A TestBed for the Evaluation of Link Quality Estimators in Wireless Sensor Networks

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***Abstract*—Link quality estimation is a fundamental building block for the design of several different mechanisms and protocols in wireless sensor networks. The accuracy of link quality estimation greatly impacts the efficiency of these protocols. Therefore, a thorough experimental evaluation of link quality estimators (LQEs) is mandatory. This motivated us to build a benchmarking testbed - RadiaLE, that automates LQEs evaluation by analyzing their statistical properties. Our testbed includes (i.) hardware components that represent the WSN under test and (ii.) a software tool for setting up and controlling the experiments and also for analyzing the collected data, allowing for LQEs evaluation. To demonstrate the usefulness of RadiaLE, we carried out a comparative performance study of a set of well-known LQEs.**

I. Introduction

Wireless sensor networks (WSNs) have severe constraints on energy consumption since nodes have to survive on a limited battery energy for extended periods of time, up to several years. This fact brings network protocols designers to provide energy-efficient solutions, namely in what concerns media-access control (MAC), routing, mobility management, and topology control protocols. One of the most important requirements to achieve this goal is to avoid excessive retransmissions over low quality links. Therefore, link quality estimation emerges as a fundamental building block for network protocols to maximize the lifetime and the throughput of WSNs.

Several link quality estimators (LQEs) have been reported in the literature [1]–[4]. They can be classified as either hardware-based or software-based. Hardware-based LQEs, such as LQI (Link Quality Indicator) and RSSI (Received Signal Strength Indicator) are directly read from the radio transceiver (e.g. the CC2420). Most of software-based LQEs enable to either count or approximate the packet reception ratio or the average number of packet transmissions/retransmissions.

The accuracy of link quality estimation greatly impacts the efficiency of network protocols. For instance, routing protocols rely on link quality estimation to select high quality routes for communication, i.e. routes composed of with high quality links. The more accurate the link quality estimation is, the more correct the decision made by routing protocols in selecting such routes. Therefore, it is important to assess the performance of the LQE before integrating it into a particular the network protocol.

The experimental performance evaluation of LQEs requires performing link measurements through packet statistics collection. Several testbeds have been designed for the experimentation (test, validation, performance evaluation, etc.) of WSNs [5]–[9], but only [10] and [11] targeted link measurements. However, these were exploited for analyzing low-power links characteristics rather than the performance evaluation of LQEs.

Despite its importance, the experimental performance evaluation of LQEs remains an open problem, mainly due to the difficulty to provide a quantitative evaluation of their accuracy. This motivated us to build a benchmarking testbed - RadiaLE, aiming at the experimental evaluation and optimization of LQEs. RadiaLE includes (i.) hardware components that represent the WSN under test and (ii.) a software tool for setting up and controlling the experiments and also for analyzing the collected data, allowing for LQEs evaluation.

The rest of this paper is organized as follow. Following the related work on experimental testbeds (section II), we give an overview on our testbed RadiaLE (sction III). Then, we present an empirical study demonstrating the capabilities of RadiaLE in evaluating the performance of LQEs (Section IV).

II. Related work

Several testbeds have been designed for the the experimentation of WSNs. They can be classified into two categories:

Testbeds of the first category, such as [5]–[9] have been designed and operated to be remotely used by several users

