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

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***Abstract*—Link quality estimation (LQE) in wireless sensor networks (WSNs) is a fundamental building block for an efficient cross-layer design of higher layer wireless network protocols. Several link quality estimators have been reported in the literature; however, none of the proposed estimators have been the subject of a thorough evaluation. Further, there is a need for a comparative study of these estimators as well as the assessment of the impact of each on higher layer protocols. In this work, we perform an extensive comparative simulation study among the well-known link quality estimators using TOSSIM simulator. We first analyze the statistical properties of the link quality estimators independently of higher-layer protocols, then we investigate their impact of the Collection Tree Routing protocol (CTP). We believe that this work provides a fundamental step in understanding the statistical behavior of LQE techniques, which helps network designers to choose the most appropriate one for their higher-layer protocols.**

I. Introduction

Wireless communication links are known to be unreliable as their behavior unpredictably varies over time and space. Links unreliability poses a major handicap for self-organizing wireless networks, such as sensor, ad-hoc and mesh networks, for maintaining their correct behavior, unless it is taken into account by higher layer communication protocols. Particularly, sophisticated routing protocols aim to overcome link unreliability in order to efficiently maintain network connectivity. To achieve this goal, they rely on link quality estimation (LQE) as a support mechanism to select the most stable routes for data delivery [1]–[4]. Stable routes are built by selecting links with the highest quality and discarding those of bad quality. Building such routes will definitely improve the network throughput and maximize its lifetime. In fact, data delivery over stable routes has the advantage of (*i.*) increasing the end-to-end probability of delivery rate, which infer on the accuracy (*ii.*) avoiding excessive re-transmissions over low quality links and thus to considerably reduce energy consumption at each node performing its routing task, which infers on the cost, (*iii.*) minimizing the route re-selection operation triggered by links failure, which infers on the stability. 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 the other traditional wireless mesh and ad-hoc networks, because sensor nodes are densely deployed and basically use low-power radios. It has been experimentally shown that low-power radios are more prone to noise, interference, and multipath distortion [5]. As a result, communication links in WSNs exhibit more unreliability as compared to those of traditional mesh and ad-hoc networks [5]–[11].

Link quality estimation in WSNs is still an open research challenge, although there have been several recent works that have introduced new LQE metrics for sensor networks [6], [12]–[15] and others have assessed the convenience of traditional estimation metrics for sensor networks [16]. However, none of the proposed link quality estimators have been the subject of a thorough evaluation.

In this paper, we conduct a comparative simulation study of link quality estimators. We particularly present an extensive performance evaluation of five existing link quality estimators for wireless sensor networks: *PRR*, *WMEWMA*, *RNP*, *ETX* and *Four-Bit*.

II. Related Work

In this section, we briefly review the literature related to link quality estimators in WSNs, as well as their performance evaluation.

A. Link Quality Estimators

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

Hardware-based estimators include Link Quality Indicator (LQI) Received Signal Strength Indicator (RSSI) and Signal-to-Noise Ratio (SNR). These estimators are directly obtained from the hardware, namely CC2420 radio transceiver [17]. Their advantage is that they do not require any computation overhead as they are built-in directly on the hardware. However, as it was observed and reported in pervious experimental studies, hardware-based estimators do not provide accurate estimate [13], [18], [19], mainly for the following reasons: First, these metrics are measured based on 8 symbols of a received packet and not the whole packet. Second, these metrics are only measured for successfully received packets. Therefore, when a radio link suffers from excessive packet loss, they could overestimate the transmission performance by not considering the information of lost packets.

On the other hand, Software-based estimators enable to *count* or *approximate* either (*i.*) the reception rate, or (*ii.*) the average number of packet transmissions/re-transmissions, required before its successful reception.

The Packet Reception Rate (PRR) and the Acquitted Reception Rate (ARR) count the reception rate. The first is performed at the receiver side and the second at the sender side. These link quality estimators are simple, yet they have been widely used in routing protocols (e.g. in [20]).

The Required Number of Packet transmissions (RNP) counts the average number of packet transmissions/re-transmissions, required before its successful reception. It is introduced by Cerpa et.al. In [6], 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) [12], the Kalman filter based link quality estimator [15]and the packet success probability (PSP) [10], approximate the packet reception rate.

Furthermore, the link inefficiency metric (LI) [13], expected transmission count (ETX) [21], and *Four-Bit* [14]approximate the average number of packet transmissions/re-transmissions, required before a successful reception.

A through presentation of LQEs under evaluation will be presented in Section 3.

B. Performance Evaluation of Link Quality Estimators

To the best of our knowledge, there is no previous comparative study of link quality estimators in WSNs other than [12] and [6].

In [12], the authors introduced the Window Mean with Exponentially Weighted Moving Average (WMEWMA), a filter-based link quality estimator. The performance of *WMEWMA* was compared against other filter-based link quality estimators: Exponentially Weighted Moving Average (EWMA), Moving Average (MA) and Time-Weighted Moving Average (TWMA). The comparative study conducted in [12] has the advantage that it takes into account various performance criteria. However, it is restricted to filter-based LQEs. Further, the comparison is based on a simple generated trace, which does not take into account accurately the characteristics of channel communication. 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. It has been measured by the settle time, which is defined as the time needed by the estimator to reach the measured value, within an error bound of e. Stability is the ability to resist to transient (short-term) variations, also called fluctuations, in link quality. It is has been measured by the coefficient of variation, which is defined as the ratio of the standard deviation to the mean. History refers to the time window used to produce the estimate. A larger history yields a more stable, but less agile estimator [12]. Finally, resource utilization refers to the computation and storage overhead. Based on the above performance criteria, Woo et al. have shown that *WMEWMA* performs better than the other filter-based LQEs.

On the other hand, in [6]the main goal was to study the temporal characteristics of low-power links, using a real deployment of a WSN. Meanwhile, the authors of [6] compared *PRR* and *RNP* in order to select the suitable metric for link characterization. Cerpa et al. argued that *RNP* is better than *PRR* for estimating link quality. To justify their finding the authors observed different links during several hours, by measuring *PRR* and *RNP* each one minute. They found that for bad-quality and good-quality links, i.e. links having high (>90%) and low reception rates (<50%) respectively, *PRR* follows the same behaviour as *RNP*. However, for medium-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 usefulness of the link. As a matter of fact, a packet that cannot be delivered is retransmitted many times before being abandoned. The authors of [6] also studied the relationship between *RNP* and the inverse of *PRR* (1/*PRR*) statistically 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. Studied Link Quality Estimators

In what follows, we present the different estimators under evaluation.TABLE I presents the most important characteristics of these estimators.

TABLE I
STUDIED LINK QUALITY ESTIMATORS CHARACTERISTICS

	Monitoring type	Location	Metric	Direction
PRR	Passive	Receiver	Reception rate	Unidirectional
WMEWMA	Passive	Receiver	Reception rate	Unidirectional
RNP	Passive	Sender	Number of packet transmissions	Unidirectional
ETX	Active	Receiver	Number of packet transmissions	Bidirectional
four-bit	Hybrid	Sender	Number of packet transmissions	Bidirectional

The first estimator is the *PRR* metric, which measures the average of successfully received packets. This metric is computed at the receiver for each window of *w* received packets, as follows:

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

The number of lost packets is determined using the sequence number of packets. 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* [12], which is a filter-based estimator that approximates the *PRR* estimator as shown in the following equation:

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

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 computed at the receiver side for each *w* received packets.

The third estimator is *RNP* [6], 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:

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

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* [21], which is a receiver-initiated estimator that approximates *RNP*. It uses active monitoring, which means that each node explicitly broadcasts probe packets for collecting 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:

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

Note that $PRR_{forward}$ is simply the *PRR* of the uplink determined at the receiver, for each *w* received probe packets. On the other hand, $PRR_{backward}$ 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* [14], which is a hybrid estimator as it uses passive and active monitoring and 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:

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

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

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

In Eq. (6), the metric $estETX_{up}$ estimates the quality of the unidirectional link from the sender to the 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:

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

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

IV. THE SIMULATION MODEL

A. Simulation environment

In our simulation study, we have used TOSSIM 2.x [22], which is an event-driven simulation environment for sensor networks. TOSSIM is used to simulate the code of real sensor nodes that are implemented using the second release of TinyOS (TinyOS 2.x) [23]. TinyOS 2.x is an operating system and a programming framework developed at UC Berkeley and was specifically designed for sensor networks with small resource capacities. It is written in NesC [24], a C-based language that provides a support for the TinyOS component and concurrency model.

