Low-Power Link Quality Estimation in Smart Grid Environments

Sana Rekik, Nouha Baccour, Mohamed Jmaiel
ReDCAD Laboratory
University of Sfax, Tunisia
{sana.rekik, nouha.baccour, mohamed.jmaiel}@redcad.org

Khalil Drira
LAAS-CNRS, France
Univ. de Toulouse, France
khalil.drira@laas.fr

***Abstract*—Several Link Quality Estimators (LQEs) have been proposed for Wireless Sensor Networks. However, their adequacy to smart grid environments has not been properly investigated. This paper addresses the problem of efficient low-power link quality estimation for smart grid environments. The first part of this paper presents a performance study of representative LQEs, namely ETX, four-bit and F-LQE, in three typical smart grid environments. These LQEs are evaluated in terms of reliability, stability and reactivity, by analyzing their statistical behavior. This study shows that F-LQE is more reliable and more stable than ETX and four-bit. However, it is not the most efficient for smart grid due to the lack of reactivity and also its higher complexity. Hence, the second part of this paper introduces Opt-FLQE, an optimized version of F-LQE that overcomes its limitations. The performance analysis of Opt-FLQE shows that it is more reactive than F-LQE while still being more reliable.**

Keywords*— *Wireless sensor networks, smart grid, link unreliability, link quality estimation, performance analysis.

I. INTRODUCTION

The need for energy conservation and environmental compliance has driven governments and utility industry over the world to transform their existing electrical grid into smart electrical grid or shortly "smart grid" [1]. Communication networks play an important role in the migration to a smarter grid [2], [3]. In particular, Wireless Sensor Networks (WSNs) have been recognized as a promising communication technology for smart grid monitoring and control applications [4], [5]. The potential applications enabled by WSNs in smart grid spread throughout the entire electric grid network, from power generation to transmission, distribution and consumption.

One of the challenges for the application of WSNs in smart grid monitoring applications is the unreliability of low-power links. This unreliability is firstly due to the low cost and low-power radio transceivers, typically used in WSNs. These radios turn links prone to noise, interference and multipath effects. Secondly, smart grid applications are commonly deployed in harsh environments characterized by highly corrosive conditions (e.g. wind, rain, solar radiation, humidity, etc.), vibrations, dust, etc, which turns low-power links even more unreliable. For example, field tests conducted in [5] reveal that low-power links in smart grid environments have high packet error rates and variable link delivery due to electric equipment's noise, electromagnetic interference, obstructions, multipath effects, and fading.

Efficient link quality estimation plays a crucial role to overcome low-power link unreliability and ensure reliable end-to-end communication, that represents a key requirement for smart grid applications [2]. For instance, link quality-aware routing allows delivering data over paths constituted of high quality links, which increases the end-to-end delivery rate and avoids excessive retransmissions over low quality links.

Despite its importance, few of works [6] addressed low-power link quality estimation in smart grid environments. In [6], the authors conduct a performance analysis of five LQEs in smart grid environments. The evaluation methodology consists in studying the impact of each LQE on routing performance, specifically the Collection Tree routing Protocol (CTP). However, this evaluation methodology does not provide definitive conclusions about LQEs performance because what is effectively evaluated is not the LQE alone, but the designed routing metric that is based on a particular LQE.

In this work, we propose to study the adequacy of representative LQEs, namely ETX, four-bit and F-LQE, to smart grid as in [6]. However, we adopt a different evaluation methodology, which consists in analyzing the statistical properties of LQEs independently from any external factors like MAC collisions or routing [7]. Considered LQEs (Section II) are evaluated in terms of reliability, stability and reactivity, in three typical smart grid environments: outdoor substation environment, indoor main power control room, and underground network transformer vaults. Our study (Section III) shows that F-LQE is more reliable and more stable than ETX and four-bit. However, it has the limitation to be not sufficiently reactive and also more complex. Thus, we introduce Opt-FLQE (Section IV), an optimized version of F-LQE that overcomes its limitations. The performance analysis of Opt-FLQE shows that it is more reactive than F-LQE while still being more reliable.

