Experiencing low power wireless links in distribution smart grid environments

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***Abstract*—Wireless Sensor Networks (WSNs) have been recognized as a promising communication technology for the Internet of Things (IoT). In particular, smart grid applications rely on WSNs for enabling pervasive monitoring and control of the electric grid. However, these applications are commonly deployed in harsh environments that adversely impact the reliability of low-power wireless links in WSNs. Efficient link quality estimation has been shown as a prerequisite to overcome link unreliability. Several WSN Link Quality Estimators (LQEs) have been proposed in the literature. However, there is a lack of real world experimentations that investigate their adequacy to assess low-power links in smart grid environments. To fill this gap, this paper presents a thorough experimental study of representative LQEs in a smart grid distribution substation. Both single and composite LQEs are evaluated in terms of reliability, stability and reactivity, by analyzing their statistical behavior. This study would help system designers choose the most appropriate estimators for smart grid environments. Especially, it shows that composite LQEs, such as Opt-FLQE, F-LQE, and four-bit, are more reliable than single LQEs, including PRR, WMEWMA, and RNP. Further, experimental results show that Opt-FLQE is found to be the most reliable estimator, F-LQE, PRR, and WMEWMA are the most stable estimators, while Opt-FLQE, RNP, and four-bit are the most reactive LQEs.**

Keywords— Wireless sensor network, smart grid environment, link quality estimation, experimentation.

I. Introduction

With the asset of its unprecedented flexibility and low cost, Wireless Sensor Networks (WSNs) have witnessed an integration in several monitoring and tracking domains, such as medical monitoring, military tracking, agriculture and environment monitoring. Over the years, WSN applications are more and more diversified, e.g. smart homes, intelligent transportation, smart water networks, etc., which are usually associated to the concept of the Internet of Things (IoT). In particular, WSNs have been recently recognized as a promising communication technology to enable the pervasive monitoring in smart grids, the next generation of traditional electric grids [1], [2],

The equipment failures and the limited monitoring and control capabilities in the traditional electric grid are among the main motivations for the migration to a smarter grid with advanced communication and monitoring skills. WSNs enable several smart grid monitoring applications in order to avoid the impact of electric equipment failures and natural accidents leading to power disturbances and outages [3], [4]. These potential monitoring applications include monitoring of wind farms and photo-voltaic panels, distributed energy generation, monitoring of substation equipments, Automatic Meter Reading (AMR), Advanced Metering Infrastructure (AMI), and home/building energy management [5]–[9].

The deployment of WSNs in smart grids brings new challenges, including the unreliability of low-power links. This unreliability is due to the harsh electric grid environments. Field tests conducted in [4] 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. Link quality estimation plays a crucial role to overcome low-power link unreliability and to ensure reliable communication, that represents a key requirement for smart grid applications [10]. For instance, link quality-aware routing allows delivering data over paths constituted of high quality links, which avoids excessive retransmissions over low quality links and increases the end-to-end delivery rate.

Several Link Quality Estimators (LQEs) have been proposed. Their adequacy to smart grid environments has been investigated in [11], [12], based on network simulation, using channel parameters of typical smart grid distribution environments derived in [4]. However, to our best knowledge, the performance analysis of these LQEs in real smart grid environments has not been assessed based on experimentation. Such experimental studies are of paramount importance, as they provide performance results with high confidence. To fill this gap, this paper presents a thorough experimental evaluation study of representative LQEs in an electrical substation, situated at the distribution side of the smart grid. Both single and composite LQEs are considered in our study. These LQEs are evaluated in terms of reliability, stability and reactivity, by analyzing their statistical behavior, such as the distribution of their link quality estimates.

The rest of this paper is organized as follows: in the next section, we discuss related work. In Section III, a description of the link quality estimators considered in our study is given. The methodology used to compare these estimators is presented in Section IV. The experiment description and results are presented in Section V and VI respectively. We conclude in Section VII.

II. Related work

Several LQEs have been designed to enhance the accuracy of link quality estimation in WSNs. They can be classified into two categories: (i) single LQEs, which are based on a single link metric and then assess a particular link property and (ii) composite LQEs, which combines several metrics in order to provide a more holistic link quality estimation.

