Practical RSSI Long Distance Measurement Evaluation in Wireless Sensor Networks

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Abstract—Distance measurement between neighboring nodes in Wireless Sensor Networks (WSNs) is a rudimentary requirement for localization and position estimation algorithms. Common techniques exploit the signal strength to estimate the distance between two nodes. Although this has been widely accepted in research during the last two decades, practical evaluations of these techniques in outdoor scenarios under realistic conditions are rare. In this paper we evaluate distance measurement based on the received signal strength indicator (RSSI) under different conditions to analyze the quality and precision in real-world environments.

Keywords—Wireless Sensor Network; localization; positioning; RSSI evaluation; distance measurement; long distance estimation

I. INTRODUCTION

Localization and self-positioning in Wireless Sensor Networks (WSNs) describe the process of estimating the sensor’s own location in a deployment area. Nearly all data collected in a WSN only will serve its purpose if it is assigned to additional spatial information. Although the easiest solution would be to mount a GPS device on every sensor node, this solution has several drawbacks:

- Additional energy consumption
- Additional space for GPS chipset and antenna
- High costs for one-way sensor systems which are not expected to be recovered after use or might get destroyed or lost during their application (e.g. bushfire monitoring)

Instead of using GPS, research focused on techniques to estimate the location of each sensor node using the help of beacon nodes which are always aware of their position and active sensing techniques to estimate distances to these beacon nodes. A simple example of a very common algorithm for position estimation which uses active sensing information is trilateration.

The quality of these range-based localization techniques relies on the goodness of the distance estimation performed during the operation phase of the WSN. One of the most common techniques to estimate distances is to exploit the signal path loss. Based on the signal strength the distance between two neighboring nodes can be determined given a suitable path loss model. Research mainly focused on developing algorithms which reduce the distance estimation error and precise path loss models for different environments, but stuck to simulations of ranging techniques without validating them on real hardware or chose ideal environment scenarios in which outer influences like obstacles or weather effects have not been considered. As a result a variety of algorithms and models exists, but practical implementations and realistic evaluations are rare. Existing studies mainly focused on shorter distance estimations of about 1-10 m. However, lots of applications for WSNs require estimations of bigger distances, e.g. Wildlife Monitoring or Traffic Sensing.

In this paper we investigate the quality of distance measurement using the Received Signal Strength Indicator (RSSI). We perform a variety of experiments to analyze the robustness of distance estimations in indoor and outdoor scenarios especially for longer distances between neighboring nodes. Prior to that, we discuss possible problems and influences which might affect the measurements and therefore the reliability of localization algorithms.

The paper is organized as follows. Section II gives an overview of related work and some examples of active sensing techniques. In Section III we review several sources of impact for distance estimations using RSSI. Section IV describes our evaluation setup and the technical details of our sensor equipment. In Section IV we present the results of our measurements. Finally, in Section V we conclude our work and give an outlook on our future projects.

II. RELATED WORK

While plentiful of localization algorithms exist which are based on distance measurement, only a few studies of the quality of these estimations are available. Especially for applications where longer radio ranges are required studies of RSSI performance are rare.

In [1] a similar work to ours is presented. RSSI is validated as a distance estimator in indoor and outdoor scenarios, unfortunately only with a maximum distance of 10 m. The authors both did simulations and a practical evaluation and show differences between the optimal results of the simulation and...
and their implementation on IRIS sensor motes. They monitor RSSI readings over time which show variations, but do not give any reasons for that. In the end the authors use their collected data to calibrate the log normal shadowing model to have a perfect match for their measuring environment. Although their results look promising for short distances up to 5m, the average estimation error is growing tremendously for higher distances.

In [2] the authors provide a study of RSSI in an optimal indoor environment. They observe that RSSI measurement is related to the direction of measurement, e.g. measurements northwards will show different results compared to measurements eastwards. However, this might be related to antenna irregularities and is not further commented in the paper. Unfortunately, their study also only considers distances up to 10ft or ca. 3m.

Reference [3] gives a detailed report on the existence of nonlinearities in well-known radios. The paper derives the RSSI response curves experimentally by measuring in an indoor scenario with multiple devices and proposes a calibration method to get rid of the found nonlinearities. The authors conclude that application designers must keep in mind that RSSI response curves usually include nonlinearities and need to provide countermeasures.

Several works focus on studying the usage of RSSI for indoor localization. In [4], authors use a testbed composed of Tmote sky nodes to evaluate RSSI in a grid scenario with maximum distances up to 6m. They conclude that node orientation, i.e. antenna orientation, has heavy influence on the obtained results.

Reference [5] provides a similar study with measurement distances up to 25m. Different transceiver modules are used and compared. The authors conclude that RSSI measurement is depending on the transceiver chip and the level of precision required by the application determines if RSSI can be used for distance estimation.

