A Comparative Simulation Study of Link Quality Estimators in Wireless Sensor Networks

Nouha Baccour[*] [†], Anis Koubâa[†] [‡], Maissa Ben Jamâa[*], Habib Youssef[§], Marco Zuniga[¶], and Mário Alves[†]

[*]ReDCAD Research Unit, National school of Engineers of Sfax, Sfax, Tunisia.
[†]CISTER Research Unit, Polytechnic Institute of Porto (ISEP/IPP), Portugal.
[‡]Al-Imam Mohamed bin Saud University, College of Computer Science and Information Systems, Riyadh, Saudi Arabia.
[§]Prince Research Unit, University of Sousse, Sousse, Tunisia.
[¶]Digital Enterprise Research Institute, National University of Ireland, Galway

Emails: nabr@isep.ipp.pt, aska@isep.ipp.pt, mbenj@redcad.org,
habib.youssef@fsm.rnu.tn, marco.zuniga@deri.org, mjf@isep.ipp.pt

***Abstract*—Link quality estimation (LQE) in wireless sensor networks (WSNs) is a fundamental building block for an efficient and cross-layer design of higher layer network protocols. Several link quality estimators have been reported in the literature; however, none has been thoroughly evaluated. There is thus a need for a comparative study of these estimators as well as the assessment of their impact on higher layer protocols. In this paper, we perform an extensive comparative simulation study of some well-known link quality estimators using TOSSIM. We first analyze the statistical properties of the link quality estimators independently of higher-layer protocols, then we investigate their impact on the Collection Tree Routing Protocol (CTP). This work is a fundamental step to understand the statistical behavior of LQE techniques, helping system designers choose the most appropriate for their network protocol architectures.**

I. Introduction

Radio links are known to be unreliable, as their behavior unpredictably varies over time and space. The quality of the radio links greatly impacts network performance, namely in what concerns topology control, routing and mobility management. In particular, routing protocols must overcome link unreliability in order to efficiently maintain network connectivity. Link quality estimation emerges as an important mechanism to select the most stable routes for communication [1]–[3]. Stable routes are built by selecting good quality links and discarding bad quality ones; they enable improving the network throughput and energy-efficiency, namely (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.

The accuracy of the link quality estimate will impact the goodness-of-decision made by routing protocols in selecting stable routes. The more accurate the estimate is, the more stable routes will be, and this improves delivery rates. Therefore, accurate link quality estimate is a prerequisite for efficient routing mechanisms that manage to overcome problems imposed by link unreliability.

In Wireless Sensor Networks (WSNs), link quality estimation is more challenging than in traditional wireless networks, due to factors such as network scale/density, system/network dynamics and the use of low-cost, low-power radio transceivers. It has been experimentally shown that low-power radios are more prone to noise, interference, and multipath distortion [4]. As a result, communication links in WSNs exhibit more unreliability as compared to those of traditional mesh and ad-hoc networks [4]–[9].

Link quality estimation in WSNs still has many open research challenges, although there have been several recent works that have introduced new link quality estimation metrics for WSNs [5], [10]–[13] and others have assessed the convenience of traditional estimation metrics for WSNs [14]. However, none of the proposed link quality estimators have been subject of a thorough evaluation.

In this paper, we contribute to the state-of-the-art (Section II) by presenting an extensive performance evaluation and comparison (Section V) of the most representative link quality estimators for WSNs: *PRR*, *WMEWMA*, *RNP*, *ETX*, and *four-bit* (described in Section III), both independently from higher layer protocols and based on the behavior of the Collection Tree Routing Protocol (CTP). Section IV describes the simulation model, namely the simulation environment and scenarios and Sections VI and VII provide an intuitive summary of the results, general conclusions and future research directions.

II. Related Work

A. Link Quality Estimators

Link quality estimators in wireless sensor networks can be classified in two categories: hardware-based estimators and software-based estimators.

Hardware-based estimators are directly obtained from the radio module (e.g. [15]), requiring no computation overhead. They include the Link Quality Indicator (LQI), the Received Signal Strength Indicator (RSSI), and the Signal-to-Noise Ratio (SNR). However, as previously observed in [11], [16], [17], hardware-based estimators are inaccurate, since these metrics are measured based on just 8 symbols of a received packet (not the whole packet) and they are only measured for successfully received packets. Therefore, when a radio link suffers from excessive packet losses, the transmission performance is overestimated, by not considering the information of lost packets.

Software-based estimators enable to *count* or *approximate* either the reception ratio or the average number of packet transmissions/re-transmissions before its successful reception. Some of the most relevant are outlined next and further intuition about the ones under evaluation is provided in Section III.

The Packet Reception Ratio (PRR) and the Acquitted Reception Rate (ARR) count the reception ratio. The first is performed at the receiver side and the second at the sender side. These link quality estimators are simple and have been widely used in routing protocols (e.g. in [18]).

The Required Number of Packet transmissions (RNP) [5] counts the average number of packet transmissions/re-transmissions, required before its successful reception. The authors argue that *RNP* is better than *PRR* for characterizing the link quality because *PRR* provides a coarse-grain estimation of the link quality since it does not take into account the underlying distribution of losses, in contrast to *RNP*.

The Window Mean with Exponentially Weighted Moving Average (WMEWMA) [10], the Kalman filter based link quality estimator [13], and the Packet Success Probability (PSP) [8], approximate the packet reception ratio.

On the other hand, the Link Inefficiency metric (LI) [11], Expected Transmission Count (ETX) [19], and *four-Bit* [12] approximate the average number of packet transmissions/re-transmissions before a successful reception.

B. Performance Evaluation of Link Quality Estimators

To our best knowledge, the only previous comparative study of link quality estimators in WSNs were [10] and [5].