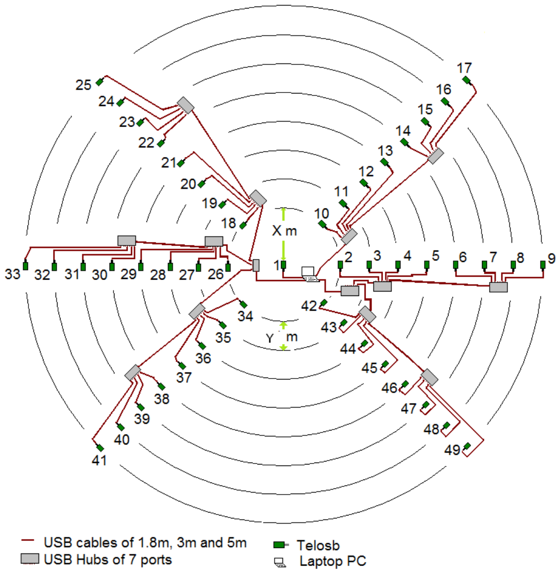


Fig. 1. Nodes distribution according the Radial topology

having *different research objectives*. Roughly, each of these testbeds has four building blocks: (*i.*) the underlying WSN, (*ii.*) a network backbone providing reliable channels to remotely control sensor nodes, (*iii.*) a server that handles sensor nodes reprogramming and data logging into a database, and (*iiii.*) a web-interface coupled with a scheduling policy to allow the testbed sharing among several users. The testbed users have to be expert on the programming environment supported by the tesbeds (e.g. TinyOS, Emstar), in order to be able to provide executable files for motes programming. They must also create their own software tool to analyze the experimental data and produce results.
These testbeds suffer from several weaknesses. Their tendency to cover multiple research objectives and being used by multiple users prevent them from advancing a specific research objective to the next level. In fact, the testbed resources cannot be available for a given user for a long time as they are shared with several others. Further, the physical topology of sensor nodes as well as the environment conditions cannot be managed by the user.

Many researchers support developing their own tesbeds to achieve *a specific goal*. These represent the second category of testbeds. To our best knowledge, none of the existing testbeds was devoted for the performance evaluation of LQEs. Some testbeds have been dedicated for link measurements such as SCALE [10] and SWAT [11], but they were exploited for analyzing low-power link characteristics rather than the performance evaluation of LQEs.

SCALE [10] is a tool for measuring the PRR (Packet Reception Ratio) LQE. It is built using the EmStar programming model. Each sensor node runs a software stack, allowing for sending and receiving probe packets in a round robin fashion, retrieving packet statistics, and sending them through serial communication. All Sensor nodes are connected to a central PC via serial cables and serial multiplexors. The PC runs different processes -one for each node in the testbed- that perform data collection. Based on the collected data, other processes running on the PC allow for connectivity assessment through the derivation of the PRR of each unidirectional link. Thus, the network connectivity can be visualized during the experiment runtime.

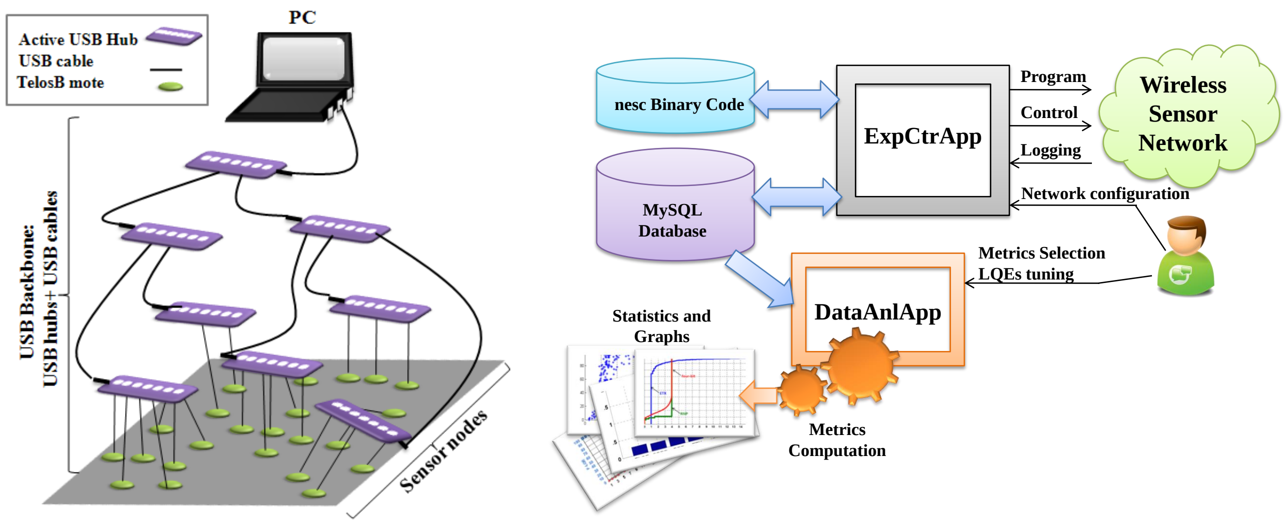
SWAT [11] is a tool for link measurements. The supported metrics (or LQEs) include PRR, RSSI, LQI, noise floor, and SNR (Signal-to-Noise Ratio). SWAT uses the same infrastructure as SCALE but with more sophisticated platforms (micaZ or TelosB): Sensor nodes are connected through serial connections or Ethernet to a central PC. SWAT provides two user-interfaces (UIs), written in HTML and PHP. Through the HTML UI, users can specify the experiment parameters. The PHP UI is used to set-up link quality metrics, and some statistics (e.g. PRR over time) correlation between PRR and RSSI. Then the UI invokes Phyton scripts to process the collected data and display reports.

