A Quantitative Evaluation of the Simulation Accuracy of Wireless Sensor Networks

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ABSTRACT

In the field of wireless sensor networks, network simulators are commonly used to evaluate properties of software components or the network as a whole. Their advantages in reduced experimental overhead, flexibility, and repeatability come at the expense of questionable credibility of the results. In order to quantify the simulation accuracy of wireless sensor networks, we have conducted a field test measuring the packet loss rate and compared the data with the results obtained from a carefully configured simulation of the same scenario. Our evaluation gives insight into how much trust can be put into the results of simulations of comparable scenarios.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*wireless communication*; I.6.4 [**Simulation and Modeling**]: Model Validation and Analysis; D.2.8 [**Software Engineering**]: Metrics—*performance measures*

Keywords

Wireless Sensor Networks, Simulation, Accuracy, ScatterWeb, ns-2

1. INTRODUCTION

Simulating a Wireless Sensor Network (WSN) provides distinct advantages over a full-scale, real-world deployment when it comes to evaluating new software components: A simulation can be set up in less time, is more flexible with regard to network layout and communication parameters, and allows for different algorithms to be run under exactly the same conditions. These advantages of reduced experimental overhead, flexibility, and repeatability come at the expense of questionable credibility of the results. For most simulations it is unknown how closely the results obtained resemble those from a similar real-world deployment.

The contribution of this paper is to quantitatively evaluate the inaccuracy incurred by relying on a simulation rather than a real deployment. Our approach is to first measure certain metrics in a field test, and then recreate the exact conditions of this test as closely as possible in a simulation with the goal of comparing the measurements taken. While doing so, we pay special care not to use our knowledge of the results of the field test to over-optimize the simulation parameters with regard to reducing the discrepancy between simulative and real-world measurements. Instead, our intention is for this simulation to be just as accurate as any other simulation that is configured carefully following the recommendations from the literature.

For our field test, we used ScatterWeb ESB sensor nodes based on the Texas Instruments MSP430 ultra-low power microcontroller with 60 KB Flash and 2 KB RAM [12]. Inter-node radio communication takes place at 868 MHz on the license-free ISM band using the RF Monolithics TR1001 radio transceiver at a data transfer rate of 19.2 kbps [11]. For the simulations, we relied on our previous work [14] that allows us to run the same software components on both real sensor nodes and the `ns-2` network simulator. This work is briefly summarized in Section 2.1.

The remainder of this paper is structured as follows: Section 2 summarizes key aspects of preliminary work that led up to the current experiment. Section 3 describes in detail the experiment, which consists of both a field test using ScatterWeb sensor nodes and a corresponding simulation. Section 4 presents and evaluates the results. Section 5 gives a brief overview of current research in the area of simulation accuracy, and Section 6 concludes.

2. PRELIMINARIES

In this section, we briefly recapitulate the most important aspects of preliminary work.

2.1 ScatterWeb on ns-2

As pointed out above, simulations offer several advantages over regular deployments when it comes to evaluating new software components for WSNs. Therefore, we have developed an approach to run the same software components both on ScatterWeb sensor nodes and the `ns-2` network simulator [3]. In a nutshell, this was achieved by porting the C API provided by the ScatterWeb firmware to `ns-2`, which was chosen as a simulation platform due to its architectural compatibility with existing ScatterWeb software components, its wide-spread use in research, and in order to avoid the pitfalls of implementing a network simulator from scratch. The key advantage of our simulation approach is that – except for the effects of program execution speed and energy consumption which we intend to address in future work – it leaves the higher-layered software components oblivious to whether they are being executed on a real sensor node or as part of a simulation.

In our previous work [14], we concentrated on API compatibility and the transparent integration of ScatterWeb software components into `ns-2`, while leaving questions regarding the simulation accuracy for future work. In this paper, we add to these results by evaluating the simulation accuracy with regard to packet transmissions over the wireless interface.