In [10], the authors introduced the Window Mean with Exponentially Weighted Moving Average (WMEWMA), a filter-based LQE. The performance of *WMEWMA* was compared against other filter-based LQEs: Exponentially Weighted Moving Average (EWMA), Moving Average (MA), and Time-Weighted Moving Average (TWMA), considering various performance criteria. However, it was restricted to filter-based LQEs and the comparison was based on a simple generated trace, not accurately considering the radio channel characteristics. The trace generator is based on the assumption that packets transmission corresponds to independent Bernoulli trials.

Performance comparison between filter-based LQEs is performed in terms of accuracy, agility, stability, history, and resource utilization. Accuracy is quantified by comparing the measured link quality and the estimated link quality, using the Mean Square Error. Agility is the ability to quickly react to persistent changes in link quality. Stability is the ability to resist to transient (short-term) variations, also called fluctuations, in link quality. History refers to the time window used to produce the estimate. Based on the above performance criteria, [10] defended that *WMEWMA* performs better than the other filter-based LQEs.

TABLE I
CHARACTERISTICS OF LINK QUALITY ESTIMATORS UNDER EVALUATION

	Monitoring type	**Location**	**Direction**	**Class**
PRR	Passive	Receiver	Unidirectional	PRR-based
WMEWMA	Passive	Receiver	Unidirectional	PRR-based
RNP	Passive	Sender	Unidirectional	RNP-based
ETX	Active	Receiver	Bidirectional	PRR-based
four-bit	Hybrid	Sender	Bidirectional	PRR, RNP-based

In [5], the main goal was to study the temporal characteristics of low-power links, using a real WSN deployment. The authors compared *PRR* and *RNP* in order to select the best metric for link characterization, concluding that *RNP* is better than *PRR*. To justify their finding the authors observed different links during several hours, by measuring *PRR* and *RNP* every one minute. They found that for good-quality and bad-quality links, i.e. links having high (>90%) and low reception rates (<50%) respectively, *PRR* follows the same behavior as *RNP*. However, for intermediate quality links, *PRR* overestimates the link quality because it does not take into account the underlying distribution of packet losses. When the link exhibits short periods during which packets are not received, the *PRR* can still have high value but the *RNP* is high so that it indicates the quality of the link. As a matter of fact, a packet that cannot be delivered is retransmitted several times before aborting transmission. The authors also analyzed the statistical relationship between *RNP* and the inverse of *PRR* (1/*PRR*) by (i.) measuring the cumulative distribution function (CDF) of *RNP* as a function of 1/*PRR* and (ii.) measuring the Consistency level between *RNP* and 1/*PRR*. They found that *RNP* and *PRR* are not directly proportional.

III. LINK QUALITY ESTIMATORS UNDER EVALUATION

We classify the LQEs under evaluation in two main classes:

- *PRR-based* link quality estimators, including *PRR*, *WMEWMA*, *ETX*, and *four-bit*. The computation of these estimators relies on *PRR* metric.
- *Packet retransmissions-based* link quality estimators, including *four-bit*, and *RNP*. These estimators use *RNP* metric in their computation.

TABLE I presents the most important characteristics of these LQEs.

PRR metric can be computed as the average of the ratio of the number of successfully received packets to the number of transmitted packets and can be computed at the receiver, for each window of *w* received packets, as:

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

The number of lost packets is determined using the packets sequence number. The *PRR* is based on passive monitoring, which means that useful statistical data is collected from received/sent data packets over that link.

The second estimator is *WMEWMA* [10], which is a filter-based estimator that approximates the *PRR* estimator as:

$$WMEWMA(\alpha, w) = \alpha \times WMEWMA + (1 - \alpha) \times PRR \quad (2)$$

where $\alpha \ \epsilon$ [0,1] is the history control factor, which controls the effect of the previously estimated value on the new one. This estimator is based on passive monitoring and is updated at the receiver side for each *w* received packets.

The third estimator is *RNP* [5], which counts the average number of packet transmissions/re-transmissions required before a successful reception. Based on passive monitoring, this metric is evaluated at the sender side for each *w* transmitted and re-transmitted packets, as follows:

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

Note that the number of successfully received packets is determined by the sender as the number of acknowledged packets.
The aforementioned estimators are not aware of the link asymmetry in the sense that they provide an estimate of the quality of the unidirectional link from the sender to the receiver.

The fourth estimator is *ETX* [19], which is a receiver-initiated estimator that approximates *RNP*. It uses active monitoring, which means that each node explicitly broadcasts probe packets to collect statistical information. *ETX* takes into account link asymmetry by estimating the uplink quality from the sender to the receiver, denoted as $PRR_{forward}$, as well as the downlink quality from the receiver to the sender, denoted as $PRR_{backward}$. The combination of both *PRR* estimates provides an estimation of the bidirectional link quality, expressed as:

$$\textit{ETX(w)} = \frac{1}{PRR_{forward} \times PRR_{backward}} \quad (4)$$

Note that $PRR_{forward}$ is simply the *PRR* of the uplink determined at the receiver, for each *w* received probe packets, while $PRR_{backward}$ is the *PRR* of the downlink computed at the sender and sent to the receiver in the last probe packet.

The fifth estimator is *four-bit* [12], which is a hybrid estimator as it uses both passive and active monitoring and is initiated at the sender. During active monitoring, nodes periodically broadcast probe packets. Based on w_a received probe packets, the sender computes the *WMEWMA* estimate and derives an approximation of the *RNP*, denoted as $estETX_{down}$, as follows:

$$estETX_{down}(w_a, \alpha) = \frac{1}{WMEWMA} - 1 \quad (5)$$

This metric estimates the quality of the unidirectional link from the receiver to the sender based on active monitoring. During passive monitoring, the sender computes *RNP* based on w_p transmitted/re-transmitted data packets to the receiver.