SCALE is compatible to old platforms, Mica1 and Mica2 motes, which do not support the LQI hardware-based LQE. On the other hand, SWAT is not practical for large-scale experiments, as some configuration tasks are performed manually. Both SWAT and SCALE allow for link measurements through packet statistics collection but the collected data do not enable to compute various LQEs, namely sender-side LQEs, such as four-bit [2], [12] and RNP [13]. The reason is that SWAT and SCALE do not collect sender-side packet-statistics (e.g. number of packet retransmissions).

Most of existing testbeds use one-Burst traffic, where each node sends a burst of packets to each of their neighbours then passes the token to next node to send its burst. This traffic pattern cannot accurately capture link *Asymmetry* property as the link two directions (uplink and downlink) will be assessed in separate time windows. Thus, traffics patterns that improve the accuracy of link Asymmetry assessment are mandatory. In addition, as it has been observed in [14], the traffic Inter-packets Interval has a noticeable impact on channel characteristics. For that reason, it is important to understand the performance of LQEs for different traffic configurations.

In what follows, we present RadiaLE, our testbed solution that solves the above mentioned deficiencies in the existing testbeds. It presents the following advantages/contributions:

- Provides abstractions to the implementation details by enabling its users to configure and control the network as well as analyzing the collected packet-statistics database, using convivial graphical user interfaces.
- Due to the flexibility and completeness of the collected database, a wide range of LQEs can be integrated to RadiaLE software tool.
- Use a different traffic pattern, called *Bursty Traffic*, having different parameters that can be tuned by the user in the network configuration step.
- Provides a holistic and unified methodology (by the mean of graphical user interfaces) for the performance evaluation of LQEs.



(a) Hardware architecture

(b) Software architecture

Fig. 2. Testbed Hardware and Software architectures

III. RadiaLE overview

RadiaLE is an open source tool (available at [15]) that allows the performance evaluation of LQEs by analyzing their statistical properties, independently of any external factor, such as collisions (each node transmits its data in an exclusive time slot) and routing (a single hop network). These statistical properties impact the performance of LQEs, in terms of:

- **Reliability**: It refers to the ability of the LQE to correctly characterize the link state. RadiaLE provides the means for a *qualitative* evaluation of the LQE reliability, by analyzing (i.) its temporal behavior, and (ii.) the distribution of link quality estimates, illustrated by the a scatter plot and the empirical cumulative distribution function (CDF).
- **Stability**: This metric refers to the ability of the LQE to resist to transient (short-term) variations (also called fluctuations) in link quality. RadiaLE evaluates the stability of a LQE *quantitatively* by the measure of the coefficient of variation (CV) of its estimates.

A. Methodology

In order to evaluate the performance of LQEs, the first step is to establish a rich set of links with different qualities. The second step is to create a bidirectional data traffic over each link, enabling link measurements through packet-statistics (such as packet sequence number, from received and sent packets) collection. Finally, collected data are analyzed, enabling the evaluation of LQEs.

The first step relies on setting-up a single-hop network, where nodes $N_2..N_m$ are placed in different circles around a central mote N_1, as shown in Fig. 1. The distance between two consecutive circles is denoted as *y* (m), and circle nearest to N_1 has a radius of *x* (m). Since distance and direction greatly affect link quality, by placing nodes $N_2 \ldots N_m$ at different distances and directions from the central node N_1, the underlying links $N_1 \longleftrightarrow N_i$ will have different qualities.

In the second step, we have designed a Bursty traffic over each link $N_1 \longleftrightarrow N_i$, where N_1 first sends a burst of packets to a given node N_i. Then, node N_i sends its burst of packets to N_1. This operation is repeated for a pre-determined number of bursts. Recall that existing testbeds use a one-Burst traffic. Considering more that one burst in our Bursty traffic is like dividing the traditional on-Burst into a number of small bursts, which allows to reduce the time that separates the uplink and the downlink assessments.

Exchanged traffic over each link allows for link measurements though packet-statistics collection. Some packet-statistics are collected from received packets, such as sequence number, RSSI, LQI, and background noise. Other packet-statistics are collected at the sender side, such as, packet retransmission count. All these packet-statistics are forwarded through a reliable serial connection to a central PC and then stored in a database.

The third step consists of processing the stored data (packet statistics), to compute, tune, and analyze LQEs.

B. Implementation

RadiaLE includes hardware components (Fig. 2a) and a software tool (Fig. 2b).

The RadiaLE hardware architecture involves a set of TelosB motes (49 motes in our experiments), connected to a control station (PC) via a USB tree, for controlling and collecting data from the motes without interfering with the wireless communications. In our experiments, the nodes are arranged according to a radial layout as shown in Fig. 1.