2.2 Network Metrics

Table 1: Metrics for Different Network Layers as Applicable in the Field of WSNs

Layer	Metrics
PHY	Bit Error Rate (BER) Radio Signal Strength (RSS)
DLL	Packet Loss Rate (PLR) Packet Collision Rate (PCR)
NET	Packet Delivery Rate (PDR) Hop Count, Latency Overhead Traffic
APP	Application QoS Parameters

Several options are available when deciding which metric to use for comparing simulation and reality. The choice depends on the ISO/OSI layer that we intend to look at. Table 1 lists commonly used metrics sorted by the layers they correspond to.[1] While it would certainly be interesting to compare simulation and reality for measurements of all of these metrics and explore how inaccuracies at lower layers interact with those on the upper layers, this is beyond the scope of this work. Instead, we focus on the Packet Loss Rate (PLR) as seen by the network layer. This choice is motivated by the fact that layer 2 packets are well supported as a networking concept in virtually all simulation tools on one side (bit errors, for instance, are not), and because we want to avoid tying our results to any particular routing protocol on the other side.

2.3 Radio Propagation Models

Given the experimental setup proposed above, the most crucial component of the simulator with regard to the expected results is the radio propagation model. `ns-2` implements three radio propagation models: free space, two-ray ground reflection, and shadowing [3]. The first two are variations of the unit disc graph model, i.e. within a certain radius of the sender all nodes always have perfect reception. These models are known to resemble reality quite poorly [9]. The shadowing model is the only one to include a probabilistic term as part of the calculation of the received signal power:

$$\left[\frac{P_r(d)}{P_r(d_0)}\right]_{dB} = -10\beta\log\left(\frac{d}{d_0}\right) + X_{dB}$$

where $P_r(d)$ is the mean received power at distance d as computed relative to a reference power $P_r(d_0)$ at distance d_0. β is the path loss exponent, and X_{dB} is a Gaussian random variable with zero mean and standard deviation σ_{dB}, called the shadowing deviation. For an accurate simulation, both β and σ_{dB} need to be measured at the site of the planned deployment. Typical values for an urban outdoor area range between 2.7 and 5 for the path loss exponent β and between 4 dB and 12 dB for the shadowing deviation σ_{dB} [10].

We also considered using more sophisticated radio propagation models, e.g. the Radio Irregularity Model (RIM) proposed by Zhou *et al.* [15]. However, the drawback of more recent models is that less data and recommendations exist for a realistic choice of parameter values. Hence, we decided to only consider well-established models for this experiment.

3. EXPERIMENTAL SETUP

This section describes the field test using ScatterWeb sensor nodes as well as the corresponding simulation. In both tests, we transmitted several packets from one sending sensor node to another receiving sensor node and varied both the distance between the nodes as well as the transmission power setting while observing the PLR.

3.1 Field Test

We conducted the field test using two ScatterWeb ESB sensor nodes placed in an urban outdoor environment at a height of 60 cm without any obstructions in their direct line of sight. The distance between the nodes was varied in the range from 5 m to 90 m in steps of 5 m. At each of the distances, we varied the transmission power setting on the firmware API between 0 and 100 (which corresponds to the full range of the TR1001 as connected on the ESB) in steps of 10. For all these combinations of distance and transmission power setting, we sent 20 128-byte packets from one node, counted the correctly received packets on the other node, and calculated the PLR.

3.2 Simulation

For the simulated sensor nodes, we mapped the information from the datasheet [11] and as extracted by inspecting the implementation of the low-level ScatterWeb firmware as closely as possible to the simulation. We tried to reuse existing `ns-2` components wherever possible by adapting their parameters to match the characteristics of the real sensor nodes. As the version of `ns-2` used in our experiments had no support for changing the transmission power for individual packets during the simulation, we modified the simulator to add this feature. Further, there was no information available on how the transmission power setting between 0 and 100 maps to the actual transmission power in milliwatts, so we separately measured these values and configured the simulated sensor nodes accordingly. Due to space constraints we omit the details of these measurements.