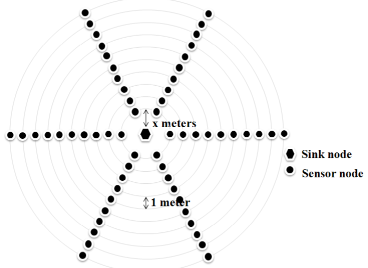
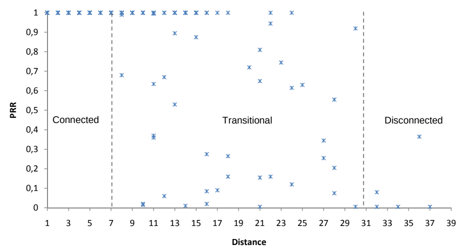
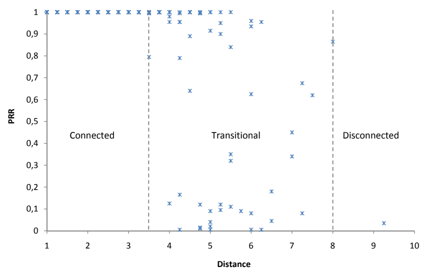


Fig. 1. Network Configuration for Reception Regions Evaluation



(a) Indoor environment: aisle of building [20]



(b) Outdoor environment: football field [20]

Fig. 2. Reception Regions identification

Then, it uses EWMA filter to smooth *RNP* into $estETX_{up}$, expressed as follows:

$$estETX_{up}(w_b, \alpha) = \alpha \times estETX_{down} + (1 - \alpha) \times RNP \quad (6)$$

In Eq. (6), $estETX_{up}$ estimates the quality of the unidirectional link from sender to receiver, based on passive monitoring.
Thus, the *four-bit* estimator combines both *estETXup* and *estETXdown* metrics via the EWMA filter, in order to obtain an estimate of the bidirectional link expressed as follows:

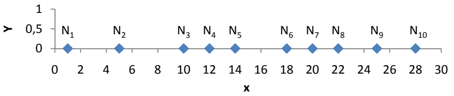
$$\textit{four-bit}(w_a, w_b, \alpha) = \alpha \times \textit{four-bit} + (1 - \alpha) \times estETX \quad (7)$$

where *estETX* corresponds to $estETX_{up}$ or $estETX_{down}$. At w_a received probe packets, the sender derives the *four-bit* estimate according to Eq. (7) by replacing *estETX* by $estETX_{down}$. At w_p transmitted/re-transmitted data packets, the sender derives the *four-bit* estimate according to Eq. (7) by replacing *estETX* by $estETX_{up}$.

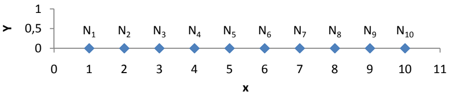
IV. The Simulation Model

A. Simulation environment

Our simulation study was based on TOSSIM 2.x [21], since it provides an accurate wireless channel model (for further details, please refer to [22], [23]).



(a) Indoor environment: aisle of building



(b) Outdoor environment: football field

Fig. 3. Topology layout of the 10 sensor nodes in indoor and outdoor environments. Nodes $N_2 \ldots N_{10}$ belong either to the *connected*, *transitional* or *disconnected* region of N_1, so that links ($N_1 \longleftarrow N_i$), for *i.* ϵ [2, 10], have different qualities.

```
For index = 2 to 10 {
      For counter = 1 to 6 {
            N1 sends 100 packets to Nindex
            Nindex  sends 400 packets to N1
      }
}
```

(a) Traffic Pattern 1. It is close to real world traffics as a node receives a first bunch of packets then sends another bunch of packets. This traffic is used for showing the temporal behavior of LQEs.

```
For index = 2 to 10 {
      N1 sends 10000 packets to Nindex
      Nindex  sends 50000 packets to N1
}
```

(b) Traffic Pattern 2.It involves much more packets than traffic Pattern 1 in order to reach the steady state of the simulation. This traffic is used for statistical analysis of LQEs.

Fig. 4. Traffic pattern of the first simulation study.

In order to properly configure the simulation models, it was necessary to identify the three reception regions in the simulated sensor network, i.e. *connected*, *transitional* and *disconnected* regions.

We considered 60 sensor nodes deployed around one sink node, as illustrated in Fig. 1. These sensor nodes were divided in 10 sets, where each set contain 6 nodes, all placed in a circle around the sink node. The distance between two consecutive circles is equal to 1 meter. The first circle, i.e. the nearest to the sink, has a radius of *x* meters. Each sensor node has an exclusive time slot (to avoid collisions) during which it sends 200 data packets to the sink node. Further, the packet retransmission mechanism has been activated. For the outdoor environment, we simulated several scenarios while varying *x* in the set 1, 1.25, 1.5, 1.75 meters, whereas *x* has been varied in the set 1, 10, 20, 30 meters for the indoor environment.

Fig. 2 presents the *PRR* as a function of the distance for both indoor and outdoor environments, where it is possible to observe the bounds of the three reception regions. As it can be observed, this figure resembles empirical observations, which reflects the accuracy of TOSSIM 2. It is also shown that the width of the transitional region is larger in the indoor environment than in the outdoor environment. This is due to the fact that in the outdoor environment (i.e. football field), there are more multipath and dispersion effects due to grass foliage.

B. Simulation scenarios

This section describes two simulation scenarios to evaluate and compare the performance of the pre-cited LQEs, based on [20] an indoor environment (aisle of building) and an outdoor environment (football field).

1) First simulation scenario: statistical properties of LQEs: This simulation scenario aims at analyzing and understanding the statistical properties of the link quality estimators independently of any external factor, such as collisions and routing. We only consider the impact of the physical layer and the retransmission mechanism of the data link layer.

