# Poster Abstract: Simulation analysis and validation of a Fuzzy Link Quality Estimator

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***Abstract*—We consider the problem of link quality estimation in wireless sensor networks. Existing link quality estimators (e.g. *PRR*, *ETX*, *Four-bit*, and *LQI* ) are only able to assess a single link property, thus providing a partial view on the link quality. It is therefore important, yet challenging, to design link quality estimators that perform holistic link characterization by considering several properties.**

**In this poster, we propose *F-LQE*, a novel link quality estimator, that estimates link quality on the basis of four link quality properties namely, packet delivery, asymmetry, stability, and channel quality. Combination of link properties is performed using Fuzzy Logic. We show through extensive TOSSIM simulation that *F-LQE* outperforms existing link quality estimators.**

## I. Introduction

Link quality estimation is a fundamental building block for wireless sensor networks (WSNs), namely for a reliable deployment, resource management and routing . Several link quality estimators (LQEs) have been reported in the literature, including *PRR* (Packet Reception Ratio), *WMEWMA* (smoothed PRR) [1], *RNP* (Required Number of Packet retransmissions) [2], *Four-bit* (an apprixmation of the *RNP*) [3], *LQI* (Link Quality Indicator), and *ETX* (Expected Transmission Count) [4]. Except of *four-bit*, existing LQEs rely on a single metric for link quality assessment. A single link quality metric is not able to provide a holistic characterization of the link [5]. On the other hand, the *Four-bit* estimates link quality by combining individual estimation of uplink and downlink qualities, based on measured *RNP* and *PRR*, respectively. All existing LQEs ignore other important properties that have an impact on link quality characterization [5]. Example of such properties are stability and channel quality.

In order to better estimate link quality, it is important, yet challenging, to combine different metrics to assess important link properties and to get a holistic characterization of the link. In this poster, we propose a LQE that combines multiple metrics, using Fuzzy Logic, in order to achieve this goal.

## II. *F-LQE* design

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. In the rest of this section 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.

*F-LQE* combines four link properties to express the goodness of a given link. Each property is assessed by a particular metric:

**Packet delivery** is measured by *SPRR* [1], a Smoothed *PRR*:

$$SPRR(\alpha, w) = \alpha \times SPRR + (1 - \alpha) \times PRR \qquad (1)$$

The *PRR* 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. $\alpha \ \epsilon$ [0..1], controls the smoothness.

**Asymmetry** is the difference between the uplink *PRR* and the downlink *PRR*, noted as *ASL* (ASymmetry Level).

**Stability** is the variability level of the link. It is assessed by the stability factor (SF), which is defined as the coefficient-of-variation of *PRR*.

**Channel quality** is evaluated by the measure of the Signal-to Noise-Ratio (SNR), averaged over *w* packets, where *w* is the estimation window .

*F-LQE* considers each of the aforementioned link properties 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 [6], the above rule

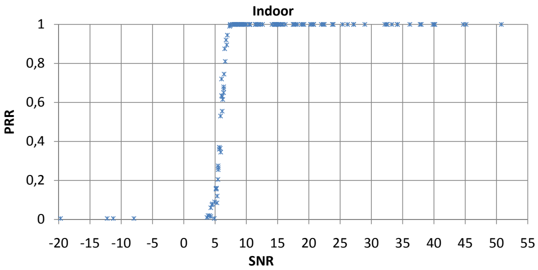



Fig. 1. *PRR*/*SNR* curve for an indoor environment.

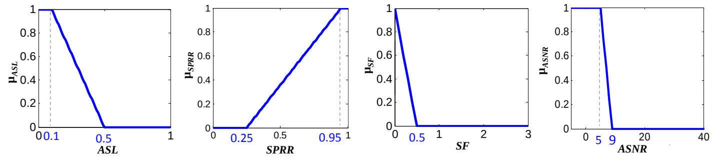



Fig. 2. Definition of membership functions. For instance, for $\mu_{SPRR}$, for values of *SPRR* below 25%, the link is considered totally out of the fuzzy subset of links with high *PRR*. Starting from 95%, the membership to the fuzzy subset of links with high *PRR* is of 1. For values of *SPRR* between 25% and 95%, the membership increases linearly from 0 to 1.

translates to the following equation of the fuzzy measure of the link *i* high quality.

$$\mu(i) = \beta.min(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) + (1-\beta).mean(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) \quad (2)$$