II. LQEs UNDER STUDY

Several Link Quality Estimators (LQEs) have been proposed. They can be classified into two categories: (i) single LQEs, such as PRR (Packet Reception Ratio), RNP (Required Number of Packet re-transmissions), WMEWMA (the Window Mean with Exponentially Weighted Moving Average), SNR (Signal-to-Noise Ratio), and RSSI (Received Signal Strength Indicator) and (ii) composite LQEs, such as ETX

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(Expected Transmission Count), four-bit, and F-LQE (Fuzzy-Link Quality Estimator).

Generally, single LQEs are based on a single link metric and then assess a particular link property, while composite LQEs combines several metrics in order to provide a more holistic link quality estimation. Currently, there is a growing awareness that reliable link quality estimation cannot be achieved only through a composite LQE [8]. Hence, we select in our study the most representative composite LQEs, namely ETX, four-bit and F-LQE. A brief overview of these LQEs is given next.

ETX [9] and four-bit [10] approximate the required number of packet re-transmissions. ETX takes into account link asymmetry by combining the inverse of the PRR in both directions of the link. Four-bit also takes into account link asymmetry by combining a sender-initiated metric — RNP and a receiver initiated metric — the inverse of WMEWMA, using the EWMA filter for the combination. F-LQE [11] is a recent composite LQE. It combines four metrics, namely PRR, SNR, ASL (link ASymmetry Level) and SF (link Stability factor), using Fuzzy Logic for the expression and combination of the metrics. It provides a score ranging in [0..100], where 0 is the worst quality and 100 is the best.

III. Performance analysis of LQEs

In this section, we propose to evaluate the performance of ETX, four-bit, and F-LQE in smart grid environments. Our study is based on TOSSIM 2 simulator [12]. Importantly, we set our simulations using channel parameters empirically derived in [5] where log-normal shadowing path loss model has been adopted to model the wireless channel. These channel parameters (refer to Table I) reflect radio propagation behavior in typical smart grid distribution environments, including outdoor 500 kV substation, indoor main power control room and underground network transformer vault environments.

As for our evaluation methodology, we adopted the methodology introduced in [7], which consists in analyzing the statistical properties of LQEs independently of any external factor, such as routing (a single-hop network) and collisions (each node transmits its data in a separated time slot). These properties impact the performance of LQEs, in terms of:

- **Reliability:** It refers to the ability of a LQE to correctly characterize the link state (to capture the real behavior of the link). It is assessed *qualitatively*, by analyzing its temporal behavior and the distribution of its link quality estimates, illustrated by the cumulative distribution function (CDF).
- **Stability:** It refers to the ability of a LQE to tolerate transient (short-term) degradation in link quality mainly due to the environmental factors (noise, obstacles, etc.). It is assessed *quantitatively*, by computing the coefficient-of-variation (CV) of the link quality estimates, which is defined as the ratio of the standard deviation to the mean.
- **Reactivity:** It refers to the ability of a LQE to quickly react to persistent changes in link quality. It is assessed *qualitatively*, by observing their temporal behavior.

It should be pointed out that in link quality estimation, there is no real link quality metric of reference, which other link quality estimators can be compared to. Therefore, as in [7], we mutually compare the empirical behaviors of LQEs under study by means of statistical analysis of empirical data.

The rest of this section is organized as follow. We first identify the reception regions, with respect to each power distribution environment, based on extensive simulation. Then, we describe the simulation scenario for our performance analysis of LQEs. Finally, we present the simulation results.

A. Reception regions identification

An important spatial feature of low-power links is the existence of three reception regions [8]: (i.) *connected*, where links are often of high packet delivery (i.e., PRR is greater than 90%), stable, and symmetric (ii.) *transitional*, where links are of moderate packet delivery (i.e., PRR in long-term assessment is between 10% and 90%), unstable, and often asymmetric (iii.) *disconnected*, where links have low packet delivery (i.e., PRR is less than 10%), and are overall inadequate for communication.