RadiaLE software tool contains two independent applications: *Experiment Control* java application (ExpCtrApp), and *Data Analysis* Matlab application (DataAnlApp).

1) The experiment Control application (ExpCtrApp): It provides user interfaces to ensure multiple functionalities,

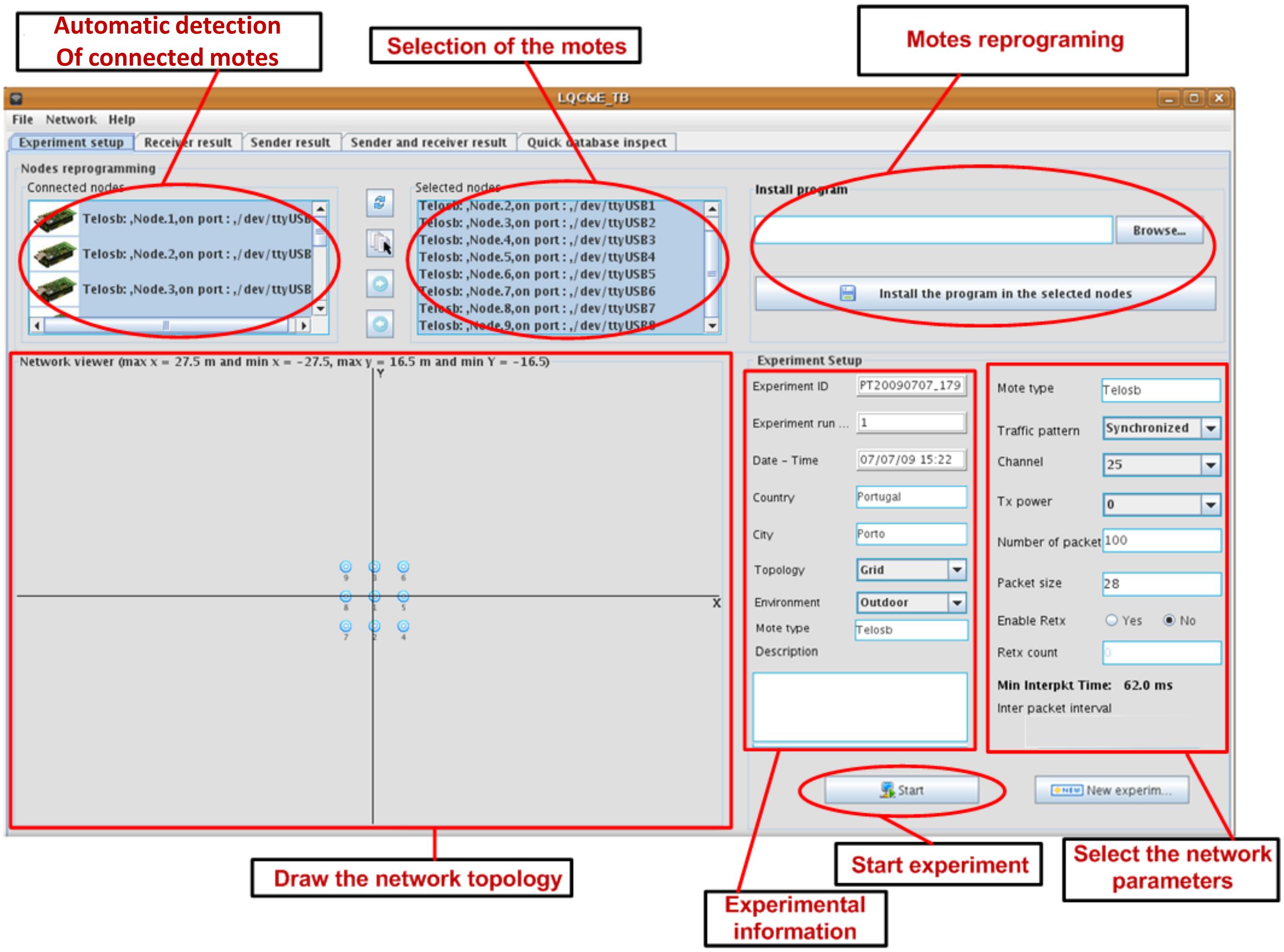


Fig. 3. ExpCtrApp Java application main functionalities

namely motes programming/control, network configuration and data logging into a MySQL database (Fig. 3). These functionalities are described next.