$\mu(i)$ is the membership in the fuzzy subset of high quality links. $\beta$ 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 [7]. $\mu_{SPRR}$, $\mu_{ASL}$, $\mu_{SF}$, 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. On the other hand, the choice of the two thresholds for the membership function $\mu_{ASNR}$ depends on the environment and the hardware characteristics. They can be determined based on the *PRR*/*ASNR* curve, which is in turn determined experimentally. In order to gather the *PRR*/*ASNR* curve, we carried out extensive simulations, using TOSSIM 2 simulator [9]. Fig. 1 depicts the *PRR*/*ASNR* curve for an indoor environment, plotted based on the same settings that are used in the performance evaluation of LQEs. This curve shows that when *ASNR* is greater than 9dBm, the *PRR* is equal to 1, which implies good channel. When *ASNR* is less than 5 dBm, the *PRR* is less than 0.15 and the channel is bad. In between, a small variation in the *ASNR* can cause a big difference in the *PRR*; links are typically in the transitional region and the channel has moderate quality. The *PRR*/*ASNR* curve shown in Fig. 1 reassembles that determined empirically in [8], which confirms the realism of TOSSIM physical layer.

The final step toward *F-LQE* computation is detailed in the rest of this section. Let $LQ = 100.\mu(i)$. $LQ$ attributes a score to the link, ranging in [0..100]. Using EWMA filter, we smooth *LQ* to get the *F-LQE* metric:

$$FLQE(\alpha, w) = \alpha.FLQE + (1-\alpha).LQ \quad (3)$$

where, $\alpha$ = 0.9, to provide stable link quality estimates.

## III. Performance Evaluation

This section focuses on analyzing and understanding the statistical properties of *F-LQE* that imply on its performance in terms of *reliability* and *stability*. Reliability refers the the ability of the LQE to correctly characterize the real link state and stability is the ability to resist to transient (short-term) variations, also called fluctuations, in link quality. We compare the reliability and stability of *F-LQE* to those of *PRR*, *WMEWMA*, *ETX*, *RNP*, and *four-bit*, using extensive TOSSIM 2 simulation [9].

### A. Simulation scenarios

The simulation scenario aims at analyzing the statistical properties of *F-LQE*, independently of any external factor, such as collisions and routing. To achieve this goal, we considered a single-hop network of 10 sensor nodes ($N_1$, $N_2 \ldots N_{10}$) placed in a linear topology. The couple of nodes ($N_1$, $N_i$) exchanges data packets then passes the token to ($N_1$, $N_{i+1}$). The above described scenario is simulated 10 times while varying the nodes inter-distance. We choose a history control factor $\alpha$ = 0.9 for *four-bit*, as in [3], and $\alpha$ = 0.6 for *SPRR*, as suggested in [1]. The estimation window *w* is set to 5 packets.