The identification of the reception regions in each smart grid environment, especially the extent of the transitional, allowed us to properly place the nodes to have links belonging to the three reception regions, as depicted in Table II, and then get a rich set of links having different qualities. It also allowed us to better interpret the decisions made by LQEs in classifying and estimating links. For example, a link of the transitional region classified by a giving LQE as having perfect quality means that this latter is inaccurate or over-estimate link quality.

We derive the bounds of the three reception regions with respect to each smart grid environment, through measurements of PRR as a function of the distance, as illustrated in Fig. 1. This figure shows that the width and the proportion of the transitional region vary from one environment to another, which not only confirms observations made by experimental studies on low-power links [8], but also illustrates the accuracy of TOSSIM simulator.

B. Simulation scenario description

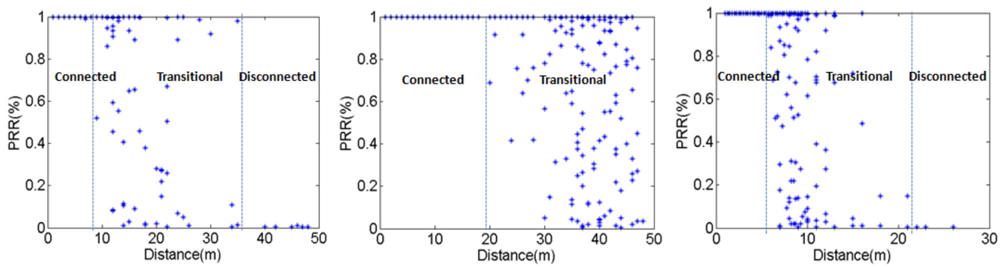
We have considered a single-hop network of 10 sensor nodes (N1, N2...N10) placed in a linear topology, where N1 is the sink. The nodes layout in different smart grid environments is illustrated in Table II. N1 and Ni are synchronized to exchange packets (one packet a time) to estimate the bidirectional link quality (i.e., to evaluate link asymmetry): Each mote sends a packet to the other mote every 1 second (inter-packets interval), until reaching a total number of sent packets equal to 1000. The nodes neither rely on a particular communicating technology (such as Zigbee or 6LowPAN), nor use any particular protocol at MAC and network layers.

C. Simulation results

In this section, we present the simulation results related to the performance of ETX, four-bit and F-LQE, in terms of reliability, stability and reactivity. Due to lack of space, we only show results with respect to one smart grid environments.

TABLE I
PATH LOSS, SHADOWING DEVIATION AND NOISE FLOOR IN SMART GRID ENVIRONMENTS [5].

Propagation environment	Type of the environment	Path loss	Shadowing deviation	Noise floor (dBm)
500 kV substation	Outdoor	3.51	2.95	-93
Underground transformer vault (UTV)	Indoor	3.15	3.19	-92
Main power control room	Indoor	2.38	2.25	-88



(a) UTV (b) Indoor main control power room (c) Outdoor 500-kV substation

Fig. 1. Reception regions, in different smart grid environments (observed by TOSSIM simulation).

TABLE II
LAYOUT OF THE NODES IN DIFFERENT SMART GRID ENVIRONMENTS.

Smart grid environment	Layout of the nodes
500 kV substation	(1,0), (5,0), (8,0), (9,0), (10,0), (11,0), (12,0), (13,0), (15,0), (16,0)
Main power control room	(1,0), (20,0), (30,0), (35,0), (40,0), (45,0), (50,0), (55,0), (60,0), (65,0)
Underground transformer vault	(1,0), (8,0), (18,0), (20,0), (22,0), (24,0), (26,0), (28,0), (30,0), (32,0)