One of the main reasons behind the use of TOSSIM 2 is that it provides an accurate wireless channel model [25], [26], without which it will not be possible to consider the simulation results as valid. In the following, we give a short overview on this model.

In TOSSIM 2, the wireless channel model includes (*i.*) a *radio propagation model* and (*ii.*) a *link layer model*. The radio propagation model serves as input block for the link quality model. As for radio propagation model, TOSSIM 2 relies on the *log-normal shadowing* path loss model [27]. On the other hand, the link layer model is given by an analytical expression of the *packet reception probability* (PRP) as a function of the *signal-to-noise ratio* (SNR) [26]. This model takes into account various parameters that affect the packet delivery performance of low-power links [8], including hardware calibration, the distance between nodes, the path loss model, etc. Therefore, based on these parameters, TOSSIM 2 generates a link layer model (i.e. *PRP* as a function of the *SNR*) for each particular link in the sensor network. It also defines the ”gain” of that link, which is the signal attenuation due to the path loss. In addition, TOSSIM 2 uses a closest-fit pattern matching (CPM) model [25] to generate a distribution of environment noise samples that captures temporal variation in the environment. Whenever a simulated sensor node receives a packet, it samples a noise reading (*N*) using the CPM model and gathers the link gain (*S*) to determine the *SNR* (*SNR*=*S*/*N*). From the simulated *SNR* value, the node determines the corresponding *PRP* using its link layer model. Based on the *PRP*, a node can decide whether a packet has been successfully received or not. The interested reader can refer to [25], [26] for more details about the wireless channel model of TOSSIM 2.

B. Reception region analysis

There have been several empirical studies that performed extensive measurements of low-power links quality, in order to analyze their characteristics. Particularly, in [5], [7], [8], [10], link quality measurements have been carried out by observing the *PRR* between a pair of nodes placed at different distances. The goal was to observe the evolution of the *PRR* as a function of the distance. Based on these measurements, three different reception regions have been distinguished: *connected*, *transitional*, and *disconnected*. The connected region is the closest to the receiver. It is characterized by consistently high reception rates, i.e. greater than 90%, for most of the links. In contrast, the disconnected region, which is the farthest to the receiver, is identified by consistently low reception rates, which do not exceed 10%. In between, the transitional region, also referred to ”*gray area*”, is often quite large in width as compared to both other regions. In this region, reception rates are moderate, i.e. between 10% and 90%, and with high variance, which implies the existence of *moderate quality*, *instable*, and *asymmetric* links.

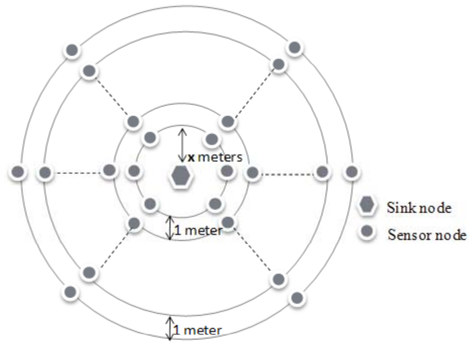


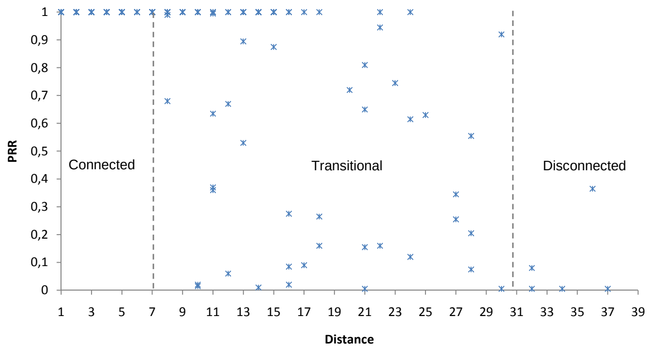
Fig. 1. Network Configuration for Reception Regions Evaluation

In order to properly configure the simulation models (refer to Section 4.3), it was necessary to identify the three reception regions in the simulated sensor network. In fact, the general methodology that we adopt for LQEs performance comparison is (*i.*) to inject to each LQE a number of links, with different characteristics, i.e. links of the connected region, others of the transitional region and others of the disconnected region, and (*ii.*) comparing the ability of LQEs to estimate the quality of these links efficiently. Therefore, it is necessary to know the boundaries of the three reception regions in order to set the distance between the sender and the receiver constituting the given link to estimate. In addition, as we consider two environment types: (*i.*) an indoor environment (aisle of a building) [28], and (*ii.*) an outdoor environment (football field) [28], it is also mandatory to analyze the three reception regions for each of these environments.

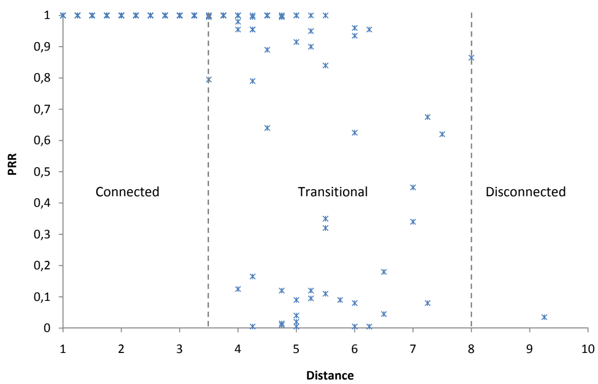
For that purpose, we placed 60 sensor nodes around one sink node, as illustrated in Fig. 1. These sensor nodes were divided in 10 sets, where each set contain 6 nodes, all placed in a circle around the sink node. The distance between two consecutive circles is equal to 1 meter. The first circle, i.e. the nearest to the sink, is placed at a distance to the sink node, equal to x meters. Each sensor node has an exclusive time slot during which it sends 200 data packets to the sink node. Note that sensor nodes send their data in non overleaping time slots in order to avoid collisions between sent packets. Further, 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 meter, whereas x has been varied in the set 1, 10, 20, 30 meter for the indoor environment. Simulation parameters are presented in TABLE II.

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: connected, transitional and disconnected.
It is important to note that the Fig. 2 proves the accuracy of the wireless channel model of TOSSIM. In fact, the majority of network simulators use an ideal link layer model [29] according which there are only two reception regions: connected and disconnected. On the other hand, TOSSIM uses a realistic link quality model because it leads to the three reception regions,



(a) Indoor environment: aisle of building



(b) Outdoor environment: football field

Fig. 2. Network Configuration for Reception Regions Evaluation

TABLE II
SIMULATION PARAMETERS FOR THE RECEPTION REGION EVALUATION

Environment	Asymmetry level of links	High
	Type of the Environment	Indoor: Aisle of building
		Outdoor: Football field
Number of sensor nodes	61	
Number of data sources	60	
Total sent packets / node	200	
Traffic type	CBR	rate: 61/8 packet/s
Simulation time	1700 ticks/s	

whose existence have been proven with experimental studies on actual sensor networks.
In addition, Fig. 2 shows that the width of the transitional region is larger in the indoor environment as compared to the width in the outdoor environments, in contrast to what might be expected due to multipath fading, dispersion, in indoor environments. This phenomenon is due to the fact that in the football field grass foliage creates a lot of multipath and dispersion which leads to a narrow transitional region. Therefore, for these particular environments, link qualities in the football field will be worse than in the aisle of building.

C. Simulation studies

In this section, we describe both simulation scenarios that we have designed to evaluate and compare the performance of the pre-cited link quality estimators. The first simulation scenario aims at analyzing and understanding the statistical properties of the link quality estimators independently of any external factor, such as collisions in MAC layer and routing in network layer. We only consider the impact of the physical layer and the re-transmission mechanism of the data link layer. On the other hand, the purpose of the second simulation scenario is to evaluate the impact of these estimators on higher layer protocols, namely the Collection Tree Protocol (CTP), which is a routing protocol already supported by TOSSIM 2. In the rest of this section, we give a detailed overview of both scenarios.