Motes programming: A nesC application defines a set of protocols for any bidirectional communication between the motes and between the motes and the ExpCtrApp. The ExpCtrApp automatically detects the motes connected to the PC and programs them by installing the nesC application binary code.

Network configuration: The ExpCtrApp enables the user to specify network parameters (e.g. traffic pattern, packets number/size, inter-packet interval, radio channel, transmission power, link layer retransmissions on/off and max. count). These settings are transmitted to the motes to start performing their tasks.

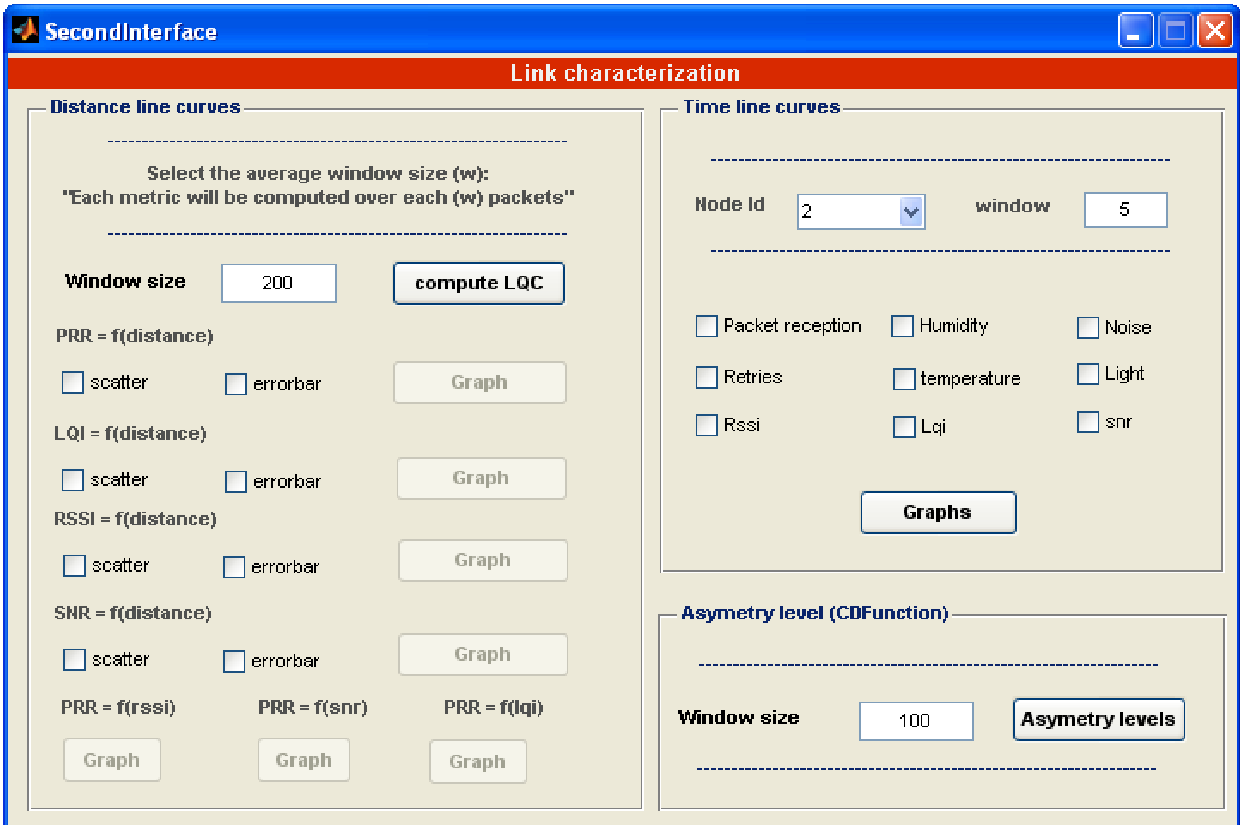
Link measurements gathering: Motes exchange data traffic in order to collect packet statistics such as sequence number, RSSI, LQI, SNR, time stamp or background noise, which are sent via USB to the ExpCtrApp in the PC, which stores these log data into a MySQL database.

Motes control: ExpCtrApp exchanges commands with the motes to control data transmission according to the traffic pattern set at the network configuration phase. The ExpCtrApp also provides: (*i.*) a *network viewer* to visualize the network map and the link quality metrics (e.g. PRR, RSSI) in real-time; and (*ii.*) a *database inspector* to view raw data retrieved from the motes in real-time.