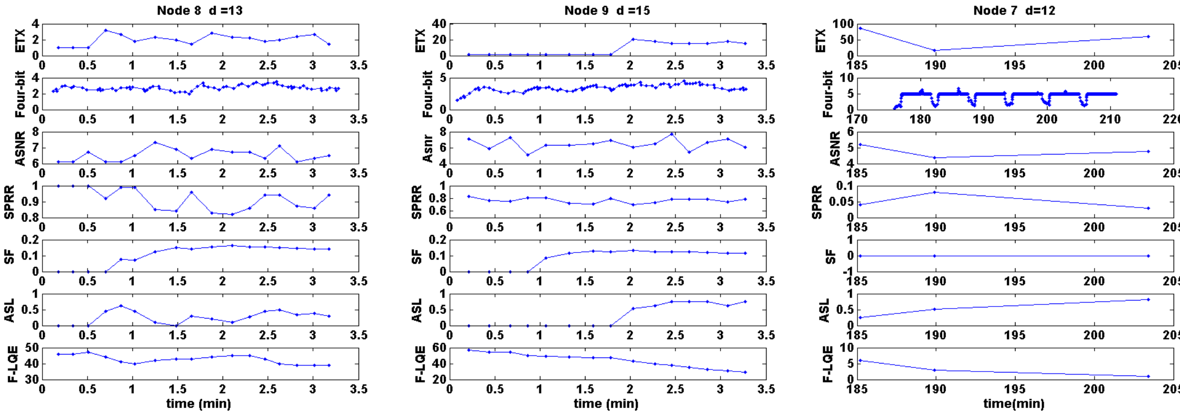
1) ***Reliability****:* LQEs reliability can be inferred from the temporal behaviour of links as well as the distribution of link quality estimates, illustrated by the empirical cumulative distribution function (CDF). Notice that in CDF, link quality estimates have been normalized to the interval [0..100], where 0 represents the worst link quality and 100 represents the best. This normalization aims to better compare link quality estimates with respect to each LQE. In the following, we summarize simulation results into high-level observations:

Observation 1: Four-bit is more reliable than ETX, which overestimates link quality. Fig. 2 shows the temporal behaviour of each estimator with respect to three different links belonging to the substation environment. For instance, in Fig. 2b, ETX partially over-estimates link quality, precisely until time 1,8 min, because it estimates the link to have perfect quality, i.e., 0 retransmissions. However, as this link belongs to the transitional region (refer to Fig. 1), its overall quality should not be as good. On the other hand, four-bit does not over-estimate link quality as it provides scores that correspond to a moderate quality link. This observation can be also confirmed by the distribution of link quality estimates shown in Fig. 3. This figure presents the global empirical CDFs, with respect to each LQE, in the underground network transformer vault environment. Again, ETX over-estimates link quality: almost 80% of links have ETX equal to 100.

Observation 2: F-LQE is more reliable than ETX and four-bit. This observation can be justified by the fact that F-LQE accounts for four link properties namely, link delivery, link asymmetry, link stability and channel quality; against three and two link properties for four-bit and ETX respectively. The reliability of F-LQE is well confirmed by analyzing its temporal behaviour and the distribution of its link quality estimates.

The temporal behaviour of F-LQE and its related metrics is illustrated in Fig. 2. This figure shows that F-LQE provides more reasonable link quality estimates than ETX and four-bit. The moderate link depicted in Fig. 2a has good packet delivery and high stability, but it has also some negative features, namely medium channel quality (i.e., ASNR between 6 and 8 dBm) and high asymmetry. As a result, F-LQE link quality estimates are between 40 and 50 (out of 100). These link scores appear reasonable, given the link properties and given the fact that the link is situated in the medium of the transitional region (refer to Fig. 1). The same observation holds for the second moderate link in Fig. 2b. Besides, F-LQE shows that the link clearly degrades over time from 60 to 25. This is due to asymmetry property which also follows the same degradation. Recall that both ETX and four-bit are asymmetry-aware, but their temporal behavior shows that only ETX was able to capture this degradation. This is because in contrast to ETX and F-LQE, four-bit does not explicitly evaluate link asymmetry property. Rather, it considers link asymmetry property by combining RNP (which estimates the quality of the unidirectional link from the receiver to the sender) and smoothed PRR (which estimates the quality of the unidirectional link from sender to receiver).

In Fig. 3, it is clear that the distribution of F-LQE is near to uniform distribution, which proves the ability of F-LQE to distinguish between links having different qualities in a noisy environment such the underground transformer vaults. Note that F-LQE link quality estimates are between 10 and 100, where 50% of the links have an average link estimate equal to 80, which reflects moderate quality links.