1) First simulation study: Performance Evaluation of LQEs: In the first simulation study, we consider the following scenario: a single-hop network of 10 sensor nodes ($N_1, N_2 ... N_{10}$) placed in a linear topology. We set node N_1 as a sink that receives data packets sent from each node ($N_2 ... N_{10}$). In addition, node N_1 sends a data flow of packets to each of these nodes, thus enabling asymmetry-aware estimators, i.e. *ETX* and *four-bit*, to estimate the bidirectional link quality (refer to Fig. 3). Sensor nodes send their data in non overleaping time slots in order to avoid collisions between sent packets. Further, packet retransmission mechanism has been activated. As depicted in Fig. 3, we used two different traffics: Trafic 1 and Traffic 2. Traffic 1 is relatively a small traffic (each of nodes ($N_2 ... N_{10}$) send 2400 packets). However, it is close to real world traffics as a node receives a first bunch of packets then sends another bunch of packets. Traffic 1 is used for showing the temporal behavior of LQEs. On the other hand, Traffic 2 involves much more packets (each of nodes ($N_2 ... N_{10}$) send 50000 packets), in order to reach the steady state of the simulation. Especially, this traffic is used for statistical analysis of LQEs.
We placed nodes $N_2 ... N_{10}$ as described in TABLE III, such that each one belongs to the *connected*, *transitional* or *disconnected* region of N_1.

In this study, we propose to estimate the quality of the unidirectional links ($1 \longleftarrow i.$), for *i.* ϵ [2, 10] for both indoor and outdoor environments. To achieve this purpose, we simulated the scenario described above, with each of the five link quality estimators, i.e. *PRR*, *WMEWMA*, *RNP*, *ETX* and *four-bit*, in addition to a filtered-*RNP*, that we denote 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 application level of nodes. On the one hand, *RNP* and *F-RNP* were implemented at sender nodes, $N_2 ... N_{10}$, as they rely on outgoing traffic to estimate link quality, whereas *PRR* and *WMEWMA* were implemented at the receiver node, i.e. N_1, since they rely on incoming traffic. On the other hand, *ETX* was implemented at node N_1 and *four-bit* at nodes $N_2 ... N_{10}$. *ETX* and *four-bit* use both incoming and outgoing traffics to estimate the link quality.

We choose a history control factor α = 0.9, as suggested in [14] and an averaging window w =5 for evaluating short-term

TABLE III
SIMULATION PARAMETERS FOR THE FIRST SIMULATION STUDY

Environment	Asymmetry level of links		High
	Type of the Environment		Indoor: Aisle of building
			Outdoor: Football field
Number of sensor nodes	10		
Traffic type	CBR		rate:1024/720 packet/s
Topology	Type	Linear	
	Nodes location	Indoor	(1,0), (5,0), (10,0), (12,0), (14,0), (18,0), (20,0), (22,0), (25,0), (28,0)
		Outdoor	(1,0), (2,0), (3,0), (4,0), (5,0), (6,0), (7,0), (8,0), (9,0), (10,0)
Simulation time	26700 ticks/s		

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

(a) Traffic 1

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

(b) Traffic 2

Fig. 3. Traffic pattern of the first simulation study

estimation and w =100 for evaluating long-term estimation.

2) Second simulation study: Impact on CTP routing protocol: In the second simulation study, we consider a multi-hop network where nodes compete to deliver their data to the sink node using Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as medium access protocol, and CTP [30] as routing protocol. The CTP is a routing and data collection protocol that builds a tree toward the sink node according to the qualities of the links. It has three basic components [30]:

- *The link quality estimator* which enables each node to estimate the quality of the links to its neighbors using *four-bit* estimator [14] by default.
- *The routing engine*, which enables nodes 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 the scheduling of their transmission to next hops.

We aim at evaluating the impact of link quality estimator on the CTP routing protocol, while varying different simulation parameters including environment type, topology configuration, number of nodes, number of data sources and traffic type. The five simulation sets in this study are presented in TABLE IV and TABLE V. For every set of simulations, we vary only one parameter in order to investigate its impact on the performance of the link quality estimators under evaluation. Nodes begin their transmission after a delay of 300s, i.e. after the topology establishment. Each simulation is repeated 30 times to reach a steady state with 95% of confidence interval.

TABLE IV
SIMULATION SETS OF THE SECOND SIMULATION STUDY

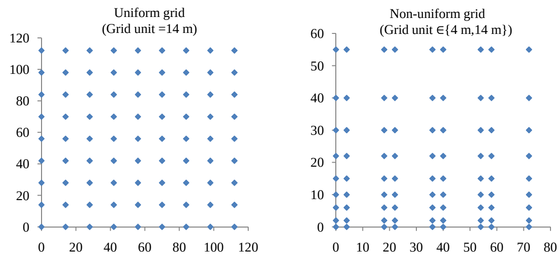
	Environment type	**Grid topology type**	**Number of nodes**	**Number of data sources**	**Traffic type**
First set of simulations	{Indoor, Outdoor}	Non-uniform	81	10	Poisson
Second set of simulations	Outdoor	{Uniform, Non-uniform}	81	10	Poisson
Third set of simulations	Outdoor	Non-uniform	{16, 25, 36, 49, 64, 81}	=number of nodes	Poisson
Fourth set of simulations	Outdoor	Non-uniform	81	{10, 20, 40, 80}	Poisson
Fifth set of simulations	Outdoor	Non-uniform	81	10	{Poisson, CBR}

TABLE V
SIMULATION PARAMETERS FOR THE SECOND SIMULATION STUDY

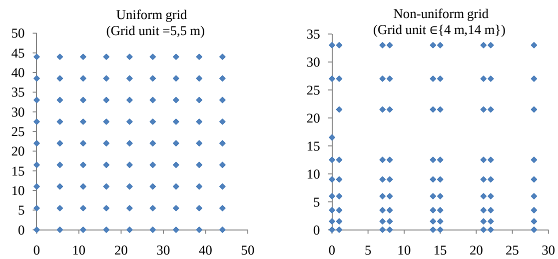
Environment	Asymmetry level of links	High
	Type of the Environment	Indoor: Aisle of building
		Outdoor: Football field
Traffic type	CBR	rate: 1/8 packet/s
	Poisson	mean rate: 1/8 packet/s
Simulation time	600 ticks/s	

Sensor nodes were deployed in a grid topology with two different layouts: uniform grid topology and non-uniform grid topology. Fig. 4 shows the distribution patterns of 80 sensor nodes and a single sink node, in the uniform grid topology and the non-uniform grid topology, for indoor and outdoor environments. The sink node is the one located in the corner of the topology at coordinates (0,0).

The choice of the different grid units (in meters) is carried out based on the previous receptions region analysis. In the uniform grid topology, the grid unit is constant. We choose a value of the grid unit such that links are of moderate or bad qualities (see Fig. 4). This means that each two neighbor nodes are far-away by a distance in the range of the transitional or the disconnected regions. By this way, we make sure that link quality estimators operate in extreme conditions. In the non-uniform grid topology, we aim at building a topology with a mixture of links qualities: good, moderate and bad. For that purpose, we used a variable grid unit so that two neighboring nodes can be far-away by a distance in the range



(a) Indoor environment: aisle of building



(b) Outdoor environment: football field

Fig. 4. Distribution pattern of 80 sensor nodes and a single sink node, in uniform and non-uniform grid topologies

of the connected, transitional or disconnected regions.
Note that *four-bit* is the native estimator for CTP, thus, we have additionally implemented the other four link quality estimators in TOSSIM. We choose a history control factor α = 0.9 and averaging window w to 5 [14].

V. Performance Analysis

In this section, we analyze the complexity and resource usage of the estimators, and we evaluate their performances based on the results of both simulation scenarios, described in the previous section.

A. First simulation study: performance of LQEs

In the first scenario, we study (*i.*) the temporal behaviour of LQEs, as illustrated in Fig. 5, and (*ii.*) the statistical properties of LQEs, shown in Fig. 7, Fig. 6, Fig. 8. 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, presented in Fig. 6. The over-estimation level is defined as "how much the estimator deviate from reality by estimating the link at a certain level of goodness when it is not good as it has been estimated". We have presented the results by considering all nodes of the indoor environment simulation. These results 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. Results related to LQEs stability are presented in Fig. 7.
- The absolute value of the coefficient of correlation (CC), which expresses the degree of linear dependency between a pair of Link quality estimators. Results are presented in Fig. 8.

In what follows, we present the main lessons learnt from the first simulation study.

1) Over-estimation: In Fig. 6, 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 the *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 count-based estimates, which are quite sensitive to retransmissions, hidden to the receiver.

This finding is clearly illustrated in Fig. 5b for the link (1←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 demonstrate that the link is not as good as inferred by *PRR*-based metrics.

2) Stability: Fig. 7 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 2 has been used in this simulation.

First, according to Fig. 7, we observe that *WMEWMA* and *F-RNP* are the most stable in general. This can also be observed through the temporal behavior in Fig. 5. The main reason is that these estimators are based on filtering technique, which smoothes the variation of the link quality 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 impact on the stability of filter-based estimators, as shown in Fig. 9a. It is easily observed that the coefficient of variation of the filter-based estimators linearly decreases as the history control factor α increases, which turns their behavior more stable. 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. 9aalso confirms that *WMEWMA* remains almost the most stable estimators for any value of the factor .