To achieve this goal, we consider the following scenario: A single-hop network of 10 sensor nodes (N_1, $N_2 \ldots N_{10}$) placed in a linear topology, as shown in Fig. 3, was considered. Node N_1 is a sink that receives data packets sent by the other nodes ($N_2 \ldots N_{10}$). In addition, N_1 sends a data flow to each of these nodes, enabling asymmetry-aware LQEs (i.e. *ETX* and *four-bit*) to estimate the bidirectional link quality. The traffic flow is illustrated in Fig. 4. We have used 1.42 packets/s CBR (constant bit rate).

In this first study, we propose to estimate the quality of the unidirectional links ($N_1 \longleftarrow N_i$), for *i.* ϵ [2, 10] for both indoor and outdoor environments [20]. Nodes placement enables to study the statistical properties of LQEs, when faced with different link characteristics. We simulated the scenario described above, with each of the five link quality estimators, i.e. *PRR*, *WMEWMA*, *RNP*, *ETX* and *four-bit*, and also a filtered-*RNP*, denoted as *F-RNP*. *F-RNP* uses the EWMA filter with the same parameters as *four-bit* and *WMEWMA*. All link quality estimators are implemented at the nodes application level [24]. We choose a history control factor α = 0.9, as suggested in [12] and an averaging window *w* = 5 for evaluating short-term estimation and *w* = 100 for evaluating long-term estimation.

2) Second simulation scenario: impact of LQEs on CTP: The objective is to evaluate the impact of the LQEs on higher layer protocols, namely the Collection Tree Routing Protocol (CTP), already supported by TOSSIM 2. Routing in CTP consists of building a tree towards the sink node according to the links quality. It has three basic components [25]:

- *The link quality estimator* which enables each node to estimate the quality of the links to its neighbors using, by default, *four-bit* estimator [12].
- *The routing engine*, which enables a node to select the best parent among its neighbors based on the link quality estimation result.
- *The forwarding engine*, which is responsible of storing waiting packets and scheduling their transmission to the next hop.

In this second scenario, we consider an 81-nodes multi-hop network where nodes use Carrier Sense Multiple Access with

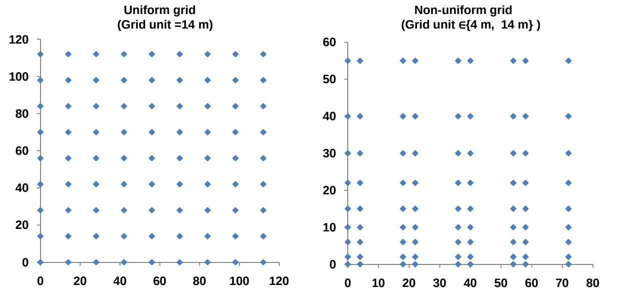


Fig. 5. Distribution pattern of 80 sensor nodes and a single sink node, in uniform and non-uniform grid topologies and for indoor environment. In uniform grid topology, grid unit is chosen so that links are of medium or bad qualities. In non-uniform grid topology, grid units are chosen so that links have different qualities:good, bad, medium, etc.

Collision Avoidance (CSMA/CA) as MAC protocol, and CTP [25] as routing protocol. Only 10 nodes behave as data sources (to avoid network congestion) and generate a Poisson traffic with a mean rate of 0.125 packets/s. Packet retransmission has been activated. Further, nodes begin their transmission after a delay of 300 s (to enable the topology establishment). Each simulation is repeated 30 times and each metric is estimated with a 95% confidence interval. The simulation time is 4800 s.

Sensor nodes were deployed in a grid topology with two different layouts: uniform grid topology and non-uniform grid topology (Fig. 5). The sink node is located at coordinates (0,0). In the uniform grid, the grid unit is constant. It is equal to 14 meters in indoor environment and 5.5 meters in outdoor environment. The choice of these grid units is based on the previous receptions region identification, such that each two neighbor nodes are far-away by a distance in the range of the transitional or the disconnected regions. Consequently, links in the uniform grid topology are of moderate or bad quality. This way, we make sure that link quality estimators operate in extreme conditions.

In non-uniform grid, the grid unit varies in {4,14} meters for the indoor environment and {1,6} meters for the outdoor environment. The choice of the different grid units is based on the previous reception regions analysis, so that the distance between two neighboring nodes is in the range of the connected, transitional or disconnected regions.Thus, in the non-uniform grid topology, we have a mixture of link qualities: good, intermediate and bad.

Note that *four-bit* is the native estimator for CTP, so we have implemented the other four LQEs in TOSSIM [24]. We choose a history control factor α = 0.9 and averaging window *w* to 5 [12]. As for *ETX*, which uses active monitoring, the beacon traffic rate is fixed to 1 packet/s [19].

V. Performance Analysis

This section presents the performance evaluation of the LQEs, based on the results obtained from the two simulation scenarios described in the previous section (for further details refer to [26]).

A. First simulation scenario: performance of LQEs

In the first scenario, we study (i.) the temporal behaviour of LQEs (Fig. 6) and (ii.) their statistical properties (Fig. 8, Fig. 7, Fig. 9). In the statistical analysis of LQEs, we measured the following metrics:

- The empirical cumulative distribution function (CDF), which assesses the level of over-estimation of each LQE (Fig. 7). The over-estimation level is defined as ”how much the estimator deviates from reality by estimating the link at a certain level of quality when it is not as good as it has been estimated”. Results consider all nodes of the indoor environment simulation and are similar to those of the outdoor environment.
- The coefficient of variation (CV) , which is defined as the ratio of the standard deviation to the mean. It compares the performance of the LQEs in terms of stability (Fig. 8).
- The absolute value of the coefficient of correlation (CC), which expresses the degree of linear dependency between a pair of LQEs (Fig. 9).