(a) First moderate link (N1,N8)

(b) Second moderate link (N1,N9)

(c) Bad link (N1,N7)

Fig. 2. Temporal behaviour of LQEs, in the substation environment.

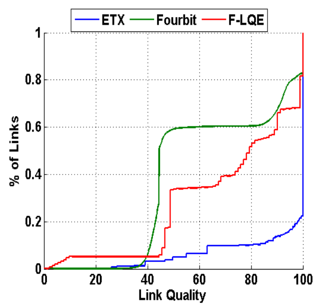


Fig. 3. Empirical CDFs of LQEs, in the UTV environment.

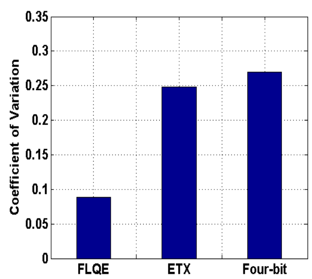


Fig. 4. Stability of LQEs, in the UTV environment.

*2) **Stability**:* The environment nature is the main responsible for transient link quality fluctuations. LQEs should be robust against these fluctuations and provide stable link quality estimates. We measured the stability of the LQEs through the coefficient-of-variation (CV) of their estimates.

Fig. 4 compares the stability of LQEs, in the underground network transformer vault environment. According to this figure, F-LQE is the most stable estimators (i.e., have the lowest CV). Especially, F-LQE stability comes from the use the EWMA filter that smoothes link quality estimates.

*3) **Reactivity**:* A link may show transient or persistent link quality fluctuations. In the previous section, we argued that an efficient LQE should be robust against transient fluctuations. However, such LQE has to be reactive to persistent changes in link quality.

To reason about this issue, we observe the temporal behaviour of a bad quality link, illustrated in Fig. 2c. From this figure, we can clearly observe that ETX and F-LQE, which are computed at the receiver side, are not responsive to link quality degradation. Generally, when the link is bad, packets are retransmitted many times without being successfully delivered to the receiver. Hence, receiver-side LQEs such as ETX and F-LQE, can not be computed and updated, which turns them not sufficiently reactive. On the other hand, four-bit is more reactive as it is computed at the sender side.

*4) **Discussion**:* Simulation results presented in the previous sub-sections show that F-LQE performs better than other considered LQEs. However, F-LQE is not the most efficient LQE for smart grid applications for the following reasons:

- First, in [5], it has been observed that low-power links in smart grid environments, suffer from excessive packet losses due to electric equipment's noise, electromagnetic interference, obstructions, multipath effects, and fading. Hence, receiver-side LQEs, such as F-LQE would not be efficient in such deployments due to their lack of reactivity as discussed in Section III-C3.
- Second, F-LQE has higher computation complexity, which not only can affect the network lifetime, but also the communication delay. In smart grid communication, a key requirement especially in delay critical applications [3] is low end-to-end communication delay. The computation of F-LQE involves an additional delay, pertaining to its complexity. This complexity mainly comes from its SF metric. As a matter of fact, F-LQE complexity is O(1) plus the complexity of the square root function in SF metric (for computing standard deviation).

Therefore, in the next section, we propose to optimize F-LQE to have a more efficient LQE for smart grid environments.

IV. Optimization of F-LQE for Smart Grid Applications

A. Overview of Opt-FLQE (Optimized F-LQE)

Our aim is to design an optimized version of F-LQE that (i) preserves the strength of the initial F-LQE in terms of reliability and stability, (ii) improves its reactivity, and (iii) reduces its computation complexity. To achieve this goal, we propose the following design optimizations:

- We omit the SF metric in F-LQE to reduce its complexity. Obviously, this will be at the cost of F-LQE reliability/accuracy. However, we believe (and prove in next section) that

F-LQE reliability can be preserved by integrating another metric, which is not complex, but contributes to a holistic link quality estimation, as detailed next.