Single LQEs: they can be either hardware-based or software-based. RSSI (Received Signal Strength Indicator), LQI (Link Quality Indicator) and SNR (Signal-to-Noise Ratio) are examples of hardware-based LQEs that assess the channel quality. Their advantage is that they do not require any additional computation overhead as they are directly read from the radio transceiver (e.g., the CC2420). However, they do not provide accurate assessment of link quality [13], [14].

PRR (Packet Reception Ratio) and RNP (Required Number of Packet re-transmissions) are basic software-based estimators [15]. RNP [15] counts the average number of packet transmissions/re-transmissions, required before successful reception. The Window Mean with Exponentially Weighted Moving Average (WMEWMA) [16] is another software-based LQE that smooths the PRR by applying EWMA filter.

Composite LQEs: the ETX (Expected Transmission Count) [17] and four-bit [18] are well known composite LQEs that approximate the RNP. The Fuzzy-link quality estimator (F-LQE) [19] is another 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. Opt-FLQE (Optimized F-LQE) [12] is a modification of F-LQE that aims to improve its reactivity and to reduce its computational complexity. It uses the Smoothed RNP (SRNP) metric instead of SF. It was developed to be suitable for harsh smart grid environments.

Despite its importance, few of works [11], [12] addressed low-power link quality estimation in smart grid environments. In [11], the authors conduct a comparative simulation study of five LQEs (PRR, WMEWMA, ETX, RNP, and four-bit) in smart grid environments. It was found that ETX and four-bit outperform PRR, WMEWMA, and RNP since they consider the link asymmetry property. The used 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 for the following reason: each LQE is integrated to CTP using a different routing metric. A routing metric allows to compute the path cost based the LQE in question. As LQEs have different natures, corresponding routing metrics have different expressions. Routing metrics design greatly impacts the overall routing performance. Hence, what is effectively evaluated is not the LQE alone, but the designed routing metric that is based on a particular LQE.

The authors in [12] use a different evaluation methodology that overcomes the limitations of that presented in [11]. This methodology consists in analyzing the statistical properties of LQEs, independently from any external factors like MAC collisions or routing. In our study, we adopt this evaluation methodology. Hence, the authors in [12] found that opt-FLQE is more reactive than F-LQE, and more reliable than ETX, four-bit, and F-LQE.

The above studies related to link quality estimation in smart grid environments are based on network simulations. This motivate us to conduct experimental evaluation of LQEs through field trials in harsh smart grid environments. In this work, we propose to experimentally study the performance of representative LQEs, including both single and composite estimators, by analysing their statistical properties.

III. Representative LQEs

A description of the LQEs considered in our study is given next. Their main characteristics are summarized in Table I.

- *PRR* is a receiver-side estimator. It is computed as the ratio of the number of successfully received packets to the number of sent packets, for each window of w received packets. The receiver uses the packets sequence number to figure out the number of lost packets and then the number of total sent packets [20]. PRR is given by the following:

$$\text{PRR } (w) = \frac{\textit{Number of received packets}}{\textit{Number of sent packets}} \tag{1}$$

- *WMEWMA* is a receiver-side estimator that smoothes PRR using filtering, as follows:

$$\textit{WMEWMA}(\alpha, w) = \alpha \times \textit{WMEWMA} + (1 - \alpha) \times \textit{PRR} \tag{2}$$

where $\alpha \in$ [0-1] controls the smoothness. Thus WMEWMA provides a metric that resists to transient fluctuation of PRRs.

- *RNP* is a sender-side estimator, which counts the average number of packet retransmissions required to send a packet successfully. It is computed as the number of transmitted and retransmitted packets divided by the number of successfully received packets; minus 1 (to exclude the first packet transmission) [20]. This metric is evaluated at the sender side for each w packets, as shown in the following equation:

$$\text{RNP}(w) = \frac{\textit{Number of transmitted and retransmitted packets}}{\textit{number of successfully received packets}} - 1 \tag{3}$$

Note that the sender determines the number of successfully received packets as the number of acknowledged packets.