Finding good recommendations for the path loss exponent β and the shadowing deviation σ_{dB} in the literature was challenging. In most cases, the focus is on communication distances one order of magnitude higher than the one commonly found in current WSNs. The most suitable values we found are due to Seidel *et al.* [13], who measured $\beta = 2.7$ and $\sigma_{dB} = 11.8$ dB for a frequency of 900 MHz. Further, ITU-R P.1546 [4] recommends $\sigma_{dB} = 9.5$ dB for a frequency of 600 MHz. The only measurements that target WSNs directly are due to Darbari *et al.* [1], whose results are not applicable to our experiment because they were measured at

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[1] Some of these metrics may also be applicable at other layers than those listed. For example, one could argue that PLR and PDR can also be observed in the NET and DLL layers respectively.

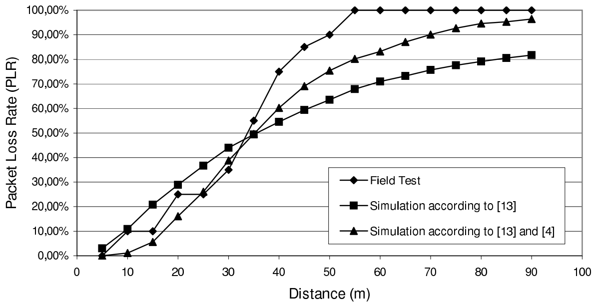

Figure 1: PLR Against Distance with Fixed Transmission Power Setting of 60

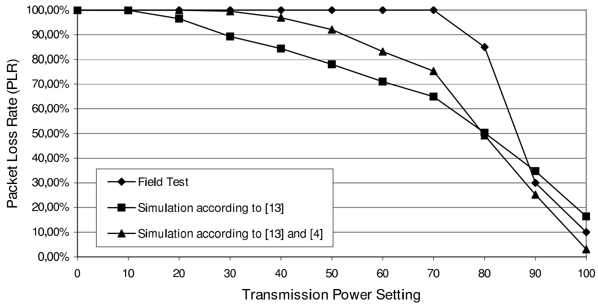

Figure 2: PLR Against Transmission Power Setting with Fixed Distance of 60 m

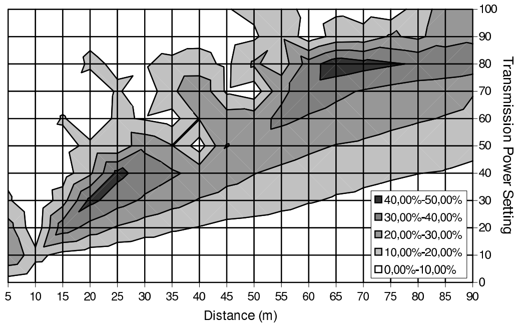

Figure 3: PLR Differences Between Simulation and Reality with Parameters According to [13]

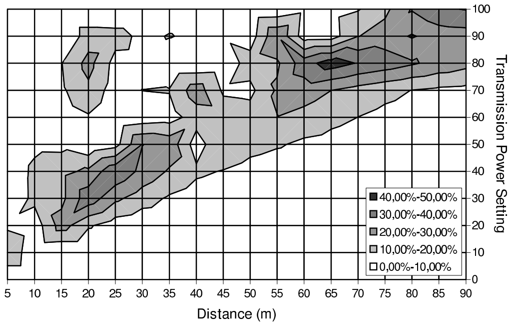

Figure 4: PLR Differences Between Simulation and Reality with Parameters According to [13] and [4]

distances below 1 m and at a frequency of 2.4 GHz. For our experiment, we decided to use the recommended values from [13] and, in a second simulation run, the path loss exponent from [13] combined with the shadowing deviation from [4].

4. RESULTS AND DISCUSSION

Given the experimental setup described in the previous section, we now proceed to present and evaluate the results obtained.