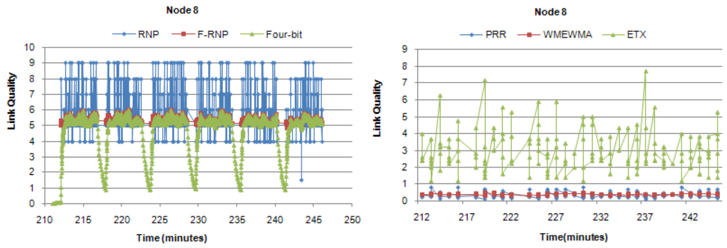
Note that the CV and the CC are averaged over all links of the transitional region. In what follows, we present the main lessons learned from this simulation study.

1) Over-estimation: In Fig. 7, it can be observed that *WMEWMA*, *PRR* and *ETX* are the most optimistic estimators and *RNP*, *F-RNP* and *four-bits* are the least optimistic estimators. This means that *PRR*-based estimators tend to over-estimate the link quality. The main reason is that the *PRR*-based estimators are not aware of the number of retransmitted packets, since they are implemented at the receiver side. A packet that is lost after one retransmission or after *n* retransmissions will produce the same *PRR*-based estimate, in contrast to estimates based on packet retransmissions, which are quite sensitive to retransmissions, hidden to the receiver.

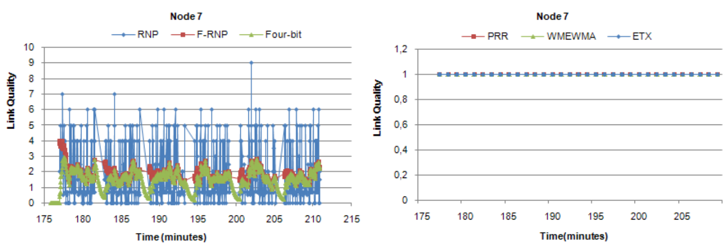
This finding is clearly illustrated in Fig. 6b for the link ($N_1 \leftarrow N_7$). In fact, *PRR*, *WMEWMA* and *ETX* estimate the link as continuously being at the best quality (100% of success), whereas *four-bit*, *RNP* and *F-RNP* shows that the link quality fluctuates between 0 and 7 retransmissions, which demonstrates that the link is not as good as inferred by *PRR*-based metrics.

2) Stability: Fig. 8 shows the average CV for each LQE from all nodes for different widow sizes : *w* = 100 (long-term estimation) and *w* = 5 (short-term estimation), and different environments: indoor, outdoor. Traffic Pattern 2 has been used in this simulation.

First, according to Fig. 8, we observe that *WMEWMA* and *F-RNP* are generally most stable. This can also be observed through the temporal behavior in Fig. 6. The main reason is that these estimators are based on filtering techniques, which smoothes the variation of the LQE and turn them more robust to quality fluctuations than other estimators. In particular, the use of a history control factor α = 0.9 increases the stability of those filter-based estimators. In fact, the history factor has an



(a) Indoor environment: aisle of building



(b) Outdoor environment:football field

Fig. 6. Temporal behaviour of link quality estimators (Traffic Pattern 1,w = 5)

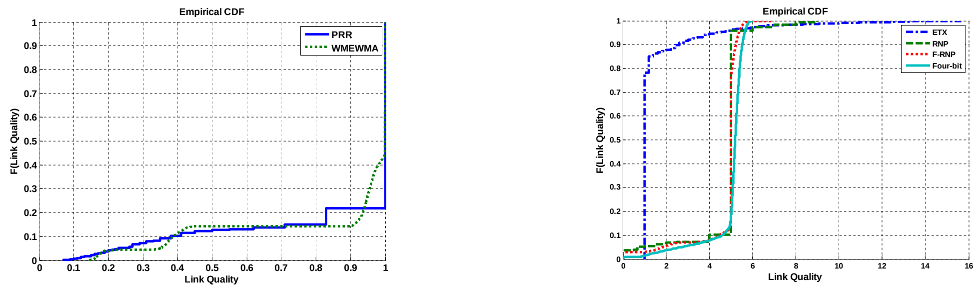


Fig. 7. Empirical CDFs of link quality estimators (Traffic Pattern 1, Indoor environment, w = 5)

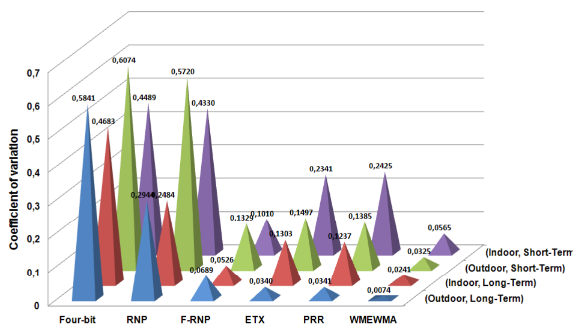


Fig. 8. Stability of link quality estimators (Traffic Pattern 2)

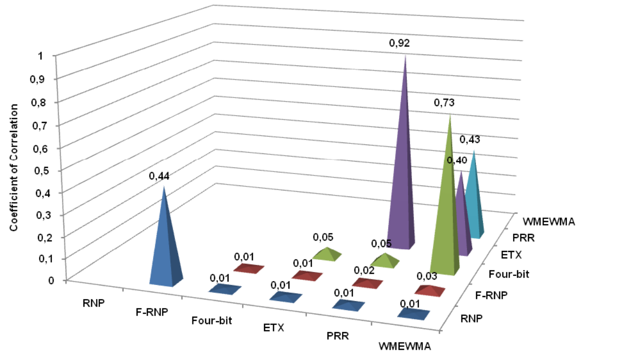


Fig. 9. Correlation between link quality estimators (Traffic Pattern 2, Indoor environment, w = 5)

impact on the stability of filter-based estimators, as shown in Fig. 10a. It is easily observed that the coefficient of variation of the filter-based estimators linearly decreases as the history control factor α increases, leading to a more stable behavior. In practice, it is important to adequately tune the history control factor to make a balance between stability and responsiveness to link quality changes. Fig. 10a also confirms that *WMEWMA* is the most stable estimators.