- *ETX* is a receiver-side estimator that approximates the packet retransmissions count (RNP). It is computed as the inverse of the product of PRR of the uplink (from the sender to the receiver) and the PRR of the downlink (from the receiver to the sender). The combination of both PRR estimates provides an estimation of the bidirectional link quality (i.e., an estimation that takes into account link asymmetry), expressed as:

$$\text{ETX}(w) = \frac{1}{PRR_{uplink} \times PRR_{downlink}} \tag{4}$$

Note that ETX computes the PRR of the uplink in the same way with PRR, while the PRR of the downlink is computed at the sender and sent to the receiver in the probe packet.

- *Four-bit* approximates the packet retransmissions count (RNP) by combining two metrics (i) RNP, computed based on w_t transmitted/retransmitted data packets. It assesses the quality of the uplink and it is denoted as $estETX_{up}$, and (ii) the inverse of WMEWMA, minus 1; computed based on w_r received beacon packets. This metric assesses the quality of the downlink and it is denoted as $estETX_{down}$. Four-bit is then both a sender- and receiver-side LQE.
The combination of $estETX_{up}$ and $estETX_{down}$ allow to consider the link asymmetry property. It is performed through the EWMA filter as follow:

$$\textit{four-bit}(w_r, w_t, \alpha) = \alpha \times \textit{four-bit} + (1 - \alpha) \times estETX \quad (5)$$

estETX corresponds to $estETX_{up}$ or $estETX_{down}$: at w_r received beacons, the node derives Four-bit estimate by replacing estETX in Eq.5 for $estETX_{down}$. At w_t transmitted/re-transmitted data packets, the node derives Four-bit estimate by replacing estETX in Eq.5 for $estETX_{up}$.
- *F-LQE* is a receiver-side estimator, where link quality is estimated on the basis of 4 link properties in order to provide a holistic characterization of the link: (i) packet delivery, captured by the Smoothed Packet Reception Ratio (SPRR) which is exactly the WMEWMA, (ii) link asymmetry, assessed by the measure of the difference between the uplink PRR and the downlink PRR, noted as ASL (ASymmetry Level), (iii) link stability, assessed by the measure of the stability factor (SF), defined as the coefficient-of-variation of PRR, and (iv) channel quality, evaluated through the measure of the average Signal-to-Noise Ratio (ASNR).
F-LQE considers each of these link properties as a different fuzzy variable and combines them using Fuzzy Logic. The high quality of a link is characterized by the following fuzzy rule:

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

For a particular link, the fuzzy logic interpretation of this rule gives an estimation of its quality as a membership score in the fuzzy subset of good quality links. Scores near 1/0 are synonym of good/poor quality links. Hence, the membership of a link in the fuzzy subset of good quality links is given by the following equation:

$$\mu(i) = \beta \times min(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) + (1 - \beta) \times mean(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SF}(i), \mu_{ASNR}(i)) \quad (6)$$

The parameter β is a constant in [0-1]. $\mu_{SPRR}, \mu_{ASL}, \mu_{SF}$, and μ_{ASNR} represent membership functions in the fuzzy subsets of high packet reception ratio, low asymmetry, high stability, and high channel quality, respectively. All membership functions have piecewise linear forms, determined by two thresholds. In order to provide stable link estimates, F-LQE uses the EWMA filter to smooth $\mu(i)$ values. F-LQE metric is finally given by:

$$\text{F-LQE}(\alpha, w) = \alpha \times \text{F-LQE} + (1 - \alpha) \times 100 \times \mu(i) \quad (7)$$

where, $\alpha \in$ [0-1] controls the smoothness and *w* is the estimation window. F-LQE attributes a score to the link, ranging in [0-100], where 100 is the best link quality and 0 is the worst.
- *Opt-FLQE* is an optimized version of F-LQE that (i.) reduces its computational complexity through the omission of the SF metric, and (ii.) improves its reactivity through the integration of a sender-side metric: the number of packet retransmissions over the link, assessed by smoothed RNP (SRNP) using EWMA filter. The SRNP, which is a sender-side metric, is known to be more reactive than receiver-side metrics: it can still provide a feedback on the link even when packets are not received.
Therefore, 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, receptively. These link properties are considered as fuzzy variables, and combined using a 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.

