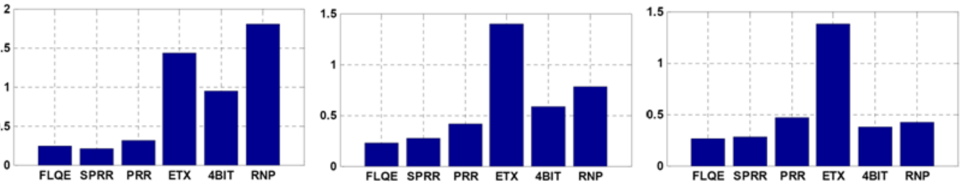
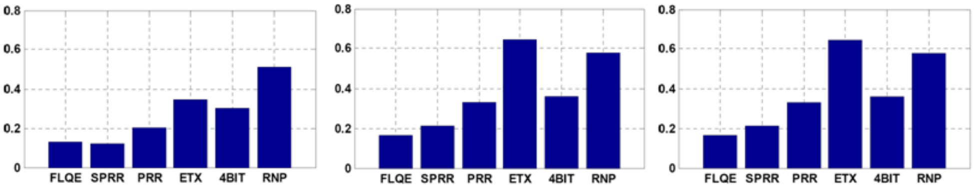


**Fig. 6.** Empirical CDFs of LQEs (Default Setting).



(a) Default settings (b) Packet size : 114 Bytes (c) Channel 20



(d) Burst(100,1000,2) (e) Burst(200,500,4) (f) Synch(200,1000)

**Fig. 7.** Sensitivity to transient fluctuation in link quality, for different network settings.

*ETX* and *SPRR* can overestimate link quality as they provide relatively high link quality estimates. The reason of this overestimation is the fact that *PRR*-based LQEs are only able to evaluate the link packet delivery property and they are not aware of the number of retransmissions to deliver a packet. A packet that is lost after one retransmission or after $n$ retransmissions will produce the same estimate. On the other hand *RNP*-based LQEs, i.e.*RNP* and *four-bit*, can underestimate link quality by providing low link quality estimates. This underestimation is due to the fact that each of these LQEs assesses the required packet retransmissions and 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. *F-LQE* estimates the link not as good as *PRR*-based estimators do, and not as bad as *RNP*-based estimators do. It takes into account different properties to provide a holistic characterization of the real link state.

Fig. 4(d) gives a preliminary idea on the stability of *F-LQE* as well as the other LQEs (a detailed analysis of the stability of *F-LQE* is given in section 6.2). Indeed, the link shown in Fig. 4(d) is generally of bad quality. Furthermore, this link is a *bursty* link, as its quality can turn to good (e.g. *PRR* equal to 1 and *RNP* equal to 0), yet in the short term. *F-LQE* is a stable LQE as it resists to these short-term link quality fluctuation whereas the other LQEs are not stable as their link quality estimates switch temporarily to very good estimates.

Now, let us see more arguments for *F-LQE* reliability by analyzing the distribution of link quality estimates.

**Link Quality estimates distribution** : Form the scatter plot of Fig. 5, we can see that *F-LQE* estimates are more scattered than those of the other link estimators. For example, the *RNP* estimates are mostly aggregated to 4 retransmissions (the maximum). That means that two links assumed to have different qualities, may be aggregated to have almost the same qualities when using *RNP* as LQE; and they would have different qualities when using *F-LQE* as LQE. The same thing holds for the rest of LQEs. This observation shows that *F-LQE* would surely perform better than the existing LQEs. Hence again, we show the reliability of *F-LQE* as it is able to provide a fine grain classification of links.

The above observations can be confirmed if we look into the CDF plot in Fig. 6. This plot is obtained based on all the links and the default setting (refer to Table 1). Notice that we did not include the CDF plots for the other settings, as they have similar shape as the CDF plot based on the default setting. Fig. 6 shows that *PRR*, *SPRR* and *ETX* overestimate link quality as they estimate most of the links to have good quality. In contrast, *RNP*, and *four-bit* underestimate link quality as they consider most of the links having bad quality. In between, *F-LQE* provides reasonable link quality estimates (neither overestimate nor underestimate link quality). Furthermore, the distribution of link quality estimates is nearly an uniform distribution, which means that *F-LQE* is able to to distinguish between links having different link qualities. These observations confirm the reliability of *F-LQE*.

In our study, we have set $\beta$ (refer to Eq.4) to 0.6. In the following, we justify this choice by studying the impact of $\beta$ on the reliability of *F-LQE*. Fig. 6 shows the effect of $\beta$ on the CDF. From this figure, we retain two important findings: First, the higher $\beta$ is, the more pessimistic *F-LQE* is. This is completely reasonable, since by increasing $\beta$, we give more importance to the *min* (refer to Eq.4). Second and more importantly, by choosing $\beta$ equal to 0.6, we get the nearest distribution to the uniform distribution, which justify the choice of $\beta$.

### 6.2 Stability

A link may show transient link quality fluctuations due to many factors principally related to the environment, and also to the nature of low-power radios, which have been shown very prone to noise. LQEs should resist to these fluctuations and provide stable link quality estimates. This property is of paramount importance in WSNs. For instance, routing protocols do not have to reroute information when a link quality show transient degradation, because rerouting is a very energy and time consuming operation.

To reason about this issue, we measure the sensitivity of the LQEs to transient fluctuations by the coefficient of variation of its estimates. Fig. 7 compares the sensitivity (stability) of *F-LQE* with that of *PRR*, *ETX*, *SPRR*, *RNP*, and *four-bit*, with respect to different setting (refer to Table 1). According this figure, we retain two observations: First, generally, *F-LQE* is the most stable LQE. Second, except *ETX*, *PRR*-based LQEs, i.e. *PRR* and *SPRR*, are 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 increase the standard deviation of *ETX* link estimates.

## 7 Conclusion

In this paper, we have presented a novel link quality estimator (F-LQE) for wireless sensor networks (WSNs). In contrast to existing LQEs, which only assess one single link property thus providing a partial view on the link, *F-LQE* combines four link metrics (*SPRR*, *ASNR*, *ASL*, and *SF*) using Fuzzy Logic, since we believed (and proved) to be an appropriate strategy to fuse different and imprecise metrics. The overall quality of the link is then specified as a Fuzzy IF-THEN rule, which combines the four metrics, viewed as linguistic variables. The evaluation of the fuzzy rule returns the membership of the link in the fuzzy subset of good links. *F-LQE* has been evaluated extensively both by simulation and experimentation, demonstrating greater performance over existing solutions, in terms of reliability and stability. The simulations were conducted using TOSSIM. Details of the Simulation scenarios and results are omitted due to lack of space.

Future work will address the impact of *F-LQE* on higher layer protocols (e.g. routing) and its use as a basic building block for proposing time-efficient mobility management mechanisms in WSNs. We also envisage to turn *F-LQE* implementation in TinyOS available to the community as an open-source.

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