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 we only consider 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. 5, where the *four-bit* estimates sharply decrease whenever *WMEWMA* is used for each incoming packet.

Third, the study also reveals that all estimators are more stable in long-term estimation (i.e. w = 100) than in short-term estimation (i.e. w = 5), as shown in Fig. 7 and Fig. 9a. This is a reasonable result since the average estimation in long-term will be closer to the steady state than that in short-term, which is more prone to changes. In this particular case, by applying a linear regression analysis on the short-term CV with their corresponding long-term CV, we found that the long-term CV of each estimator (with $w = 100$) is nearly the half of its short-term CV (with $w = 5$). This infers a strong linear correlation between the short-term and long-term CV vectors.

Stability results described above are also confirmed by observing the temporal behavior of LQEs in Fig. 5.

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. 8, we can roughly draw the following conclusions.

First, there is strong linear correlation between *PRR* and *ETX* although they are computed in completely different manner. Note that these two metrics are not correlated with the other estimators. The reason is

Second, *RNP* and *F-RNP* are weakly correlated, similarly to *PRR* and *WMEWMA*. The main reason is that the control history factor is too high such that the filter-based estimators are mostly related to the link quality history than to the current quality. For smaller values of the correlation of *RNP* and *PRR* estimators with their filter-based versions increases, as shown in Fig. 9b. Note that the behavior of the LQEs shown in Fig. 9b is similar to those for the outdoor environment and for long-term estimation.

Third, the correlation between *four-bit* and *F-RNP* on the one hand, and between *four-bit* and *WMEWMA* on the other hand is traffic-specific. It in fact heavily depends on the proportion between the traffic being sent and that being received. In fact, Fig. 8 shows a strong correlation between *four-bit* and *WMEWMA* whereas the correlation between *four-bit* and *F-RNP* is very weak. This is very much related to the use of traffic 2, i.e. a node receives a first bunch of packets then sends another bunch of packets. In contrast, Fig. 9b shows that the use of traffic 1 where sent and received packets are more evenly distributed over time makes that four-bit is no longer much correlated with its composite estimators. In general, four-bit would not be correlated neither to *WMEWMA* nor to *F-RNP*, or in best case weakly correlated since in a real deployment, the traffic between sensor nodes would be much closer to traffic 1.

B. Second simulation study: impact of LQEs on CTP routing protocol

In the second scenario, we evaluate the impact of LQEs on CTP routing protocol and we compare their performance in terms of accuracy, cost and stability, when subjected to different network conditions, including the environment type, the grid topology type, the network size, the number of data sources and the traffic type.

1) Accuracy: Fig. 10 shows a comparison between link quality estimators in terms of accuracy based on the measure of the packet delivery rate (see Section 4.4) under different network conditions. Based on this figure, we retain the following findings.

Finding1: Impact of the estimator class

In Fig. 10a to Fig. 10e, we clearly observe that the *PDR*s of the four link quality estimators are organized in the following decreasing accuracy order (from the most to the less accurate): (1) *four-bit*, (2) *ETX*, (3) *RNP*, (4) *PRR* and then (5) *WMEWMA*. This observation highlights three main outcomes.

- First, the accuracy of *four-bit* and *RNP* comparing to *PRR* and *WMEWMA* is justified by the fact that the firsts integrate *RNP* metric whereas the seconds integrate *PRR* metric. As we have shown in the previous simulation study, *PRR*-based LQEs overestimate the link quality as they provide a coarse-grain estimation of the link quality, in contrast to *RNP*-based LQEs. Nevertheless, *ETX* also integrates *PRR* metric, yet it is more accurate than *RNP*. Its accuracy is due to the fact that it relies on *active monitoring*. In fact, in the first simulation study, we have shown that *ETX* overestimate link quality just like *PRR* and *WMEWMA*. But in this study we implemented *ETX* with *passive monitoring*, instead of active monitoring. In this study, *ETX* relies on *active monitoring* to derive estimate. In addition, the beaconing rate is high (1packet/s) comparing to the data traffic rate (1/8 packet/s). Consequently, *ETX* have frequently fresh information on links states, which enable it to provide accurate link quality estimate. Therefore the accuracy of *ETX* would be due to the active monitoring and not due to the metric itself.
- Second, *four-bit* leads to slightly better delivery performance than *ETX*. This might be due to the fact that *four-bit* integrates a metric that count the required number of packet retransmissions (RNP), but *ETX* approximates the required number of packet retransmissions.
- Third, the accuracy of *four-bit* comparing to *RNP* can be explained by the following: *four-bit* integrates both *PRR* and *RNP* metrics. In one hand *PRR* have been shown to overestimate the links quality. On the other hand, we showed also that *RNP* is pessimistic. In other words, it underestimates link quality. Therefore, the performance of *four-bit* comparing to *RNP* can be due to the fact that these LQEs integrate two metrics that enable to have a balance between overestimating and underestimating link quality.
- Fourth, regarding LQEs that count or approximate the packet reception rate, we found that the *PRR* metric leads to a slightly better delivery performance than does *WMEWMA*, which means that *PRR* is more accurate than *WMEWMA*, in contrast to the results in [12]. One of the reasons is that *PRR* is more reactive to quality changes than *WMEWMA* since the latter is filter-based. Furthermore, in [12], accuracy is not measured by the *PDR* but by the mean square error between the measured link quality and the estimated link quality (refer to related work, section 2.2). Recall that in our

simulations, we choose α = 0.9 and *w*=5, for filter-based LQEs, as in [14]. These settings are different from those in [12]that introduced *WMEWMA*. However, even when setting α = 0.6 and *w* = 30 as it was set in [[12], we observed the same result, i.e. *PRR* provides better *PDR* than *WMEWAM* (see Fig. 9). This might be due to the fact that comparative results in [12]are based on a simple generated trace, which doesn't take into account accurately the characteristics of communication channel, the network configuration and other parameters, such as number of sources, environment type, etc. Fig.9 shows also that the performance of *four-bit* greatly depends on the setting of its parameters, α and *w*, since the *PDR* drops from 0.76 with the old setting to 0.39 with the new setting of α and *w*.

Finding 2: Impact of the environment type
Fig. 10a shows that the type of the environment has a major impact on the *PDR* for all link quality estimators depending on the level of multipath dispersion and interference. In indoor environment, the delivery performance is better than in outdoor environment, because links are of better quality for this particular case. Remind that the outdoor environment we used is football field whose grass foliage creates a lot of multipath and dispersion which leads to worse link qualities (see Section 4.2) as compared to the indoor environment representing the aisle of building.

Finding 3: Impact of the grid topology
Fig. 10b shows two important observations: (1) First, the measured *PDRs* are quite similar for all LQEs and they exhibit a small mutual variation. This is because all links have the same distance and thus the long-term quality will almost be constant for all estimators. The difference between estimators is, however, more significant in the non-uniform case since links have different distances and thus different qualities. (2) Second, it is clear that the delivery performance in non-uniform grid topology is better than in uniform topology for all link quality estimators. This is expected since the non-uniform topology contains a mixture of links including good, bad and moderate links. However, in uniform grid topology links are of bad or moderate qualities, which affect the delivery performance.

Finding 4: Scalability
Fig. 10c shows that the delivery performance decreases as the network size increases by a factor close to 30% for all link quality estimators. Thus, it can be concluded that all LQEs have similar scalability as they react similarly to the network scale changes. Nevertheless, the accuracy of the link quality estimators still respects the same order, listed before, for almost all network sizes, i.e. *four-bit*, *ETX*, *RNP*, *PRR* and *WMEWMA*, which confirms Finding 1.

Finding 5: Impact of data sources
It can be observed in Fig. 10d that varying the number of data sources, which is approximately equivalent to varying the application sending rate, does not significantly impact the delivery performance. The reason is that increasing the number of data sources has controversial roles: (1) degrading the network performance by having more collisions and increased congestions in at the parent node in the data collection tree, (2) improving the performance of the LQEs by computing better estimates of links due to increased traffic. For that reason, Fig. 10d depicts that the impact of increasing the number of data sources is more important on data-driven link quality estimators (i.e. using passive monitoring) than on beacon-driven link quality estimator (i.e. using active monitoring, such as*ETX*).

Finding 6: impact of traffic type
Fig. 10e shows that the difference in the accuracy between link quality estimators for CBR and Poisson traffics is not significant.