$$\mu(i) = \beta. \min(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SRNP}(i), \mu_{ASNR}(i)) + (1 - \beta).mean(\mu_{SPRR}(i), \mu_{ASL}(i), \mu_{SRNP}(i), \mu_{ASNR}(i)) \quad (8)$$

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. 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/re-transmitted, 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) controls the smoothness:

$$\text{Opt-FLQE}(\alpha, w_r, w_t) = \alpha.\text{Opt-FLQE} + (1 - \alpha).100.\mu(i) \quad (9)$$

TABLE I
CHARACTERISTICS OF LQES UNDER EVALUATION.

Software-based estimators		Assessed link property	Input	Technique to asses link state	Asymmetry support	Location
Single	PRR	Link delivery	Packets sequence number	Average	No	Receiver
	WMEWMA	Link delivery	PRR, estimate at t-1	EWMA Filter	No	Receiver
	RNP	Packet retransmissions	Packets sequence number, packet acknowledgements	Average	No	Sender
Composite	ETX	Packet retransmissions	PRRs (uplink, and downlink)	Average	Yes	Receiver
	Four-bit	Packet retransmissions	WMEWMA, RNP	EWMA Filter	Yes	Sender and Receiver
	F-LQE	Holistic link characterization	PRRs (uplink, and downlink), SNR	Fuzzy logic	Yes	Receiver
	Opt-FLQE	Holistic link characterization	PRRs (uplink, and downlink), SNR, RNP	Fuzzy logic	Yes	Sender and Receiver

IV. COMPARISON METHODOLOGY

It is known that in link quality estimation, there is no real link quality metric of reference, which other link quality estimators can be compared to. Therefore, to evaluate the performance of the LQEs described above, we adopted the same methodology as in [12], 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 (i.) the distribution of its link quality estimates, illustrated by the cumulative distribution function (CDF), and (ii.) its temporal behavior.
- **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.
- **Reactivity:** It refers to the ability of a LQE to quickly react to persistent changes in link quality. It is assessed *qualitatively*, by observing its temporal behavior.

V. EXPERIMENTS DESCRIPTION

In our experiment, we have chosen RadiaLE testbed [20], [21] to experimentally assess the performance of LQEs in a power distribution substation. We have deployed a single-hop network of 10 TelosB motes (N_1, N_2...N_{10}), distributed in a linear topology, where N_1 is the sink. Nodes N_2 ... N_{10} are placed at different distances from the sink node N_1, in order to get a rich set of links having different qualities (good, moderate, and bad). The distance between the sink node and each node N_i varies from 1 to 5 meters. The transmission power was set to (-25 dBm) to reach the transitional region at shorter distances. The TelosB motes are connected to a control station (PC) via USB cables in order to collect data from the motes without interfering with the wireless communications. The motes implement the IEEE 802.15.4 technology. In order to accurately capture the link asymmetry, we have created a bidirectional data traffic over each link $N_1 \longleftrightarrow N_i$: we have considered a bursty traffic (Burst(100,100,10)) where N_1 sends a burst of 100 packets to a given node N_i, then N_i sends its burst of 100 packets to N_1. This operation is repeated 10 times (number of bursts). The packet size was fixed to 60 Bytes. At the end of the experiments, we gathered a database that contains packets-statistics, retrieved from each bidirectional link $N_1 \longleftrightarrow N_i$.

Fig. 1 shows our experimental testbed, deployed in an indoor distribution substation (digital research center at the Technopark of Sfax/Tunisia). The substation uses power transformers, which are of the oil-filled variety, to change voltage of the electricity from high/medium to low voltages in order to be safely distributed. Oil-filled transformers are critical components that must be continuously monitored to reduce the possibility of disruptive and expensive power outages. They may fail as the result of the mechanical and thermal stresses induced by the high voltages. Thus, monitoring the health of power transformers is crucial to know when and where a transformer is beginning to fail or has failed. WSNs can provide several monitoring tasks, such as monitoring the oil-tank temperature of transformers, transformer partial discharge (PD) monitoring and vibration and acoustic signals monitoring.