- In our study of LQEs, we have observed that sender-side LQEs are more reactive than receiver-side as they can still provide a feedback on the link even when packets are not received. Hence, to improve the reactivity of F-LQE we propose to integrate a sender-side metric: the number packet retransmissions over the link, assessed by smoothed RNP (SRNP) using EWMA filter. The use of EWMA filter allows neglecting transient fluctuation of RNPs. In addition to reactivity improvement, the consideration of the SRNP metric brings a couple of advantages. First, Opt-FLQE is a hybrid LQE, as it is both sender-side (by assessing SRNP) and receiver-side (by assessing SPRR, ASL and ASNR). Consequently, it can provide a bidirectional link quality estimates as it assesses both link directions: SRNP assesses the outgoing link direction and SPRR assesses the incoming link direction. Second, the SRNP metric is expected to improve the reliability of F-LQE and overcome the suppression of SF metric. In fact, except ASNR, all F-LQE metric are PRR-based, including SPRR, ASL and SF (i.e., they rely on PRR in their computation). The consideration SRNP, allows reflecting a different link aspect, namely the number of retransmissions over the link, which contributes to holistic link quality estimation.

Thus, Opt-FLQE combines four metrics, namely SPRR, SRNP, ASNR and ASL. These metrics assess four link aspects, namely packet delivery, packet retransmissions, channel quality and link asymmetry, respectively. These link properties are considered as fuzzy variables, and combined using the following fuzzy rule that expresses the goodness of a link:

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

To produce a numerical value of the link quality, the above rule translates to the following equation of the fuzzy measure of the link *i* high quality.

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

The parameter β is a constant set to 0.6 as recommended by [11]. μ_{SPRR}, μ_{ASL}, μ_{SRNP} and μ_{ASNR} represent membership functions in the fuzzy subsets of high packet reception ratio, low asymmetry, low packet retransmissions, and high channel quality, respectively. We retain the same membership functions for μ_{SPRR}, μ_{ASL} and μ_{ASNR} as in [11]. Each membership function has piecewise linear form, determined by two thresholds.

For μ_{SRNP}, we performed several simulations while varying SRNP thresholds. Then, we retained the thresholds that lead to the best statistical behaviour of Opt-FLQE, namely 1 and 4. Thus, for values of SRNP below 1 retransmission, the membership to the fuzzy subset of links with low RNP is of 1. Starting from 4 retransmissions, the link is considered totally out of the fuzzy subset of links with low RNP. For value of SRNP between 1 and 4, the membership decreases linearly to achieve 0 when SRNP is equal to 4.

When w_r packets are received, a node computes μ_{SPRR}, μ_{ASL} and μ_{ASNR} and then computes $\mu(i)$ based on the most recent value of μ_{SRNP}. When w_t packets are transmitted/retransmitted, a node computes μ_{SRNP} and then updates $\mu(i)$. Finally, $\mu(i)$ values are smoothed using the EWMA filter, in order to provide stable link estimates. Opt-FLQE metric is then given the following equation, where α, equal to 0.9 as in [11], controls the smoothness:

$$\text{Opt-FLQE}(\alpha, w_r, w_t) = \alpha.\text{Opt-FLQE} + (1-\alpha).100.\mu(i) \quad (2)$$

B. Opt-FLQE validation

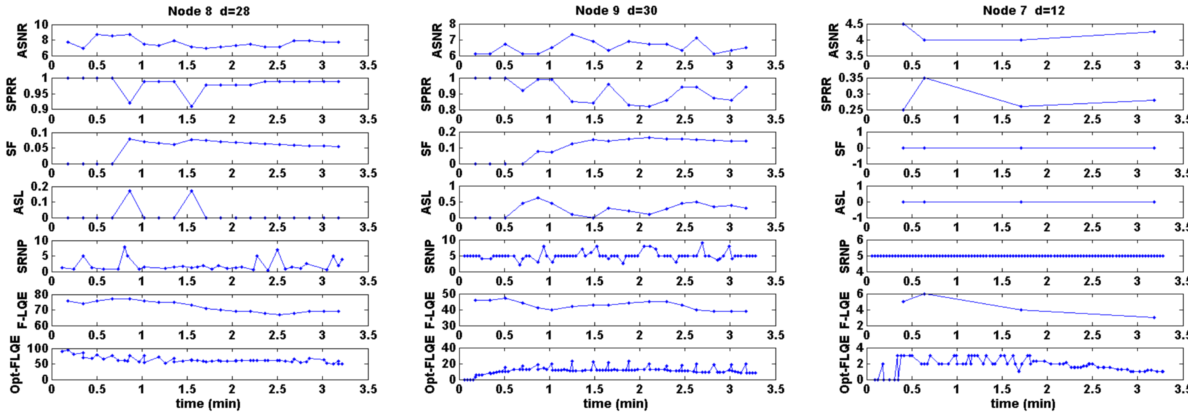
In this section, we examine the statistical properties of Opt-FLQE using TOSSIM simulation. Especially, we compare the performance of Opt-FLQE against the original F-LQE in terms of reliability, stability and reactivity.