2) Cost: Fig. 12 shows a comparison between LQEs in terms of cost under different network conditions. Findings retained from Fig. 12 are presented in the following.

Finding 1: Overall performance in terms of cost
In Figures Fig. 12a, Fig. 12b and Fig. 12e, it can be observed that *ETX* provides the best cost (consumed energy), followed by *RNP* then *four-bit*. Despite that *four-bit* showed the best delivery performance, it involves higher cost as compared to *ETX* and *RNP*. This involved *four-bit* is mainly due to the higher length of selected routes on the path to the sink. In fact, as it is depicted in Fig. 13, *four-bit* has mostly the highest average number of parent changes, which leads to longest paths to the sink node, as it is shown in Fig. 12 [14]. This is mainly a shortcoming in CTP as it does not take into account the hop count metric in route selection process during the establishment the data collection tree.

Finding 2: Impact of number of nodes
In a congested network, it appears that *four-bit* provides the best performance in terms of cost, as it is shown in Fig. 12c (starting from 49 nodes) and Fig. 12d (starting from 40 data sources). Indeed, while *four-bit* still selects longer routes, it presents the advantage of selecting routes whose links are of better quality in terms of number of packet retransmissions.

Finding 3:
As observed in Fig. 12, *PRR* and *WMEWMA* compute the shortest routes as compared to the other link quality estimators, yet they have the worst costs in most of network conditions due to excessive retransmissions. This observation demonstrates their inappropriateness for data collection routing protocols in WSNs. This finding can also be justified by the fact that *PRR* and *WMEWMA* do not count packet retransmissions in their computation. Furthermore, *WMEWMA* shows again lower performance in terms of cost than *PRR*, similarly to the results of accuracy.

3) Stability: Fig. 13 shows a comparison between LQEs in terms of stability, based on the measure of the average number of parent changes, under different network conditions. Form this figure, we retain the following findings.

Finding: accuracy versus instability
The indoor environment and the uniform grid topology are not suitable for performance comparison between link quality estimators because they do not show clear differences between

LQEs. However, in the other configurations, we find that *four-bit* is the most instable link quality estimator as it exhibit the highest number of parent changes, followed by *ETX*, *RNP*, *WMEWMA* and finally *PRR*. In fact, LQEs that are based on the number of packet retransmission are (1) more pessimistic when estimating link qualities as they take into account the short-term loss distribution of packets, and (2) are more sensitive to changes in link quality, thus present a highly reactive behavior. This finding demonstrates that there is compromise between accuracy and stability metrics. Link quality estimators that estimate more accurately links quality present more instability.

VI. Conclusion

In this paper, we proposed a comparative simulation study of a set of the well-known link quality estimators, namely PRR, RNP, WMEWMA, ETX and *Four-Bit*, using TOSSIM simulator. Our comparative study includes three essential parts:

In the first part, we analyzed and compared the temporal behavior of link quality estimators, using a simple simulation scenario in which we exclude the impact of MAC and routing. In the second part, we compared the performance of link quality estimators, by assessing their impact on CTP, a Collection Tree Routing protocol.

It has been shown that Give some future works One of the challenges is the design of estimators that make a good balance between stability and accuracy. Another challenge is design of estimators that take into account several parameters (like our ILQE proposal).

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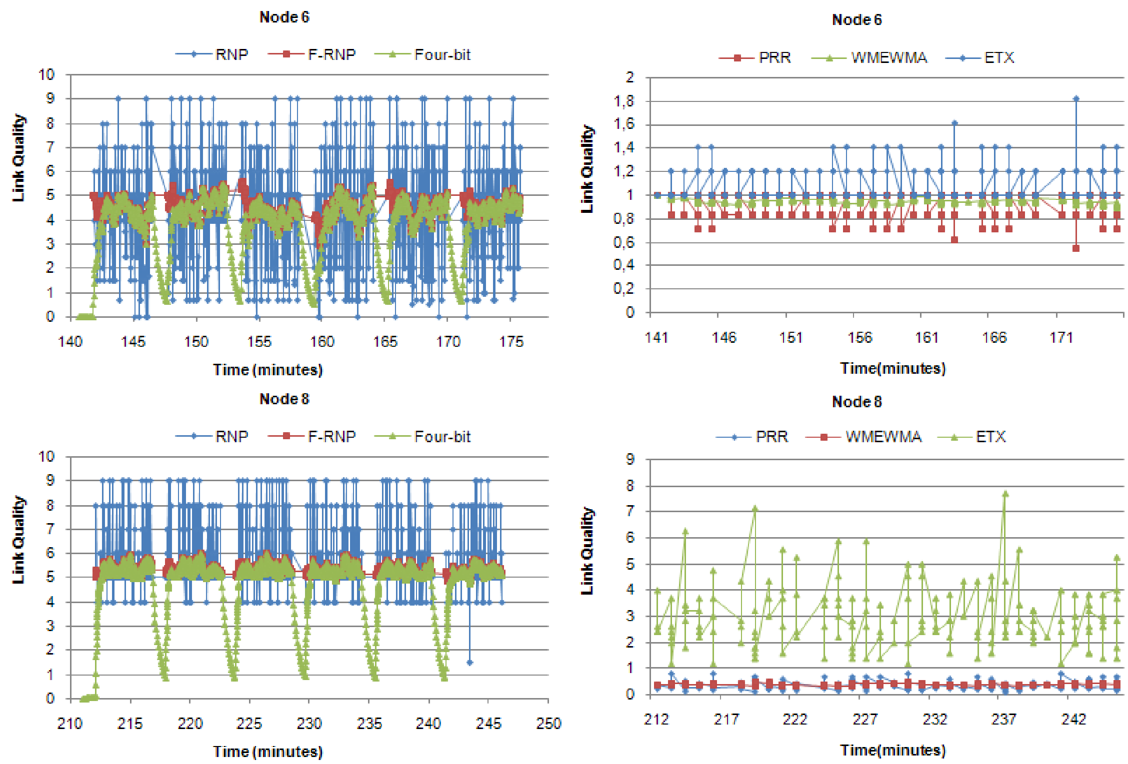
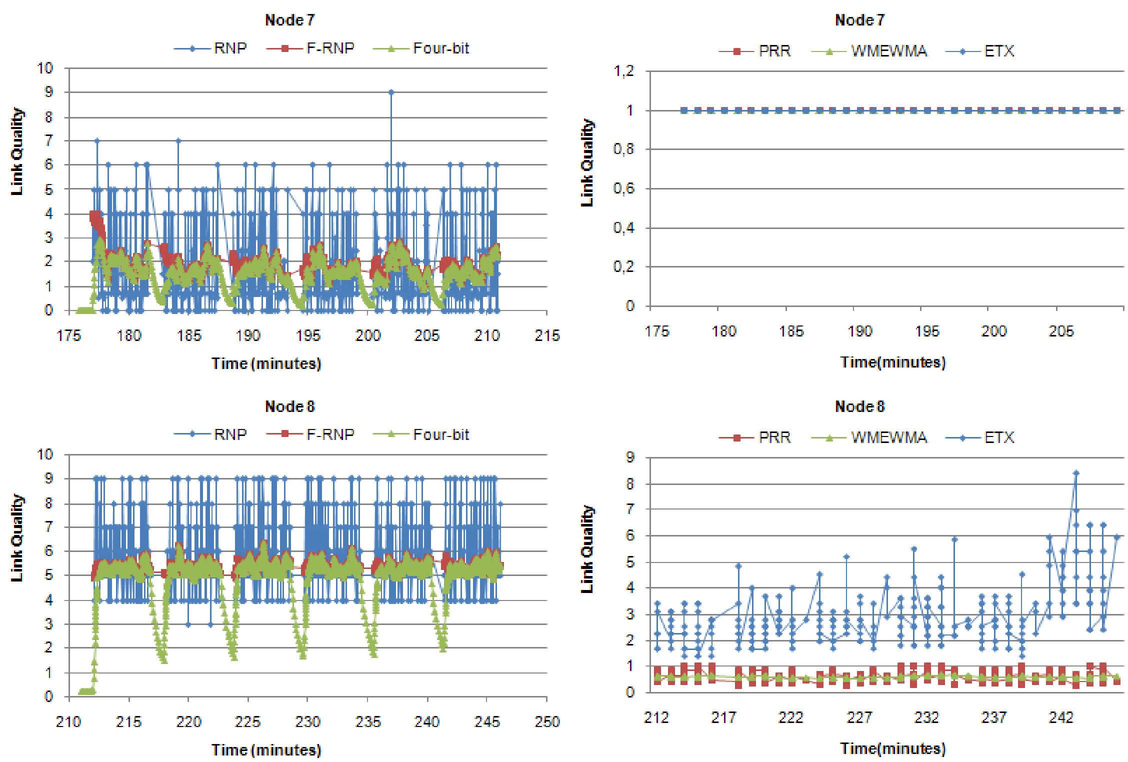