We performed different sets of experiments where we varied certain parameters to study their impact, namely the radio channel and the maximum retransmissions count. The experiment was repeated for each parameter modification. Table II shows the parameters considered in the experimentation.

TABLE II
EXPERIMENT SCENARIOS.

Scenario	Channel	Retransmission count
1: Default scenario	26	6
2: Impact of channel	20, 26	6
3: Impact of re-transmission count	26	0, 6

Fig. 1. Experimental testbed.

VI. Experimental results

The unreliability of low power radio links in smart grid has been demonstrated by previous studies, such as [4], [22]. Their quality fluctuates over time and space, and connectivity is typically asymmetric. Our experimental study also confirms these observations. For instance, Fig. 2 shows that the background noise, the LQI and RSSI continuously fluctuate over time, in accordance with changes in electric environments (e.g. temperature and interference). Thus, accurate link quality estimation is required to achieve successful deployment of WSNs in smart grids. In this section, we present the main experimental results related to the performance evaluation of representative LQEs (described in Section III) in terms of reliability, stability, and reactivity.

A. Reliability

LQEs reliability can be inferred from (i.) the distribution of link quality estimates, illustrated by the empirical Cumulative Distribution Function, i.e. CDF (Fig. 3), and (ii.) the temporal behaviour of a particular representative link (Fig. 4). Notice that in CDF, link quality estimates have been transformed to be in the range [0..100], where 0 represents the worst link quality and 100 represents the best. This transformation aims to better visualize the different link quality estimates, having different ranges, in the same X-axe. In the following, we summarize experimental results into three high-level observations:

Observation 1: *Except ETX, composite LQEs, including four-bit, F-LQE, and Opt-FLQE, are more reliable than single LQEs, including PRR, RNP, and WMEWMA, which either over-estimate or under-estimate link quality.*

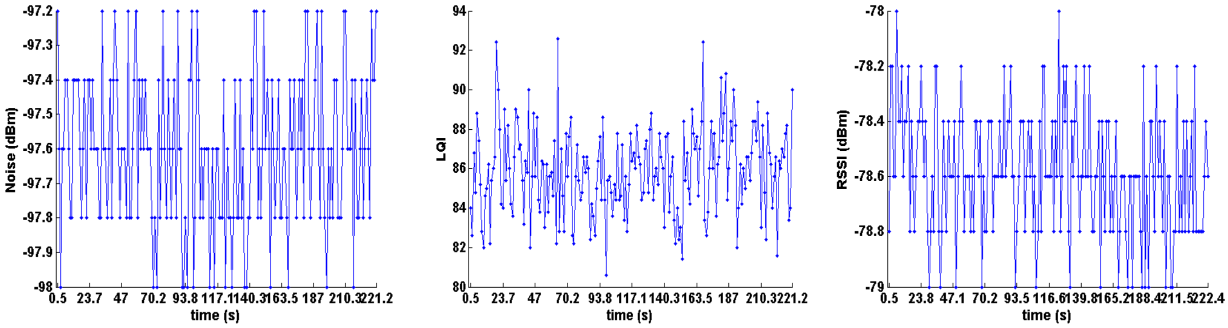
First, note that in our experimental scenario, we set the links to have diverse qualities (high/good, intermediate/moderate, and poor/bad). By doing so, we can affirm that a LQE that considers most of the links of high quality or of poor quality is unreliable because this is in contradiction with the experimental scenario. Consequently, we retain the following results: RNP cannot provide a reliable link estimate as it under-estimates link quality. For instance, as illustrated in Fig. 3a, RNP considers almost 75% of the links having bad quality. The reason of this underestimation is the fact that RNP is not able to determine if these packets are received after these retransmissions or not. On the other hand, PRR and WMEWMA overestimate the link quality. For instance, Fig. 3c shows that they consider almost 95% of links having good quality. The overestimation of PRR and WMEWMA is due to the fact that they are only aware of link delivery, and not aware of the number of retransmissions made to deliver a packet. A packet that is lost after one retransmission or after n retransmissions will produce the same estimate. Despite the fact that ETX combines two link properties, namely link delivery and link asymmetry, the distribution of its link quality estimates shows that it over-estimates link quality. For instance, Fig. 3a depicts that almost 75% of links have ETX equal to 100, which means high quality. The reason of this overestimation is the fact that the computation of ETX is based only on PRR (i.e., link delivery).