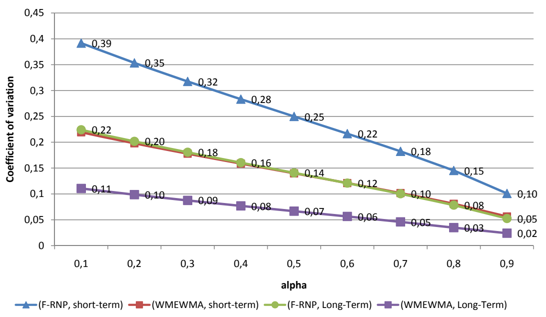
Second, *four-bit* is the least stable LQE, although it relies on two filter-based estimators. The reason is that *four-bit* combines two different estimators that have different range of values (refer to Eq. (7)), as it is based on the inverse of *WMEWMA* in the upstream direction and on *F-RNP* in the downstream direction. *Four-bit* can, however, be more stable if it only considers Eq. (6) as the actual output of the estimator and Eq. (5) as a corrective estimate when the downstream traffic is low. This can be observed in the temporal behavior in Fig. 6, where the *four-bit* estimates sharply decrease whenever *WMEWMA* is used for each w incoming packets.

The stability results just described above are also confirmed by observing the temporal behavior of LQEs in Fig. 6.

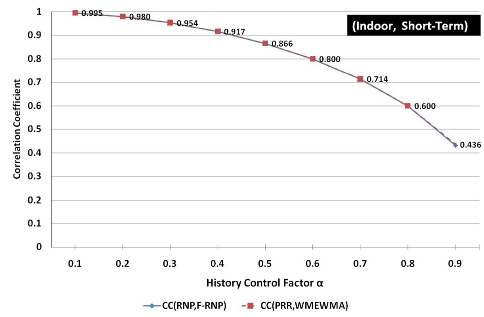
In conclusion, filter-based estimators are thus more stable and more robust to quality fluctuations than other estimators.

3) Correlation: Correlation analysis enables to classify the estimators into different classes with similar behavior. Based on the results in Fig. 9, we conclude the following.

First, there is a strong linear correlation between *PRR* and *ETX*. This correlation is justified as follow: the upstream and downstream traffics are sent in bulk, which means that $PRR_{forward}$ remains constant, as Traffic Pattern 2 is used, so that *ETX* is almost proportional to 1/*PRR*. Further, we observed that the number of different *PRR* values are not too many. In general, there should be no correlation between *PRR* and *ETX* for real-case traffic where links are asymmetric and $PRR_{backward}$ and $PRR_{forward}$ are independent. This will be illustrated in the second simulation scenario, where

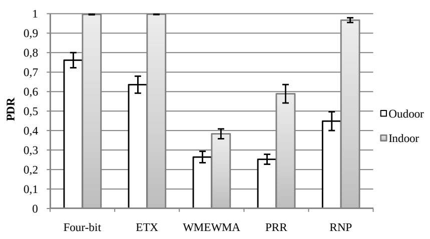


(a) Impact on the coefficient of correlation

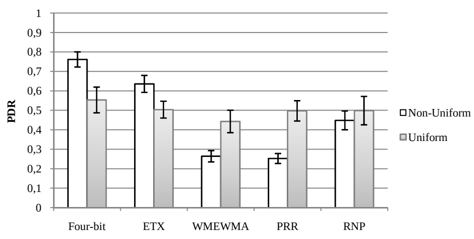


(b) Impact on the coefficient of variation

Fig. 10. Impact of the History Control Factor (Traffic Pattern 2, Indoor environment)



(a) Effect of the environment type



(b) Effect of the grid topology type

Fig. 11. Performance comparison in terms of Packet Delivery Rate (PDR)

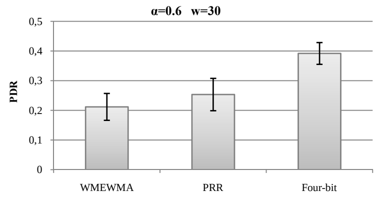


Fig. 12. Impact of α and w on the *PDR*

ETX clearly outperforms *PRR*, arguing against the correlation hypothesis. Note that *PRR* and *ETX* are not correlated with the other estimators.

Second, *RNP* and *F-RNP* are weakly correlated, similarly to *PRR* and *WMEWMA*. The main reason is that the control history factor α is too high, such that the filter-based estimators are mostly related to the link quality history, rather than to the current quality. For smaller values of α, the correlation of *RNP* and *PRR* estimators with their filter-based versions increases, as shown in Fig. 10b. Note that the behavior of the LQEs shown in Fig. 10b is similar for the outdoor environment and for long-term estimation.

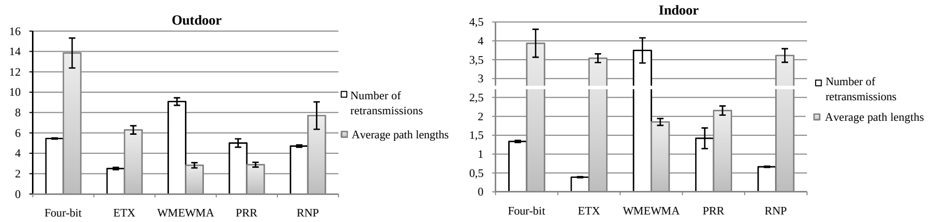
B. Second simulation scenario: impact of LQEs on CTP

In the second scenario, we evaluated the impact of LQEs on the CTP routing protocol, for different network conditions, including the environment and the grid topology types. The performance evaluation considered the following metrics:

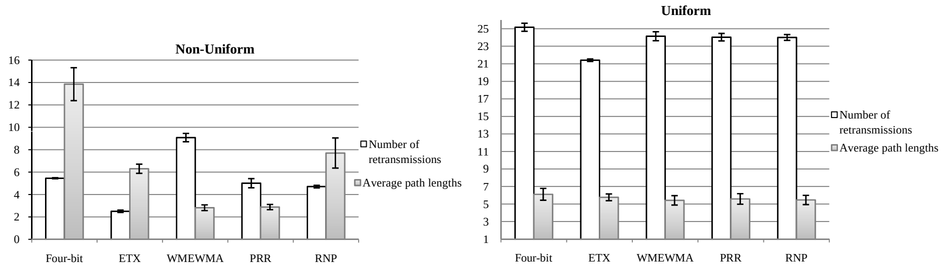
- *The packet delivery ratio* (PDR), which represents the ratio of the total number of successfully received packets in the network to the total number of transmitted packets in the network.
- *The number of retransmissions*, which is inferred from the average number of packet re-transmissions over the network before they are correctly delivered to the sink node [12].
- *The number of parent changes* in the data collection tree topology.

1) Impact on the packet delivery ratio: Fig. 11 shows a comparison between link quality estimators in terms of packet delivery ratio under different network conditions.

Finding Impact of the estimator class (refer to section III for LQEs classification). Irrespective of the configuration, Fig. 11 indicates that *four-bit* (with w = 5 and α = 0.9) and *ETX* are the best estimators in terms of PDR (*four-bit* slightly better than *ETX*). On the other hand, *WMEWMA* provides the worst PDR. In a more general perspective, LQEs based on packet retransmissions provide better performance than those based on *PRR*, except *ETX*. The reason is that *PRR*-based LQEs overestimate the link quality (as mentioned in Section V.A.1), thus they are more prone to the selection of paths with bad links, i.e. paths with low packet delivery ratio. In contrast, packet retransmissions-based estimators, provides a fine-grain estimation as they are aware of the loss distribution. As a consequence, they react more efficiently/dynamically to those losses, thus selecting more stable routes, i.e. routes with high quality links. This finding has been partially confirmed in [5], where the packet reception ratios of *PRR* and *RNP* estimators are compared.

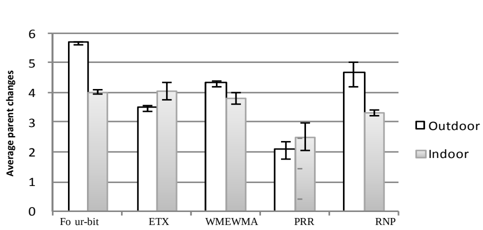


(a) Effect of the environment type

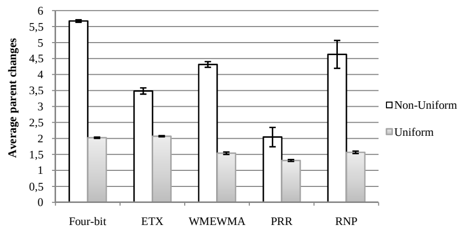


(b) Effect of the grid topology type

Fig. 13. Performance comparison in terms of number of retransmissions and average path length



(a) Effect of the environment type



(b) Effect of the grid topology type

Fig. 14. Performance comparison in terms of parent changes

The good PDR performance of *ETX* mainly a results from (i.) the use of active monitoring, (ii.) the consideration of the symmetry of links. In fact, *ETX* would have been expected have the same shortcomings as *PRR*-based LQEs. However, *ETX* uses active monitoring with high beaconing rate (1packet/s), compared to the data traffic rate (1/8 packet/s), enabling it to provide accurate link quality estimates becoming as good as *four-bit* in terms of PDR.

This study also shows that *PRR* provides a slightly better performance than *WMEWMA*. This is reasonable since *PRR* is more reactive to quality changes than *WMEWMA*, thus it selects routes more efficiently/reactively. In Fig. 12, the same results also hold with different settings of the history control factor α and the averaging window *w*: α = 0.6 and *w* = 30, as in [10]. The performance of *four-bit* is greatly influenced by the setting of α and *w* as its PDR drops from 0.76 with the previous setting down to 0.39 with the new setting of α and *w*. This is mostly due to the increase of the window size, which decreases the reactivity to link quality changes.

2) Impact on the number of retransmissions and average path lengths: Fig. 13 compares LQEs in terms of the number of retransmissions and average path lengths (number of hops) under different configurations.

It can be inferred from Fig. 13 that *ETX* outperforms in terms of number of retransmissions, and *WMEWMA* is the worst estimator with respect to this metric. This is mainly because *WMEWMA* overestimates the link quality and poorly reacts to its degradation, which confirms the previous results. In contrast, *ETX* uses the information of link symmetry, in addition to the frequent beacons broadcast in order to select links with higher quality, which reduces packet losses and thus retransmissions.

The other estimators exhibited similar performance with a small advantage to *RNP* as compared to *four-bit* and *PRR*. Note that despite that *four-bit* showed the best delivery performance, it involves greater number of retransmissions as compared to *ETX* and *RNP*. This does not mean that *four-bit* selects bad routes, but this is mainly because *four-bit* selects the longest paths to reach the destination. With links in the transitional region, the number of hops is expected to be positively correlated with the number of retransmissions, which confirms the observations. This is mainly a shortcoming in CTP as it does not take into account the hop count metric in route selection process while establishing the data collection tree.

We also observe that *WMEWMA* selects the shortest routes as compared to the other link quality estimators, yet it induces more retransmissions. These retransmissions are justified by the fact that *WMEWMA* does not consider the packet retransmissions metric in its computation. This observation demonstrates its inappropriateness for data collection routing protocols in WSNs. The same holds for *PRR*, but to a lesser extent since *PRR* is more reactive to link changes than its filtered version.