(a) Indoor environment: aisle of building



(b) Outdoor environment:football field

Fig. 5. Temporal behaviour of link quality estimators (traffic 1,w = 5)

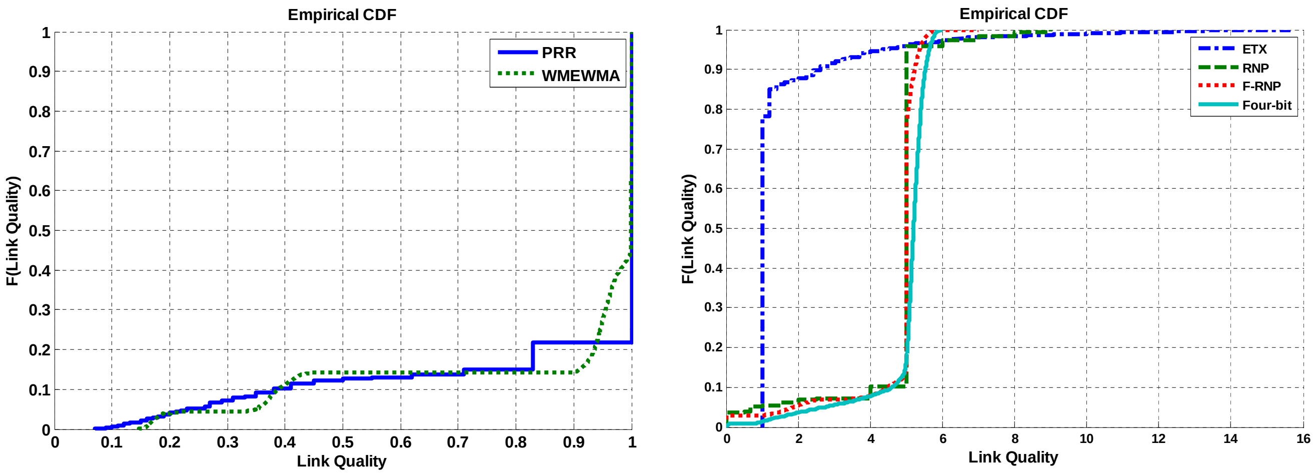


Fig. 6. Empirical CDFs of link quality estimators (Traffic 1, Indoor environment, w = 5)

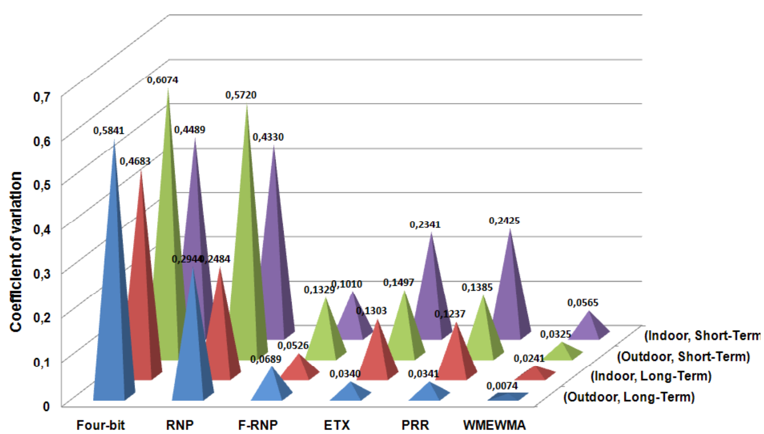
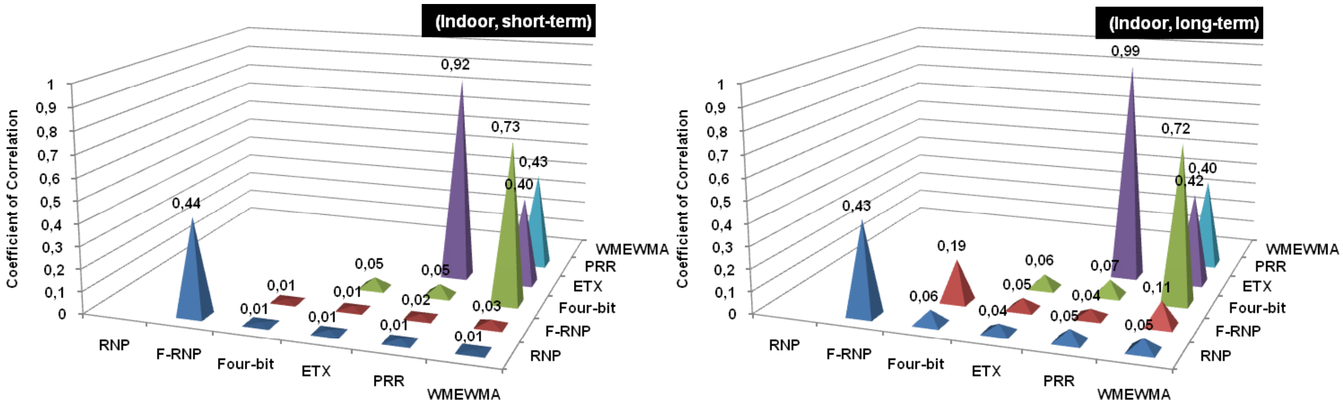
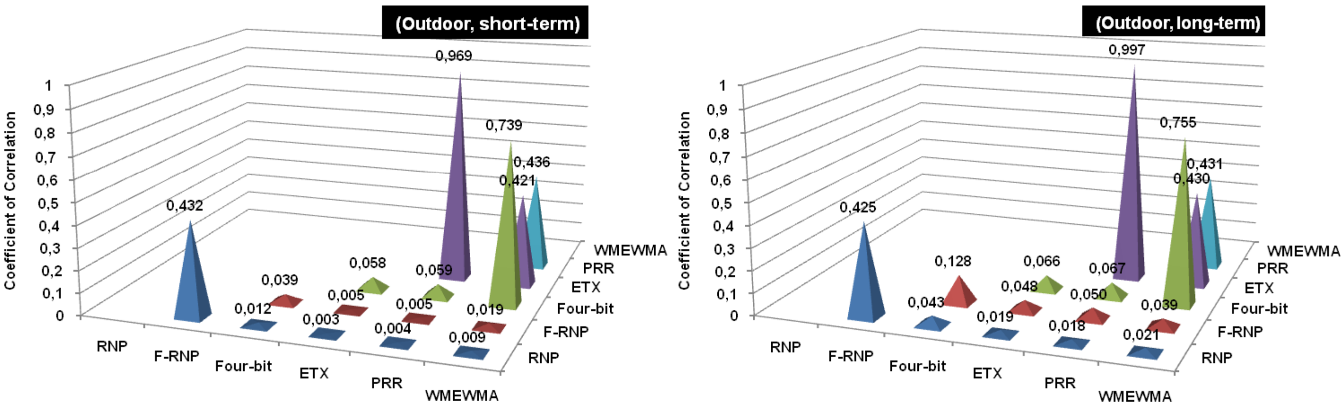


Fig. 7. Stability of link quality estimators (Traffic 2)

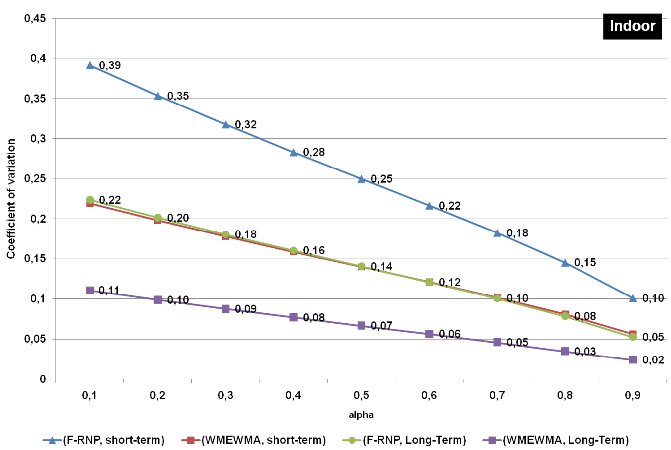


(a) Indoor environment: aisle of building

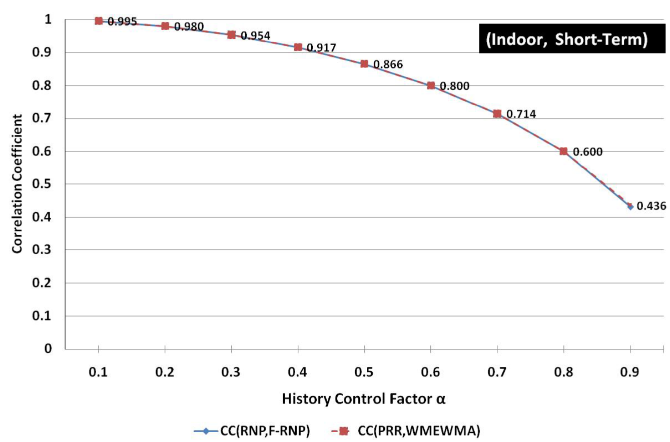


(b) Outdoor environment: football field

Fig. 8. Correlation between link quality estimators (Traffic 2)