These observations are confirmed by Fig. 4a, which shows the temporal behavior of LQEs for a particular representative link. It illustrates the difference in decisions made by LQEs in assessing link quality. For instance, PRR, WMEWMA, and ETX assess the link to have perfect quality, i.e., high reception ratio (almost 100%), whereas RNP assesses the link to have bad quality, i.e., high number of retransmissions (around 4 retransmissions). This discrepancy between PRR, WMEWMA, and RNP 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).

Four-bit, F-LQE and Opt-FLQE, however, are more reliable than single LQEs as they combine several link aspects. For instance, Fig. 3a shows that four-bit provides better characterization of the link quality than RNP, since its computation also accounts for PRR.

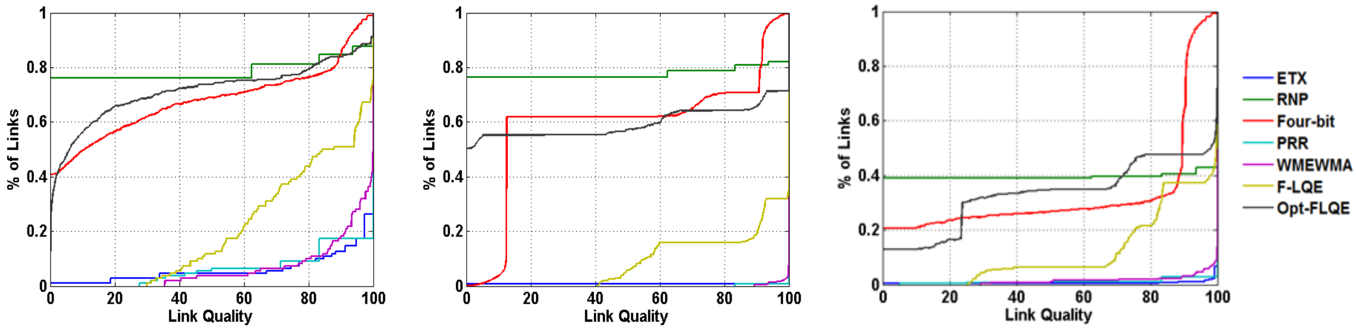
Observation 2: *F-LQE is more reliable than four-bit.* By analyzing the expressions of these LQEs, it can be inferred that F-LQE accounts for four link properties, namely link delivery, link asymmetry, link stability and channel quality; against three link properties for four-bit. Hence, it can be understood that F-LQE should be more reliable than four-bit. Our experimental results indeed confirm this observation. For instance, Fig. 3a shows that four-bit considers 40% of the links to have bad quality, which is a relatively high percentage. In contrast, F-LQE provides a more balanced characterization of the link quality than four-bit. Fig. 3a shows that 30% of links have good quality (i.e. F-LQE equal to 100), while 70% of the links have F-LQE link quality estimates between 30 and 100.

This observation is well confirmed by analyzing the temporal behaviour of the link presented in Fig. 4b. This figure shows the temporal behavior of the individual metrics that constitute F-LQE, and its overall behavior. According to this figure, the considered link has good packet delivery, high stability, and low asymmetry, but it has a negative feature, namely low channel quality (i.e., ASNR between 2 and 6 dBm). As