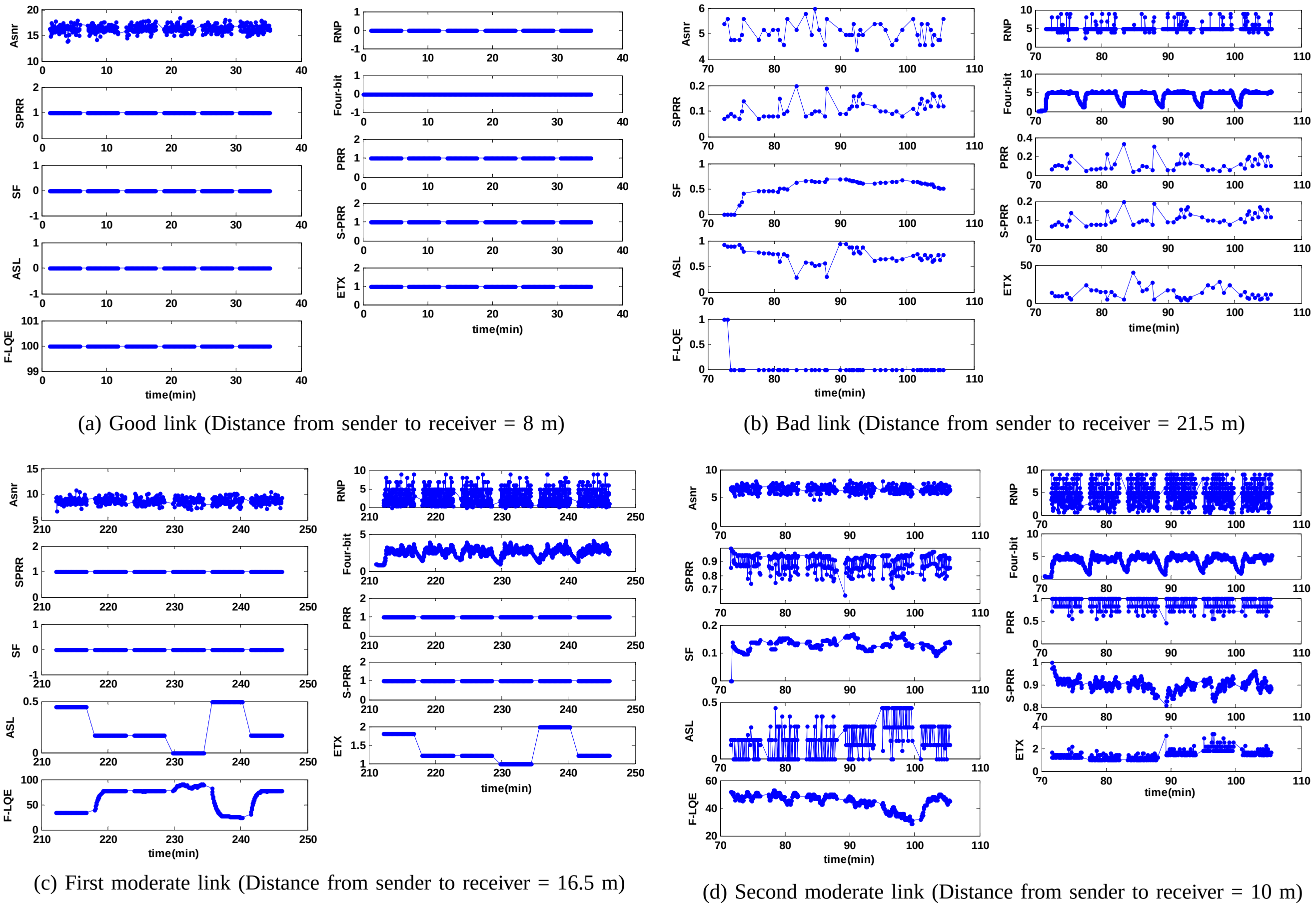
### B. Simulation Results

The performance analysis of *F-LQE* is carried out by comparing its performance, in terms of reliability and stability, to conventional link quality estimators, namely *PRR*, *SPRR*, *ETX*, *RNP*, and *four-bit*.

*1) Reliability:* The reliability of *F-LQE* is tested by studying (*i.*) the temporal behavior (Fig. 3), and (*ii.*) the distribution of link quality estimates, illustrated by the empirical cumulative distribution function, CDF, (Fig. 4).

**Temporal Behavior**: Fig. 3 shows the temporal behaviour of *F-LQE*, its related link quality metrics, and the other conventional link quality estimators, with respect to four different links. From this figure, it can be observed that all link quality estimators agree that the first link (Fig. 3a) is roughly good and the second is roughly bad (Fig. 3b). This is expected since links of good or bad quality are easy to estimate [2], [10], [11]. On the other hand, moderate links which are typically those of the transitional region are more difficult to characterize.

Fig. 3c and Fig. 3d deal with two links of moderate qualities. These figures show that *RNP* and *four-bit* underestimate link quality, and *PRR*, *SPRR*, and *ETX* overestimate link quality, whereas *F-LQE* provides reasonable link quality estimates. Indeed, *PRR*, *SPRR* and *ETX*, which are *PRR*-based estimators,




(a) Good link (Distance from sender to receiver = 8 m)

(b) Bad link (Distance from sender to receiver = 21.5 m)

(c) First moderate link (Distance from sender to receiver = 16.5 m)

(d) Second moderate link (Distance from sender to receiver = 10 m)

Fig. 3. Temporal behaviour of link quality estimators when faced to links with different qualities

estimate the two links (Fig. 3c and Fig. 3d), to have very good quality or overestimate link quality: Average *PRR* and *SPRR* is 1 in Fig. 3c and almost 0.9 in Fig. 3d and average *ETX* is almost 1.5 transmission/retransmissions (i.e. 0.5 retransmissions) for both links. The reason of this overestimation is the fact that *PRR*-based link quality estimators 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, *four-bit* and *RNP*, which are *RNP*-based estimators, estimate both links in Fig. 3c and Fig. 3d, to have less goodness, as the average *RNP* and *four-bit* is about 3 retransmissions in Fig. 3c and 5 retransmissions in Fig. 3d, shifting from 0 to 9 for *RNP*, which underestimate link quality. This underestimation is due to the fact that *RNP*-based link quality estimators are only able to assess 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 two links are correctly received (high *PRR*) but after a certain number of retransmissions (high *RNP*). More importantly, each of these link quality estimators 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. In the following we show how *F-LQE* provides reasonable link quality estimates, which make of it more reliable than conventional link quality estimators, namely *PRR*, *ETX*, *SPRR*, *RNP*, and *four-bit*.