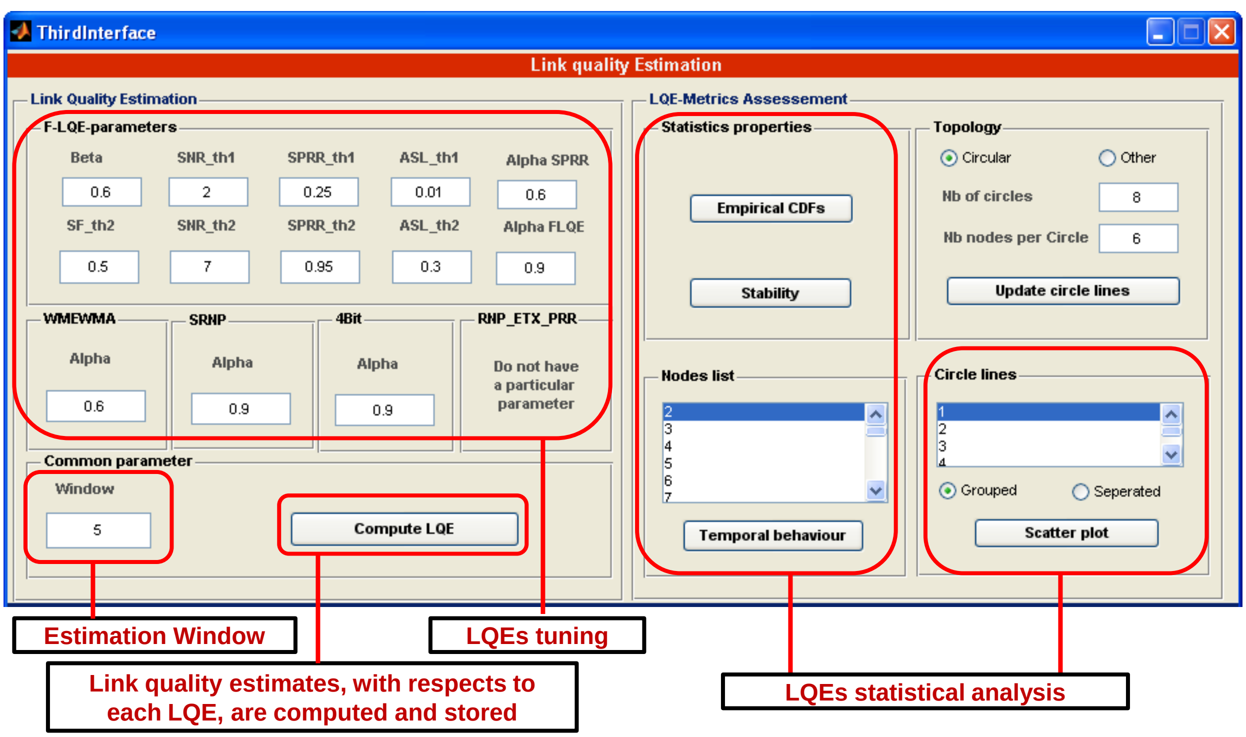
2) The data analysis application (DataAnlApp): It provides user interfaces to ensure two major functionalities (Fig. 4).

Links characterization: Fig. 4a shows the link characterization interface. This interface provides a set of configurable graphs, allowing to study the spatial and temporal characteristics as well as the asymmetry of the underlying links. Such graphs help to design new LQEs by understanding the channel behaviour.

Link quality estimation: Fig. 4b shows the link quality estimation interface. This interface provides an assistance to RadiaLE users to evaluate and optimize their LQEs. It enables to generate statistical graphs, such as the empirical cumulative distribution function and the coefficient of variation of link quality estimates. By analyzing these graphs the reliability



(a) Links characterization interface



(b) Link Quality Estimation interface

Fig. 4. DataAnlApp Matlab application main functionalities

and the stability of LQEs can be evaluated. DataAnlApp integrates a set of well-known LQEs. Other LQEs can be easily integrated and compared to existing LQEs, due to the flexibility and completeness of the collected empirical data.

C. Link Quality Estimators

A short description of five LQEs already integrated into RadiaLE is given in follow.

PRR (Packet Reception Ratio) is computed as the ratio of the number of successfully received packets to the number of transmitted packets, for each window of *w* received packets.

RNP (Required Number of Packet retransmissions) [13] counts the average number of packet retransmissions required before a successful reception. It is computed as the ratio of the number of transmitted and retransmitted packets to the number of successfully received packets; minus 1 to exclude the first packet transmission. This metric is evaluated at the sender side for each *w* retransmitted packets.

WMEWMA (Window Mean Exponentially Weighted Moving Average) [4] applies filtering on PRR to smooth it, thus providing a metric that resists to transient fluctuation of PRRs, yet is responsive to major link quality changes. WMEWMA is then given by the following.