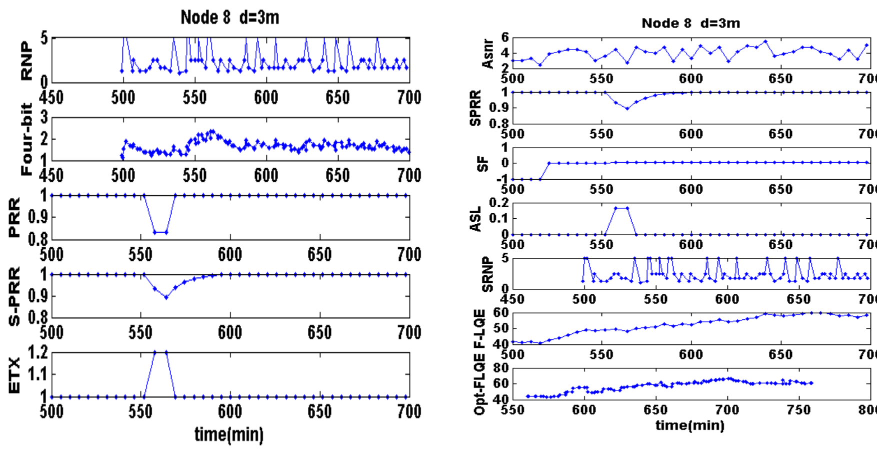
(a) Noise level (b) Link Quality Indicator (c) Received Signal Strength Indicator

Fig. 2. Noise level, LQI, and RSSI in smart grid environments.



(a) Default scenario (b) Channel 20 (c) Retransmission count: 0

Fig. 3. Empirical CDFs of link quality estimators, for different network settings



(a) Temporal behaviour of PRR, WMEWMA, RNP, ETX, and four-bit.
(b) Temporal behaviour of F-LQE, Opt-FLQE, and their related metrics.

Fig. 4. Temporal behaviour of link quality estimators for a particular representative link.

a result, F-LQE link quality estimates are between 40 and 60 (out of 100). These link scores appear reasonable given the link properties. Note that assessing the channel quality while estimating the link quality in smart grid environments is very important as many environmental factors (e.g. noise and obstacles) may affect the signal strength.

Observation 3: *Opt-FLQE is more reliable than F-LQE*. Fig. 3 clearly shows that the Opt-FLQE estimation spectrum is always more spread than that of F-LQE. The average scores of F-LQE are generally between 30 (or 40) and 100, i.e., it classifies links as either good or moderate and it often misclassifies bad links. In contrast to 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. The temporal behavior of the link presented in Fig. 4 confirms that the estimation spectrum of Opt-FLQE is larger that that of F-LQE. This estimation enhancement is due to the fact that Opt-FLQE considers the link retransmissions property, in addition to channel quality, link delivery and asymmetry. Considering link retransmissions significantly contributes to accurate link quality estimation in smart grid deployments, characterized by excessive packet losses (due to electric equipments noise, electromagnetic interference, obstructions, multipath effects, and fading) [4].

B. 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. This property is crucial in WSNs. For instance, when a link quality shows transient degradation, routing protocols do not have to recompute path cost since rerouting is a very time and energy consuming operation. We measured the stability of the LQEs to transient fluctuations through the coefficient-of-variation (CV) of their estimates.

The stability (sensitivity) of the LQEs with respect to different settings (refer to Table II) is presented in Fig. 5. According to this figure, we retain the following observations. First, PRR, WMEWMA and F-LQE are the most stable estimators (i.e., have the lowest CV). Especially, WMEWMA and F-LQE stability comes from the use the EWMA filter that smoothes link quality estimates. Second, RNP, fourbit and ETX are unstable. Four-bit is more stable compared to RNP due to the use of EWMA filter. The instability of ETX is explained as follows: when the PRR tends to 0 (very bad link), the ETX will tend to infinity, which increases the standard deviation of ETX link estimates. Third, Opt-FLQE is less stable than F-LQE, but more stable than four-bit, RNP, and ETX. This can be justified by the integration of SRNP metric.

C. 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. For example, a reactive link estimator enables routing protocols and topology control mechanisms to quickly adapt to changes in the underlying connectivity.

To reason about this issue, we observe the temporal behaviour of a link showing a bad quality (until time 160), as illustrated in Fig. 6. From this figure, we can clearly observe that PRR, WMEWMA, 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 can not be computed and updated, which turns them not sufficiently reactive. On the other hand, RNP, four-bit, and Opt-FLQE are more reactive as they are computed at the sender side.