In conclusion, *ETX* outperforms the other estimators in terms of the number of retransmissions and average path length, a clear advantage in terms of energy-efficiency. On the other hand, using active monitoring with high beaconing frequency could affect the performance of *ETX* in terms of energy cost.

3) Impact on the number of parent changes: Fig. 14 compares LQEs in terms of average number of parent changes under different network configurations.

We observe that *four-bit* has the highest number of parent changes and *PRR* has the lowest one. Regarding *four-bit* behavior, this result is expected since *four-bit* has been shown to be very reactive to link changes. This results in faster and more frequent changes of parents as link quality degrades.

On the other hand, following the same reasoning, it would have been expected that *PRR* would have more parent changes than *WMEWMA*. However, we observe the opposite. This is explained by the fact that *WMEWMA* is inaccurate, thus it may select routes with bad links, leading to unstable routes that will be quickly broken, resulting in more frequent parent changes.

The general conclusion of this observation is that the accuracy of the estimator may have a controversial effect on the stability of the routes. In fact, an accurate estimator, such as *four-bit* or *RNP*, may lead to stable paths, which minimizes the number of parent changes. Oppositely, an accurate estimator may also induce very frequent changes due to its excessive reactivity to quality changes, as it has been observed in Fig. 14, in particular when links are bad or moderate. It can also be seen that *PRR* and *ETX* provide a good compromise for these antagonist effects.

VI. Summary of the Results

We have thoroughly analysed and compared several well-know link quality estimators (LQEs), namely *PRR*, *WMEWMA*, *ETX*, *RNP* and *four-bit*. We first showed the statistical properties of each estimator, independently from their impact on higher layer protocols. Then, we evaluated their performance with respect to the Collection Tree Routing Protocol (CTP) [25], commonly used in Wireless Sensor Networks (WSNs). The results of this study are summarized in TABLE II. In particular, we retain the following general lessons from this simulation study:

- The study shows that there is no universal estimator that provides the best performances for all the metrics, simultaneously. Each LQE has its advantages and drawbacks that must be considered when applied in a certain context.
- Overall, *ETX* is found to be the best estimator, however, does not holistically satisfy at best all requirements. It rather provides a good trade-off of all metrics between packet retransmissions-based and *PRR*-based estimators. This means that filter-based estimators must be carefully tuned to provide a good compromise between stability and other performance metrics.
- High *stability* and *over-estimation* have a cost in terms of *reliability*. This can be understood from the behavior of *WMEWMA*, which has been shown to be the most stable estimator; however it has the worst performance in supporting reliable data collection and routing in WSNs, in particular for high history control factor.
- Estimators that consider bidirectional link qualities provide better performance than those that do not. This is clear from the PDR performance of *ETX* and *four-bit* in the second study.
- In general, the LQEs under evaluation are not correlated with each other. Nevertheless, filter-based estimators would be correlated with their original versions if the control history factor is small.
- *Four-bit* is a good estimator; however, it heavily depends on the tuning of its parameters. Its best performances can be achieved by (i.) setting its averaging window to a small value (such as $w = 5$), and (ii.) using high beaconing rate to improve the estimation of the upstream link quality, (iii.) tuning its history control factor.
- *PRR* and *RNP* estimators provide a good tradeoff between simplicity and performance. They may be recommended for applications requiring low complexity level at the receiver and the sender, respectively, with moderate performance.

VII. Conclusion and Future work

In this paper, we performed an extensive comparative simulation study of some well-known link quality estimators using the TOSSIM 2 simulator. This simulator has been shown to provide accurate wireless channel models [22], [23], which improves the confidence on the validity of our simulation results. However, TOSSIM 2 is lacking awareness of energy consumption, which we propose to evaluate in future works. One of the contributions of this work is the implementation of the studied LQEs in TOSSIM 2. This implementation is available for download in [24]. These LQEs have been integrated into the CTP protocol to study their impact on routing, as present in this paper.

The results of this work demonstrate that research on link quality estimation is challenging and far from being completed. Based on our observations, the link quality estimators under evaluation are limited in the sense that they provide only partial views of the real quality of the link. Each estimator computes one metric, with an exception of *four-bit*, which combines packet retransmissions-based and *PRR*-based estimation techniques. However, in order to better estimate link quality, it is important, yet challenging, to do a holistic characterization of the link, encompassing several

TABLE II
COMPARISON BETWEEN LINK QUALITY ESTIMATORS

	Statistical Characteristics		**Impact on CTP Routing**		
	Stability (CV)	**Over-estimation**	**Packet Delivery Rate**	**Retransmissions**	**Parent changes**
ETX	Fair 😐	Fair 😐	Yes ☺	Good ☺	Good ☺
Four-bit	Scenario-specific ☹	No ☺	Good, with small w ☺	Fair 😐	Fair 😐
PRR	Fair 😐	Yes ☹	Bad ☹	Fair 😐	Good ☺
RNP	No ☹	No ☺	Fair 😐	Fair 😐	Fair 😐
WMEWMA	Yes ☺	Yes ☹	Bad ☹	Bad ☹	Fair 😐
F-RNP	Yes ☺	No ☺	-	-	-

metrics simultaneously. We forecast an estimator that is a function of several metrics, thus giving a more meaningful state of the link quality level. The combination of *RSSI*, *LQI*, *PRR*, *RNP* and other potential metrics would be more reliable and accurate for describing the real link status. Yet to be unveiled is how to combine them. This is the challenge that we will tackle next.

ACKNOWLEDGMENT

This work has been partially supported by CONET (the Cooperating Objects Network of Excellence) under grant FP7-2007-2-224053, IRCSET Postdoctoral Fellow Grant PD200857, SFI Grant No. SFI08CEI1380 and by FCT under the CISTER Research Unit (FCT UI 608).

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