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

where $\alpha \ \epsilon \ [0..1]$ controls the smoothness.

ETX (Expected Transmission Count) [3] approximates the packet retransmissions count, including the first transmission. It is computed as the inverse of the product of PRR of the forward link ($PRR_{forward}$) and the PRR of the backward link ($PRR_{backward}$), which takes into account link asymmetry property.

$$ETX(w) = \frac{1}{PRR_{forward} \times PRR_{backward}} \quad (2)$$

four-bit [2] is a sender-initiated estimator, already implemented in TinyOS, that approximates the packet retransmissions count. Like ETX, four-bit considers link asymmetry property. It combines two metrics (*i.*) $estETX_{up}$, as the quality of the unidirectional link from sender to receiver, and (*ii.*) $estETX_{down}$, as the quality of the unidirectional link from receiver to sender. The $estETX_{up}$ is exactly the RNP metric and $estETX_{down}$ approximates RNP as the inverse of WMEWMA, minus 1. The combination of the two metrics is performed through the EWMA filter as follow:

$$\textit{four-bit}(w_a, w_p, \alpha) = \alpha \times \textit{four-bit} + (1-\alpha) \times estETX \quad (3)$$

estETX corresponds to $estETX_{up}$ or $estETX_{down}$: given w_a the beacon-driven estimation window and w_p the data-driven estimation window; at w_a received packets, the sender derives the *four-bit* estimate by replacing *estETX* for $estETX_{down}$ in Eq.3. At w_p transmitted/re-transmitted data packets, the sender derives the *four-bit* estimate by replacing *estETX* for $estETX_{up}$ in Eq.3.

IV. Experimental study using RadiaLE

To illustrate the usefulness of RadiaLE, we have reproduced the simulation study conducted in [16], where PRR, RNP, ETX, Four-bit, and WMEWMA, have been evaluated.

A. Experiments Description

In our experiments, we have deployed 49 TelosB motes distributed according to the radial topology as shown in Fig. 1, where *x* is equal to 3 meters and *y* is equal to 0.75 meter. Note that *x* and *y* have been chosen such that links would have moderate connectivity (assessed by average PRR). The transmission power and the channel were set to - 25 dBm and 26, respectively. For the Bursty traffic, we have set the number of bursts to 10, the number of packets per burst to 100, and the inter-packet interval to 100 ms. The packet size is 28 bytes and the Maximum packet retransmissions count is 6 retransmissions. The duration of the experiment was approximately 8 hours. At the end of the experiments, we gathered a database that contains packets-statistics, retrieved from each bidirectional link $N_1 \longleftrightarrow N_i$.

Now, we propose using RadiaLE data analysis tool: DataAnlApp, to conduct a comparative study of the performances of five well-known LQEs, already supported by RadiaLE, namely PRR, ETX, RNP, WMEWMA, and four-bit.

B. Performance evaluation of Link Quality Estimators

1) Reliability: The reliability of the LQEs under evaluation can be evaluated by analyzing the distribution of their link quality estimates, illustrated by the empirical cumulative distribution function (CDF), (Fig. 5).

Fig. 5 shows that PRR, WMEWMA, and ETX, which are PRR-based LQEs, are optimistic and therefore overestimate link quality. For instance, this figure shows that almost 80% of links in the network have a PRR and WMEWMA equals to 85%, and 75% of the links have ETX equal to 1, (i.e. 0 retransmissions). The reason of this overestimation is the fact that PRR-based LQEs are only able to evaluate the link delivery, and they are not aware of the number of retransmissions, required to deliver a packet. A packet that is lost after one retransmission or after *n* retransmissions will produce the same estimate. On the other hand, Fig. 5 shows that four-bit and RNP, which are RNP-based, are pessimistic and therefore underestimate link quality. In fact Fig. 5 shows that almost 90% of the links have RNP equal to 4 retransmissions (maximum value for RNP), which means that the link is of very bad quality. Four-bit is less pessimistic than RNP as its computation accounts for PRR. This underestimation of RNP and four-bit is due to the fact that they are not able to determine if these packets are received after these retransmissions or not. This discrepancy between PRR-based and RNP-based link quality estimates is justified by the fact that most of the packets transmitted over the link are correctly received (high PRR) but after a certain number of retransmissions (high RNP).