VII. Conclusion

This paper focused on radio link quality estimation in smart grid environments. We carried an experimental study of representative LQEs (single and composite), namely PRR, WMEWMA, RNP, ETX, four-bit, F-LQE, and Opt-FLQE. We compared these LQEs in terms of reliability, stability and reactivity, by analyzing their statistical behavior in an indoor smart grid substation. Experimental results show that, composite LQEs (such as Opt-FLQE, F-LQE, and four-bit) that are based on several link quality metrics, outperform single metrics (such as PRR, WMEWMA and RNP) in terms of reliability. Further, it was shown that Opt-FLQE is the most reliable estimator compared to the other evaluated LQEs. In terms of reactivity, experimental results show that Opt-FLQE, RNP, and four-bit are the most reactive LQEs. Finally, in terms of stability, F-LQE, PRR, and WMEWMA have shown to be the most stable estimators. This study is likely to help network designers to choose the most convenient LQE for smart grid environments.

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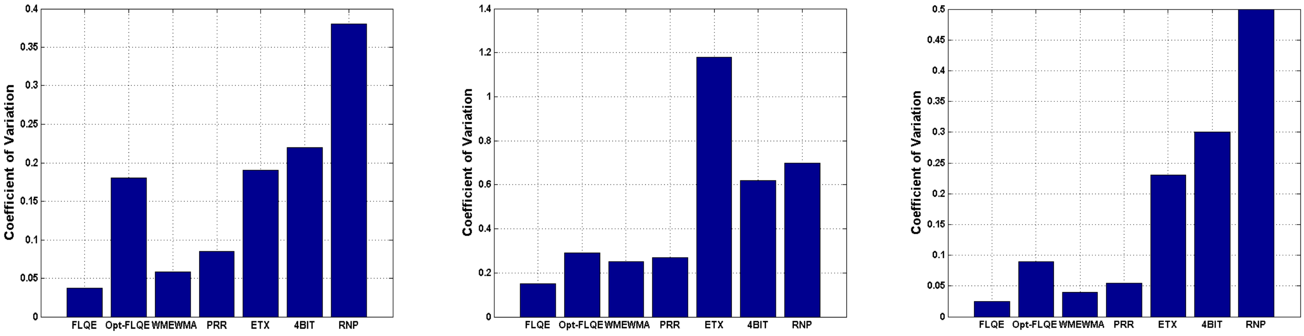
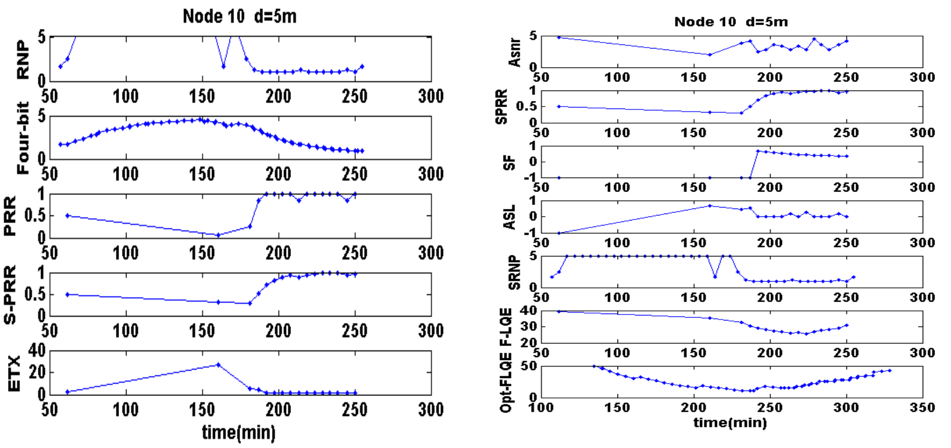


(a) Default scenario

(b) Channel 20

(c) Retransmission count: 0

Fig. 5. Stability of link quality estimators



(a) Temporal behaviour of PRR, WMEWMA, RNP, ETX, and four-bit.

(b) Temporal behaviour of F-LQE, Opt-FLQE, and their related metrics

Fig. 6. Temporal behaviour of link quality estimators for a link showing a bad quality (until time 160).

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