In fact, the link depicted in Fig. 3c has some positive features: (1) good packet delivery and (2) high stability, but it has also some negative features: (3) medium channel quality and (4) high asymmetry. The last two features justify the high number of packet retransmissions. As a results, the average *F-LQE* link quality estimates is 62 (out of 100), which is a reasonable link quality estimate, given the above link properties. The link shown in Fig. 3d is also of moderate quality. The difference with the first link is mainly (1) the channel quality is worse, which justify a higher number of packet retransmissions, and (2) the link is much more instable. There properties make this link (Fig. 3d) having worse quality compared to the first (Fig. 3c): the average *F-LQE* is 45 for the second moderate link against 62 for the first.

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

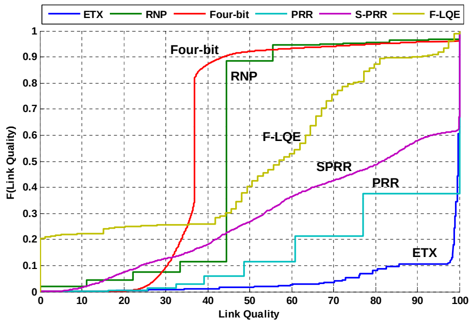



Fig. 4. Empirical CDFs of link quality estimators.

**Link quality estimates distribution**: The above observations can be confirmed if we look into the CDF plot in Fig. 4. The CDF presented in this figure is obtained based on all the links of one simulation scenario. Further, link quality estimates with respect to link quality estimators have been normalized and transformed to be in the range [0..100], where 0 is the worst link quality and 100 is the best. The aim of this transformation is to better visualize the different link quality estimates having different ranges, in the same X-axe . Fig. 4 shows that *PRR*, *SPRR* and *ETX* overestimate link quality as they estimate most of the links to have good quality. In contrary, *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 near to uniform distribution which mean that *F-LQE* is able to to distinguish between links having different link qualities. These observations confirm the reliability of *F-LQE*.

*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. Link quality estimators should resist to these fluctuations and provide stable link quality estimates. This property is of paramount importance in wireless sensor networks. For instance, routing protocols have not to reroute information when a link quality show transient degradation, because rerouting is a very energy and time consuming operation.

We measure the sensitivity of the link quality estimators to transient fluctuations by the coefficient of variation of its estimates. Fig. 5 compares the sensitivity (stability) of *F-LQE* with that of *PRR*, *ETX*, *SPRR*, *RNP* and *four-bit*. According this figure, we retain two observations: First, *PRR*-based link quality estimators, including *PRR*, *SPRR*, and *ETX* are the most stable, and *RNP*-based link quality estimators, including *RNP* and four-bit are the most instable. Second *F-LQE* is not the most stable link quality estimator, but its stability is in between *PRR*-based and *RNP*-based link quality estimators, which makes a good balance. We can not blame *F-LQE* on that because a very stable estimator trend to be less responsive to the major changes in link quality. Finally, we believe that *F-LQE* provides a good balance between sensitivity to transient changes and responsiveness to major changes, in link quality.

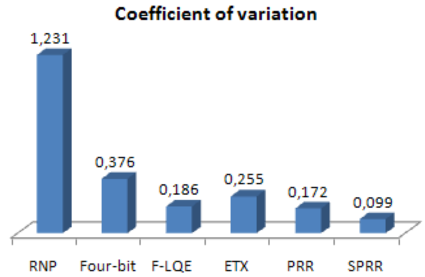



Fig. 5. Sensitivity to transient fluctuation in link quality.

## IV. Conclusion

In this poster, we have presented a novel link quality estimator (F-LQE) for wireless sensor networks, that combine several important link properties using Fuzzy Logic to provide a holistic characterization of the link. *F-LQE* has been evaluated extensively by simulation, demonstrating greater performance in terms of reliability and stability, over existing LQEs.

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