An opposite view, but with regard to link quality estimation, is provided in [6]. The authors revise RSSI measurement for link quality estimation and argue that newer chipsets as the CC2420 [8] provide a lower hardware calibration error. They examine the packet reception rate and compare it to the average RSSI received and find a strong correlation up to the edge of sensitivity threshold. One could infer from these results that RSSI will also show a good performance when used for distances estimations.

A similar study is given in [7]. The characteristics of the RSSI in wireless local area networks are evaluated in different locations and show high variations. In a static indoor scenario RSSI is observed over time and shows high variations, too. The authors conclude that RSSI is subject to the common multipath effects, e.g. scattering, diffraction and reflection, and different locations will affect the RSSI drastically.

<table>
<thead>
<tr>
<th>Radio Type</th>
<th>RSSI Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>ATMEL AT86RF230 [8]</td>
</tr>
<tr>
<td>3</td>
<td>Infineon TDA5250 [12]</td>
</tr>
<tr>
<td>4</td>
<td>Telegesis ETRX2 [13]</td>
</tr>
<tr>
<td>5</td>
<td>Semtech SX1211 [14]</td>
</tr>
</tbody>
</table>

TABLE I. RSSI VALUE RANGES OF COMMONLY USED RADIOS

III. EXTERNAL MEASUREMENT IMPACTS

In this section we list several possible influences which might have a bearing on RSSI measurement results and which often are not considered in evaluations, but strongly affect distance estimations in practice.

A. Discrete RSSI values

Especially simulation studies of RSSI based techniques usually do not consider the fact that RSSI is a discrete value in nowadays available transceiver modules. For upper layers of the protocol stack RSSI is only available as a single register value with a value range of 1 Byte, i.e. 255 possible values at maximum. In practice the real value range depends on the manufacturer’s specification and is often limited to a fraction of all possible values. All register readings must be converted to a dBm value following a formula given by the manufacturer. Often this is done by adding an offset value, but it is different for every radio type. Table 1. shows an overview of some commonly used radio modules and their number of possible RSSI values. In practice this means some radios can be used for more precise distance estimations compared to others, e.g. the SX1211 can be used to produce ~4.5 times more accurate results compared to the AT86RF230. The resolution of the RSSI register is associated directly to the value range. High resolution chips provide values with a granularity of up to 0.5 dBm, a more common value is 3 dBm. While value range and granularity can be good looking numbers in data sheets the most important variable for the quality of distance estimation is accuracy. Not all vendors publish information about the accuracy of the RSSI value readings. A common value is +6 dBm as for [8], which means that RSSI values measured at a fixed distance fluctuate up to 12 dBm.

B. Path loss models and distance estimation

The general model usually considered to calculate the distance from RSSI readings is called the log normal shadowing model.

\[
\text{RSSI} = - (10 \cdot n \cdot \log(d) + A)
\]

n: propagation exponent

\(d\): distance to sender

A: reference RSSI at distance 1m

The propagation exponent n is added to the formula to account for different environment situations. However it needs
to be found empirically for every scenario and can lead to big estimation errors if chosen badly. Choosing suitable parameters for n and A is a mandatory task and therefore a problem in self-configuring applications. Also the chosen parameters are only valid at the time of calibration and might lead to errors at a later point of time if the environment conditions change.

C. Weather effects

Another effect which is usually not considered in evaluation studies is weather influence. The most important aspect of weather for radio propagation is moisture, i.e. weather phenomena like fog, rain and snow fall. While rain and snow add scattering and reflection depending on the intensity, air moisture itself leads to additional signal attenuation. Evaluations of existing approaches usually lack testing under different air moisture conditions and scattering influence added by heavy snow or rain is not considered at all.

D. Physical hardware limitations and mobility

Physical limitations of the hardware parts have impact on transmissions. While in simulations researchers tend to assume antennas provide perfect signal emission and radio transceiver modules provide exactly linear RSSI readings, in practice this is not true. Cost restrictions for cheap and lightweight sensor nodes do not allow the usage of high quality components. In mobile scenarios, RSSI measurements are also affected depending on the velocity of the sensor mote.

E. Obstacles

Obstacles of all kinds have heavy influence on the signal propagation. Signal strength measurements for clear line of sight will show different results compared to more realistic scenarios where buildings, trees, cars, etc. impact the signal propagation. While obstacles add attenuation to the signal if they are positioned directly in the line of communication, they also affect the signal path due to reflection and scattering if they are placed next to the communicating neighbors.

IV. Evaluation Setup

Our evaluation is based on TinyOS 2.x [14] running on CM3300 sensor motes built by advanticsys [15]. These motes are equipped with an external 5dBi antenna and IEEE 802.15.4 based radio transmitters (CC2420) to enable long range distance measurements. We have chosen this type of sensor mote, because it provides a large resolution of the RSSI register and is equipped with the most commonly used radio. Since the value range of the RSSI is dependent on the radio transceiver chipset as described in section III, we are interested in sensor motes which can provide a sufficient and therefore high resolution.