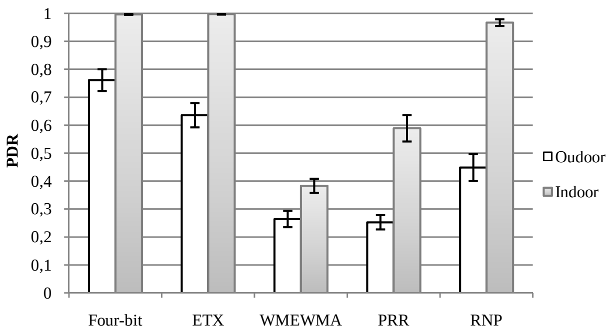


(a) Impact on the coefficient of correlation

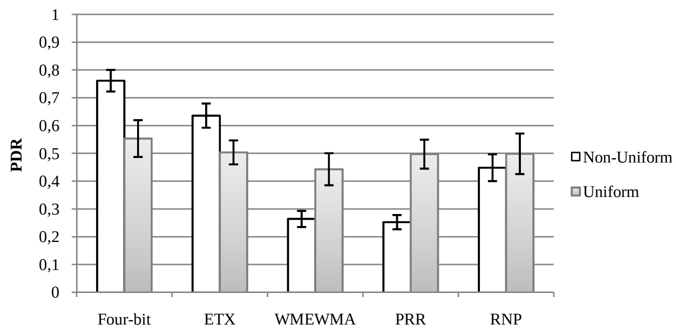


(b) Impact on the coefficient of variation

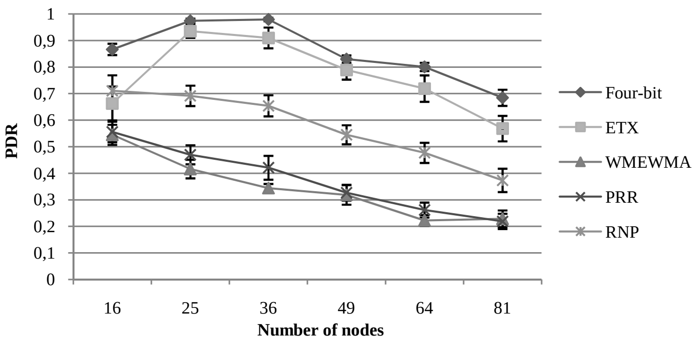
Fig. 9. Impact of the History Control Factor (traffic 2)



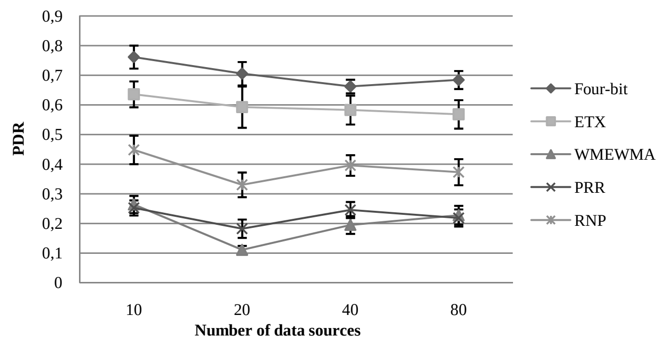
(a) Effect of the environment type



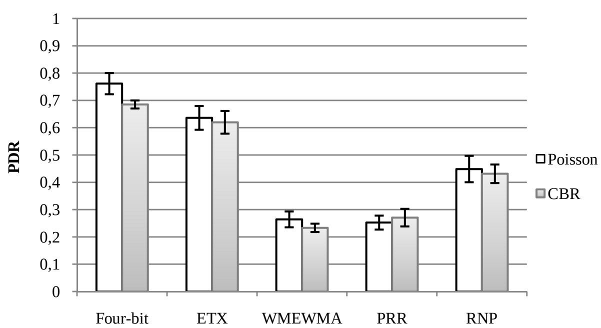
(b) Effect of the grid topolgy type



(c) Effect of the number of nodes



(d) Effect of the number of data sources



(e) Effect of the traffic type

Fig. 10. Performance comparison in terms of accuracy

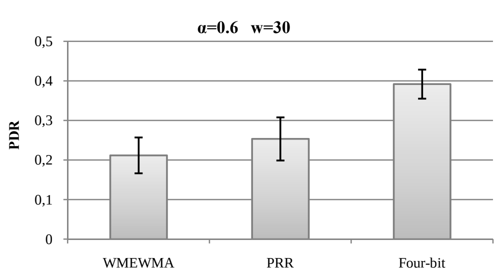
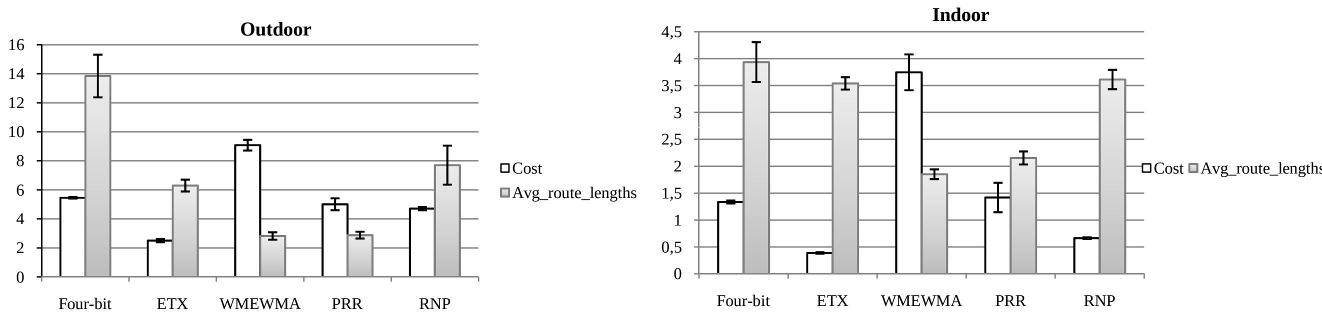
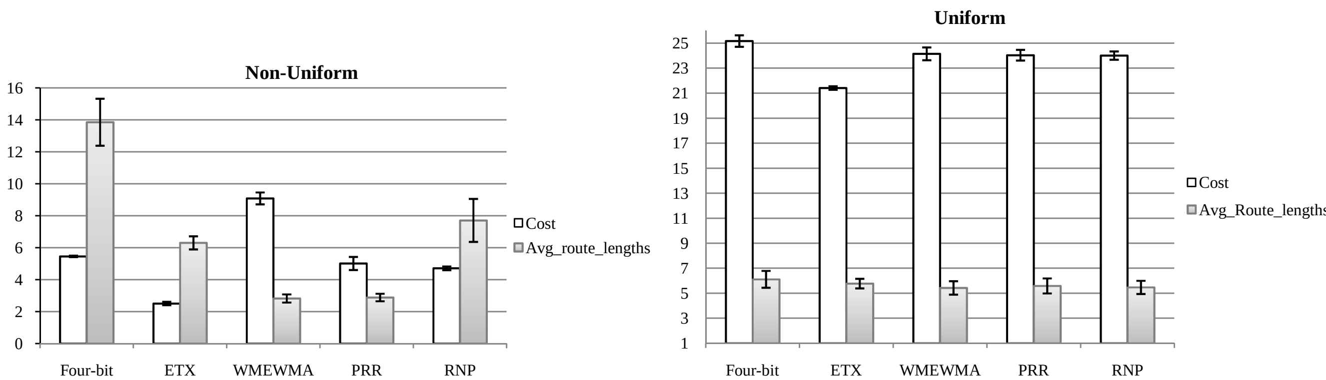