In Figure 1, the PLR is plotted against the distance between two sensor nodes. With the transmission power setting fixed at 60, the diagram representatively illustrates the effects observed and allows us to omit diagrams for the remaining transmission power settings for brevity. The three curves in the diagram correspond to the measurements from the real-world field test and two simulations with different parameters for the radio propagation model. As expected, the PLR increases with larger distances for all three curves and the rate at which it increases differs as a result of inaccuracies in the simulation. Similarly, Figure 2 shows the PLR, but this time plotted against the transmission power setting at a fixed distance of 60 m. Analogous to the observation above, the PLR decreases with higher transmission power settings and simulation inaccuracies can be observed in the different rates of decrease. Once again we omit diagrams for the remaining transmission power settings for brevity.

We now proceed to compare the complete results from the field test with each of the two simulation runs in Figures 3 and 4. These diagrams show the differences between PLRs from the field test and from one simulation respectively. In both diagrams the differences are low for both low transmission power settings at large distances and high transmission power settings at short distances. This is due to the fact that these scenarios are comparatively easy to describe correctly in the radio propagation model and hence the simulation is quite accurate. In contrast, this is not true for values along the diagonal of the diagram as both distance and transmission power setting increase. In these situations, larger differences in PLRs can be observed as the radio propagation model shows its weakness at correctly predicting the characteristics of the signal at the border of the transmission range. Outliers in the diagram, such as the local maximum in the top left quadrant of Figure 4, can be attributed to multi-path signal propagation and additive or subtractive interference at the receiver which are not part of the simulation due to lacking information about the surroundings.

For a quantitative evaluation of the simulation accuracy, one would have to estimate how likely it is for each combination of distance and transmission power setting to occur during a test run, weight the data points accordingly, and then calculate the average difference. For our particular experiment, all combination of distance and transmission power setting occurred equally often, hence no weights are necessary. The average difference between the field test and the simulation according to [13] is 12.3%. The simulation with combined values from [13] and [4] is slightly more accurate with an average difference of 8,2%. It is important to keep in mind that these numbers are closely tied to the metric used for the measurements, which in this case is the PLR, and hence one should not think of them as the one comprehensive quantifier for simulation accuracy. Still, these results give a good indication on how much confidence can be put into the results from a carefully configured simulation.

5. RELATED WORK

The accuracy of network simulators has been studied by Johnson [7] and more recently by Jansen and McGregor [6]. Both works differ from ours in that they use application and transport layer metrics, and for this reason are not directly concerned with the problems arising from transmitting over a wireless medium. Furthermore, they do not compare their results with data from field tests, and generally focus more on the validation of networking algorithms and simulation methodology. [6] is similar to our work in that we share the advantages of integrating existing implementations of software components directly into the simulator.

Liu *et al.* [8] compares data of network layer metrics from a large field test using up to 40 laptop computers communicating over IEEE 802.11 with corresponding simulations. They use different radio propagation models for their comparisons including a "generic model" that is similar to the shadowing model used in our simulations. In their evaluation they observe effects similar to those depicted in Figure 1, however they neither try to quantify the simulation accuracy nor do they elaborate on their choice of parameters.

Ivanov *et al.* [5] discusses the accuracy of `ns-2`-based simulations and emulations with regard to packet delivery ratio, the network connectivity graph, and packet latencies. They partly fine-tuned the parameters of the radio propagation model to match the observed real network topology. Hence, their results correspond to the optimal values for a given scenario, which we intentionally avoid in our approach.

Finally, Newport *et al.* [9] evaluates the impact of commonly made assumptions on simulation accuracy in general.

6. CONCLUSION AND FUTURE WORK

In this paper, we have evaluated the accuracy of a carefully configured simulation with regard to the Packet Loss Rate (PLR) by comparing the results with data from a field test using two ScatterWeb ESB sensor nodes. The average difference between simulation and reality for this metric is 12.3% or 8,2%, depending on which recommendation is followed for the choice of parameters for the radio propagation model. These results allow us to judge the credibility of other simulations for similar deployments.

As a next step we intent to undertake similar experiments for other metrics and analyze how the inaccuracies of the simulation interact over different network layers. Further experiments relying on ray-tracing-based radio propagation models such as proposed in [2] and [16] may complement this work for indoor scenarios. Finally, we are planning to improve our simulations by adding the notions of program execution speed of the simulated software components and correct modelling of energy consumption.

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