The reliability of F-LQE and Opt-FLQE is tested by studying their temporal behavior (Fig. 5) and the distribution of their link quality estimates (Fig. 6).

Fig. 5 shows the temporal behaviour of F-LQE and Opt-FLQE, and their related link quality metrics, with respect to two moderate links, belonging to the underground transformer vaults. Fig. 5a shows that Opt-FLQE should be more reliable than F-LQE as it provides a more fine grain estimation traduced by a larger spectrum of scores: Opt-FLQE scores are between 50 and 100 against 50 and 80 for F-LQE. This can be justified by the fact that Opt-FLQE can still provide a score for the link when packets are not received and thus receiver-side metrics (i.e., SPRR, ASL, and ASNR) are not updated. Further, Fig. 5b depicts that F-LQE can over-estimate link quality (scores between 40 and 50), in contrast to Opt-FLQE (generally lower than 20) thanks to SRNP metric. A common behaviour of moderate links is having packets successfully reaching the receiver but after several retransmissions due the transitional region effects. Consequently, the PRR over the link can be high but the RNP is also high. This is indeed the cause of F-LQE overestimation, caused by its SPRR metric. Opt-FLQE also integrates SPRR, but the overestimation effect of SPRR is amended and neutralized through the use of SRNP.

From the distribution of link quality estimates, depicted in Fig. 6, we can retain two observations. First, the Opt-FLQE estimation spectrum is always more spread than that of F-LQE. The average Opt-FLQE scores vary from 0 to 100, i.e., it is able to distinguish between links having different qualities (good, moderate or bad). However, the scores of F-LQE are between 33 and 100, i.e., it classifies links as either good or moderate and it often misclassifies bad links. Recall that in our simulation scenario, we set the links to have diverse qualities and spread throughout the different reception regions (see Section III-A for more details). These observations are justified by the fact that in contrast to Opt-FLQE, F-LQE is receiver-side and is not aware of the RNP.

Fig. 7 compares the stability of Opt-FLQE with that of F-LQE. This figure shows that Opt-FLQE is less stable than



(a) Moderate link (N1,N8), UTV environment (b) Moderate link (N1,N9), UTV environment (c) Bad link (N1,N7), Substation environment

Fig. 5. Temporal behaviour of F-LQE and Opt-FLQE.

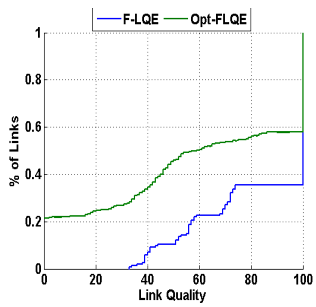


Fig. 6. Empirical CDFs of Opt-FLQE, in the UTV environment.

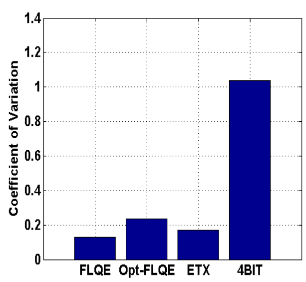


Fig. 7. Stability of Opt-FLQE, in the UTV environment.

F-LQE, but more stable than four-bit. This can be justified by the integration of SRNP metric. This instability can be easily filtered out by smoothing more SRNP using the EWMA filter. However, we believe that stability and reliability are at odds. Smoothing SRNP would alter the reliability of Opt-FLQE.