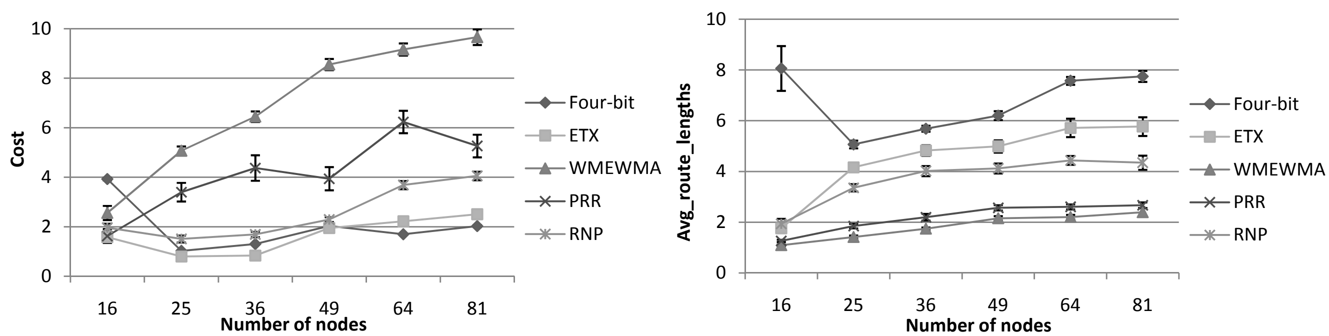
Fig. 11. Impact of α and w on *WMEWMA* accuracy



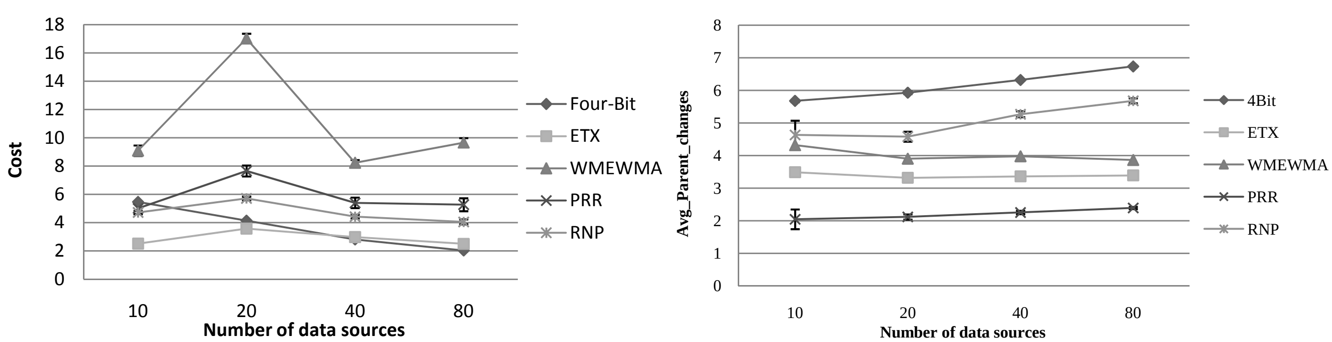
(a) Effect of the environment type



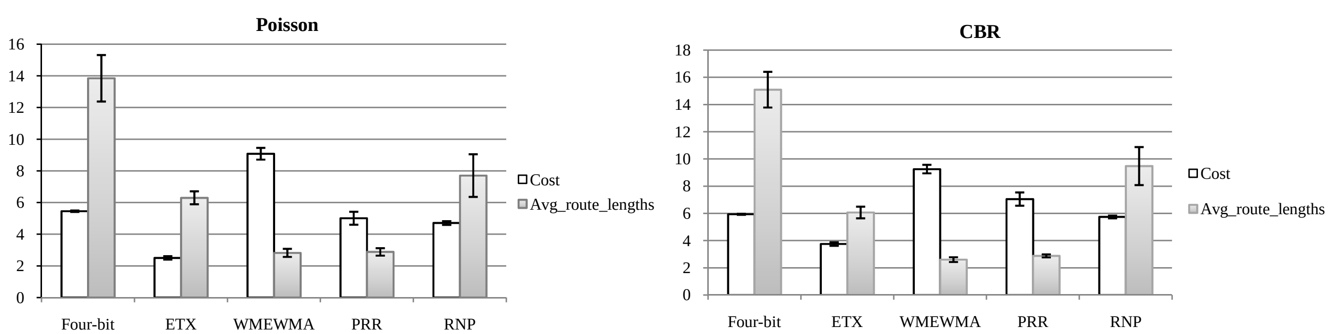
(b) Effect of the grid topolgy type



(c) Effect of the number of nodes

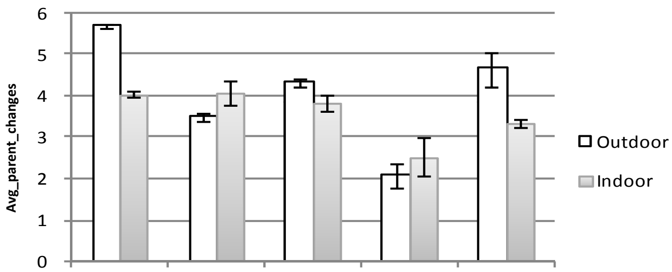


(d) Effect of the number of data sources

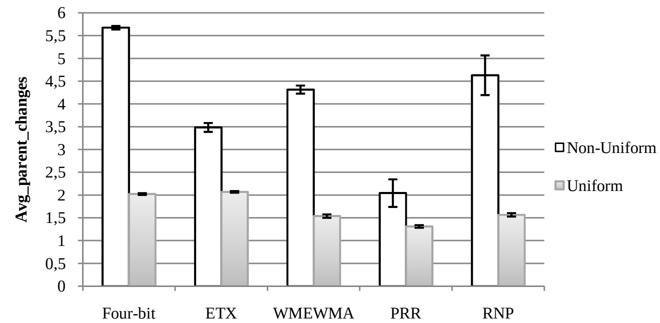


(e) Effect of the traffic type

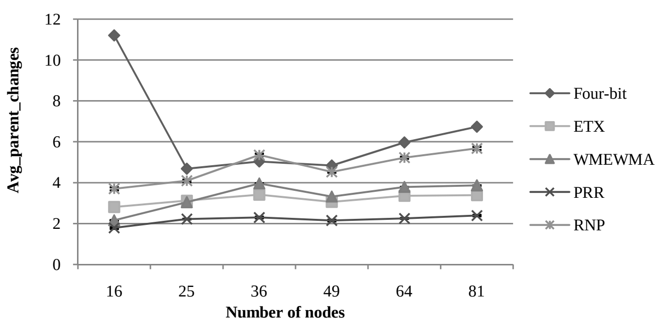
Fig. 12. Performance comparison in terms of cost and Average route lengths



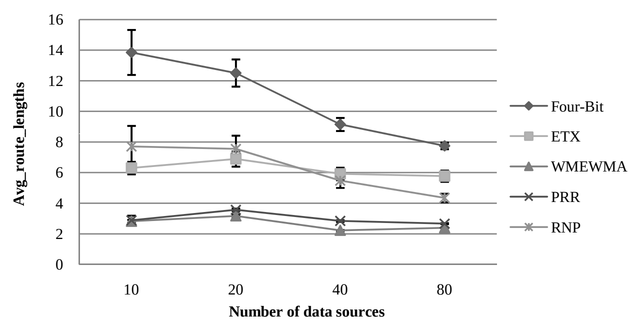
(a) Effect of the environment type



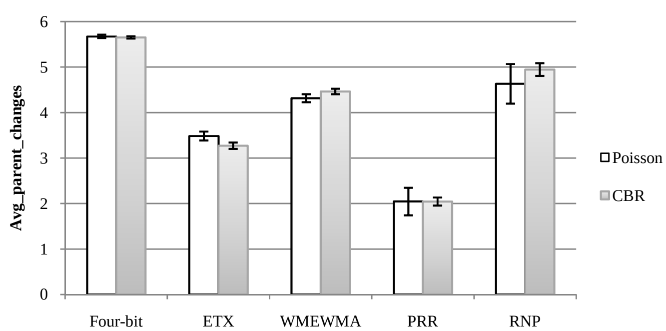
(b) Effect of the grid topolgy type



(c) Effect of the number of nodes



(d) Effect of the number of data sources



(e) Effect of the traffic type

Fig. 13. Performance comparison in terms of stability