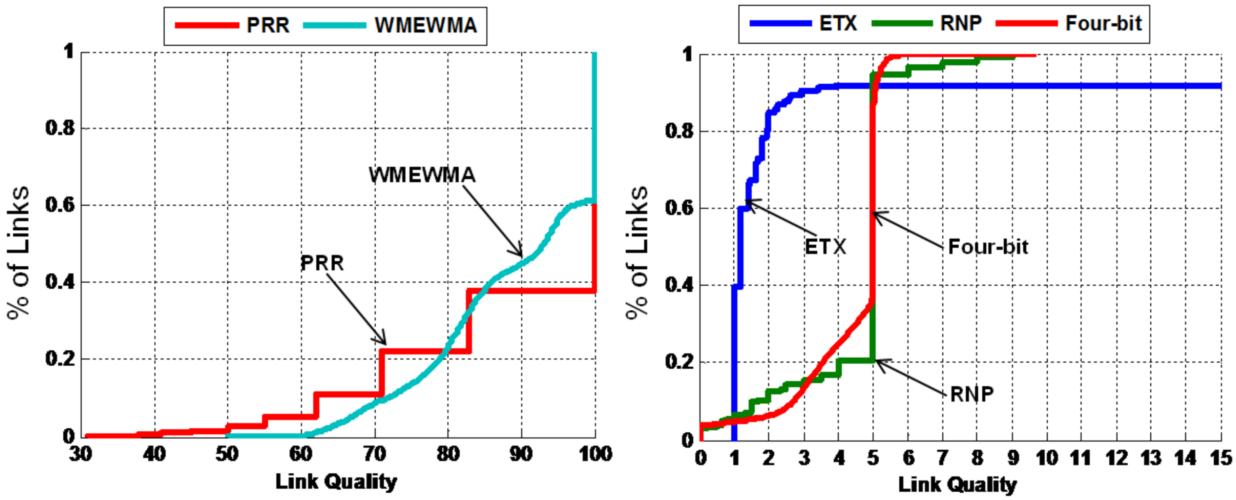


Fig. 5. Empirical CDFs of LQEs, based on all the links in the network.

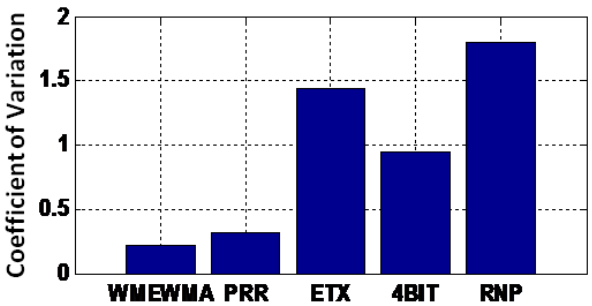


Fig. 6. Stability of LQEs.

In summary, all the selected LQEs are not sufficiently reliable, as they either overestimate or underestimate link quality.

2) Stability: LQEs should resist to link quality fluctuations and provide stable link quality estimates. Stability property of LQEs is mandatory. For instance, routing protocols do not have to reroute information when a link quality shows transient degradation, because rerouting is a very energy and time consuming operation.

To assess LQEs statbility, we measured the sensitivity of the LQEs to transient fluctuations through the coefficient of variation of its estimates. Fig. 6 compares the sensitivity (stability) of LQEs. According to this figure, we retain the following observations. First, WMEWMA is more stable than PRR and four-bit is more stable than RNP. The reason is that WMEWMA and four-bit use filtering to smooth PRR and RNP respectively. Second, except ETX, PRR-based LQEs, i.e. PRR and WMEWMA, are generally more stable than RNP-based LQEs, i.e. RNP and four-bit. ETX is PRR-based, yet it is shown as unstable. The reason is that when the PRR tends to 0 (very bad link) the ETX will tend to infinity, which increases the standard deviation of ETX link estimates.

V. Conclusion

This paper presented RadiaLE, an experimental benchmarking testbed that automates the experimental evaluation and design of LQEs. To the best of our knowlege RadiaLE is the first testbed dedicated for such objective. In addition, it presents several advantages compared to existing testbeds such as providing abstractions to the implementation details and the flexibility and completeness of the collected database. The current RadiaLE version integrates a set of well-known LQEs, namely ETX, four-bit, RNP, PRR and WMEWMA, as well as our new LQE, called F-LQE [1] (validated using RadiaLE).

To demonstrate the usefulness of RadiaLE, we have conducted a thorough comparative study of five LQEs. In summary, we found that all LQEs are not very reliable as they either overestimate or underestimate link quality. Further, ETX, RNP and four-bit were found instable, in contrary to PRR and WMEWMA. Finally, it is important to highlight that we make RadiaLE available for the community as an open source tool (see [15]).

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