As for the reactivity of Opt-FLQE, it can be clearly observed in Fig. 5c that Opt-FLQE is more reactive than the F-LQE thanks to the SRNP metric, which updates Opt-FLQE estimate even when packets are lost.

V. Conclusion

This paper targeted efficient low-power link quality estimation in smart grid environments. The carried study consists in two main parts. In the first part, we analyzed the performance of representative LQEs, namely ETX, four-bit and F-LQE. This study is likely to help network designers to choose the most adequate LQE for smart grid environments. To this end, we evaluated the considered LQEs in terms of reliability, stability and reactivity, by analyzing their statistical behavior in three typical smart grid environments. Simulation results demonstrate that, F-LQE is more reliable and more stable than ETX and four-bit. However, it has the limitations to be not sufficiently reactive, especially in smart grid environments characterized by excessive packet loss; and also more complex than other LQEs. Hence, in the second part of our study, we proposed Opt-FLQE, an optimized version of F-LQE that overcomes the limitations of original F-LQE and appears more convenient to smart grid environments.

References

[1] X. Fang, S. Misra, G. Xue, and D. Yang, “Smart grid - the new and improved power grid: A survey,” *IEEE Communications Surveys and Tutorials*, vol. 14, no. 4, pp. 944–980, 2012.

[2] W. Wang, Y. Xu, and M. Khanna, “A survey on the communication architectures in smart grid,” *Computer Networks*, vol. 55, no. 15, pp. 3604–3629, 2011.

[3] Y. Yan, Y. Qian, H. Sharif, and D. Tipper, “A survey on smart grid communication infrastructures: Motivations, requirements and challenges,” *IEEE Communications Surveys and Tutorials*, vol. 15, no. 1, pp. 5–20, 2013.

[4] M. Erol-Kantarci and H. T. Mouftah, “Wireless multimedia sensor and actor networks for the next generation power grid,” *Ad Hoc Networks*, vol. 9, no. 4, pp. 542–551, 2011.

[5] V. C. Gungor, B. Lu, and G. P. Hancke, “Opportunities and challenges of wireless sensor networks in smart grid,” *IEEE Transactions on Industrial Electronics*, vol. 57, no. 10, pp. 3557–3564, 2010.

[6] V. C. Gungor and M. K. Korkmaz, “Wireless link-quality estimation in smart grid environments,” *IJDSN*, vol. 2012, 2012.

[7] N. Baccour, A. Koubaa, M. B. Jamâa, D. do Rosário, H. Youssef, M. Alves, and L. B. Becker, “Radiale: A framework for designing and assessing link quality estimators in wireless sensor networks,” *Ad Hoc Networks*, vol. 9, no. 7, pp. 1165–1185, 2011.

[8] N. Baccour, A. Koubaa, L. Mottola, M. A. Z. Zamalloa, H. Youssef, C. A. Boano, and M. Alves, “Radio link quality estimation in wireless sensor networks: A survey,” *TOSN*, vol. 8, no. 4, p. 34, 2012.

[9] D. S. J. D. Couto, D. Aguayo, J. C. Bicket, and R. Morris, “a high-throughput path metric for multi-hop wireless routing,” *Wireless Networks*, vol. 11, no. 4, pp. 419–434, 2005.

[10] C. Dovrolis, V. Paxson, and S. Savage, Eds., *6th ACM Workshop on Hot Topics in Networks - HotNets-VI, Atlanta, Georgia, USA, November 14-15, 2007.* ACM SIGCOMM, 2007.

[11] N. Baccour, A. Koubaa, H. Youssef, M. B. Jamâa, D. do Rosário, M. Alves, and L. B. Becker, “F-lqe: A fuzzy link quality estimator for wireless sensor networks,” in *EWSN*, 2010, pp. 240–255.

[12] P. Levis, N. Lee, M. Welsh, and D. Culler, “Tossim: Accurate and scalable simulation of entire tinyos applications,” in *Proceedings of the 1st International Conference on Embedded Networked Sensor Systems*, ser. SenSys ’03. New York, NY, USA: ACM, 2003, pp. 126–137. [Online]. Available: http://doi.acm.org/10.1145/958491.958506