For all measurements the same two communicating motes are used. All results are sent to a central base station which is connected to a laptop to record the output and also operates as the control station to start and stop new measurement series. Fig. 1 illustrates the general setup. Initial tests showed a maximum communication range of about 350m in outdoor scenarios with clear line of sight. To keep a sufficient level of packet reception only measurements up to 300m are done. In all experiments the motes are static, i.e. no experiments under the effect of mobility are studied. During measurement, the motes are placed approx. 1m above ground. A student moves the mote to the next measurement point. At every measurement point both motes exchange 1000 packets to calculate the average RSSI. We use the same two communicating motes with the same antennas to avoid variations conditioned by different physical properties for all experiments. Therefore, we also evaluate RSSI readings only in one direction (i.e. only the RSSI readings of one mote are recorded).

The first experiment is illustrated in figure 2. The test track of 300m is divided into intervals of 25m. Clear line of sight is guaranteed for the whole distance. For each measurement one of the motes is moved to the next measurement point while the other one remains static at the beginning of the test track. We repeat this experiment on different days and different times to examine the effect of changing weather conditions. At this time weather parameters are not recorded.

To illustrate the effect of obstacles another test track is used. Fig. 3 illustrates how the geography department is used as an obstacle which prevents direct communication without interference. For this experiment only a maximum distance of 75m is used, since we are limited to the local conditions.

Indoor scenarios are tested in two long hallways with clear line of sight in the geography department. These hallways differ in height and width and are filled with different furnishings. Again, only a test track with a maximum length of 75m is available.
In this section we present the results we obtained during our experiments.

Fig. 4 shows the RSSI values measured in 4 different series. These measurements were done on random days with different weather conditions including snow and light rain. It is clear to see that there is a general trend for all series showing the loss of signal strength with growing distance. However, the curves are not linear although they represent the average of 1000 collected RSSI values for each measurement point. This might be related to multipath effects where some measurement spots are benefiting from more advantageous reflections even if they are farther away. The second observation is that values between different measurement series differ up to 10dBm. This has to be due to different weather situations and can be explained most likely by different air moisture concentration and additional attenuation due to rain and snow.

Fig. 5 shows two of the series plotted again with error bars showing the standard deviation for each measurement point. Even if there is a general trend when averaging 1000 samples, the measurements vary up to 6dBm as described in the product manual of the CC2420. In real distance measurement applications this means a node cannot really rely on a single measurement. However, almost all localization algorithms based on active ranging rely on beacon nodes which send single beacon packets in fixed intervals.

As we stated earlier, hardware differences can cause variations in RSSI readings. We illustrate this in fig. 6. Here, the graphs for both communication directions in series 1 and 4 are given. It is easy to observe that the signal strength is following the same profile in both directions, however, there is always a discrepancy of about 3-4 dBm. We repeated this experiment with other motes of our lab to verify this behavior. All tested motes showed similar curves but the difference in RSSI readings varied from 1 dBm to 4 dBm. Consequently, to rely on RSSI readings one would have to ensure that all used hardware components (especially antennas) have the same characteristics and give the same RSSI readings for equal distances, i.e. calibration is required.

Our indoor observations are shown in fig. 7. We compare two indoor measurements with the average of all outdoor curves. It is obvious that although clear line of sight was guaranteed for these measurements, indoor results differ a lot and provide lesser signal strength values. In addition to that different furnishings and building materials lead to differences in RSSI value readings.

The effect of obstacles is shown in fig. 8. The signal loss is tremendously, even for low distances of 25m. We conclude from our measurements that this is the biggest problem in distance measurement based on active ranging, since only specialized scenarios will provide areas without obstacles. Given a distance of 75m the difference of RSSI readings in comparison to clear line of sight is about 22dBm which would result in a very high estimation error if used in localization algorithms.
In this paper we gave an overview of possible sources of impact on RSSI readings and presented a study of long distance RSSI measurements to evaluate the suitability for distance estimation in localization applications.

The evaluation results show that RSSI is too unsteady and does not provide enough stability for a useful approximation of the distance between two nodes. Only in specialized scenarios where main sources of impact can be ruled out RSSI might be an option. However, in practice these indoor scenarios with clear line of sight and without the possibility of offline distance measurement are rare.

Nevertheless the results indicate that RSSI can be used to order a set of nodes with respect to the relative distance to one particular node and to determine one order relating to each node in the set respectively. This approach is more robust because weather effects and hardware limitations are almost equal for associated series of measurement and has the potential to identify links which are influenced by obstacles. Therefore, in future work we will frame a topology approximation algorithm based on RSSI and test it under different real-world conditions. We expect to get a general-purpose method which applies to more common application scenarios and is not subject to influences from outside. In other projects, we will try to identify the main sources of impact in our measurement scenarios and to develop countermeasures against them.

REFERENCES

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VI. CONCLUSION