Analysis of Radio Signal Parameters for Calibrating RSSI Localization Systems

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Abstract One important application field for wireless sensor networks (WSN) is object localization, thus various realizations yet exist. Here we are just interested in RSSI based localization systems. In particular, we focus on analyzing diverse system parameters, like radio base frequency, transmitting power, or modulation format, to improve the expressiveness of RSSI values. Hence, we built a real-world testbed based on sensor nodes equipped with CC1100 radio for investigating several radio configurations. Our results show that outdoor localization complies with wave propagation theory, but calibration of the radio hardware is mandatory. However, for indoor usage more knowledge about environmental effects has to be regarded to get more robust and persistent distance measurements – the basis for localization. An outlook on our further research closes this paper.

1 Introduction

Several wireless sensor network applications, e.g. for tracking and monitoring, require accurate knowledge about the current position of the observed objects. Therefore different localization techniques have been developed and analyzed, for example based on GPS [1], ultrasound [2,3,4,5] or RSSI [6,7,8,9]. The first only works properly outdoor and has a restricted accuracy, also there is a dependency on the operational availability of the satellites. Ultrasound localization systems require a considerable installation effort and are primarily designed for indoor use. Another localization technique is the interpretation of RSSI values, which has only moderate accuracy as shown in several indoor and outdoor experiments. But just few work was done in analyzing the effects of different system parameters, like various frequencies, modulation formats or transmitting powers, on the quality of the RSSI value in indoor and outdoor environments. The main question remains, which parameters can be influenced and which have to be adapted by the designer of a RSSI based localization system. Although some theoretical background is already given, validations by real-world experiments are still missing. That is why we made a series of experiments with varying system parameters to calibrate them for more accurate and more robust RSSI based localization.

Section 2 gives a short overview on related work with special focus on real-world experiences. Section 3 describes theoretical foundations about radio signal propagation. Our testbed and the test procedure are described in detail in section 4. Corresponding results and their interpretation are presented in section 5, and finally section 6 closes this paper with a conclusion and a short outlook on further research.

2 Related Work

Localization in wireless sensor networks with an emphasis on RSSI as distance estimator has been proposed several times in literature (e.g. SpotON [7,10]). The quality and reliability of the data plays a vitally important role. Srinivasan et al. [11] evaluated RSSI values provided by the CC2420 radio, and came to the conclusion that the problems older radios had with RSSI due to hardware miscalibration are no longer observable, and that RSSI is a promising indicator when its value is above a certain sensitivity threshold. The results also indicated that the RSSI value for a given link had very small variation over time. Lymberopoulos et al. [12] provided a detailed characterization of signal strength properties and link asymmetries for the CC2420 radio using a monopole antenna. They showed that the antenna orientation effects are the dominant factor of the signal strength sensitivity in 3-dimensional network deployments.

Awad et al. [8] presented localization approaches relying on the RSSI value, and evaluated two methods to estimate the distance, one based on statistical methods, and another one using an artificial neural network. In addition, they identified five parameters, which affect distance measurements: the used transmission power, which should be chosen according to the relevant distances, the radio frequency, the antenna characteristics of a node, the localization algorithm, and the quality of the reference measurements.

The experimental analysis carried out by Kvaksrud [13] addressed the influence of the ground during range measurements in an open field environment using the CC2420 radio chip. It was shown that ground presence generates more rapid signal degradation than predicted by the Friis equation for free space, and reduces the effective range.

Previous studies on distance estimation based on the RSSI value utilize radios supporting 2.4 GHz (e.g. CC2420), or analog RSSI output (e.g. CC1000). The SNoW[5] sensor nodes used to obtain our results have been equipped with a CC1100 radio supporting 8-bit digital RSSI output.

3 Basic Concepts

The propagation of electromagnetic waves in space obeys physical laws, which can be used to evaluate how different environmental conditions cause deviations of measured values from theory. In this section we describe the theoretical model we used to evaluate our measurements.

3.1 Free Space Propagation Model

This model predicts the strength of a radio signal after it traveled some distance from its origin. The model requires a direct line of sight without any obstructions causing reflection, diffraction, or scattering. In such a scenario the Friis equation gives the received signal strength depending on the spatial distance to the transmitter [14]:

$$\mathrm{friis}\left(d\right) = P_r\left(d\right) = P_t \frac{G_t G_r \lambda^2}{\left(4\pi\right)^2 d^2} \tag{1}$$

where d is the transmitter-receiver distance, P_r is the signal strength at the receiver antenna, P_t is the signal strength at the transmitter antenna, G_t is the antenna gain of the transmitter antenna, G_r is the antenna gain of the receiver antenna and λ is the wavelength of the radio signal. Note, G_t and G_r are unit- and dimensionless.

The Friis equation applies to radio wave propagation in free space. However, this ideal case cannot be achieved completely in a real-world test environment. Even in an open field environment with no obstructing objects, there is at least the ground that influences the transmitted radio signals. Since this is obviously unavoidable the free space propagation model is enhanced to properly consider ground reflection.

3.2 Free Space Propagation Model with Ground Reflection

In addition to the direct transmission, which is described by equation 1, the model with ground reflection also considers the indirectly transmitted signal caused by reflection at a perfectly flat ground, cf. Figure 1 and [13,14].

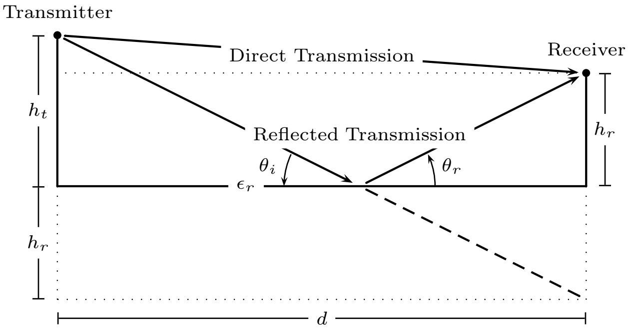

Figure 1. Reflection model

At every transition between two media with different dielectric properties, e.g. different relative permittivity ϵ_r, a part of the incident radio wave is absorbed and the other one is reflected back into the first medium. At appropriate angles θ_i and θ_r the direct and reflected signals superpose in the area of the receiver antenna. This is given by the following equation:

$$P_{r,g}(d) = \text{friis}(d_{dir}) + \cos(\mathit{\Delta}_{\varphi}) \cdot \text{friis}(d_{ind}) \cdot \mathit{\Gamma}_v \tag{2}$$

where d is the transmitter-receiver distance, $P_{r,g}(d)$ is the signal strength with ground reflection at the receiver antenna, d_{dir} is the path of the directly transmitted signal between transmitter and receiver, $\mathit{\Delta}_{\varphi}$ is the phase difference between the direct and reflected wave at the receiver antenna, d_{ind} is the path of the reflected signal between transmitter and receiver and $\mathit{\Gamma}_v$ is the Fresnel reflection coefficient for vertical polarized electromagnetic waves:

$$\mathit{\Gamma}_v = \frac{\epsilon_r \sin(\theta_i) - \sqrt{\epsilon_r - \cos^2(\theta_i)}}{\epsilon_r \sin(\theta_i) + \sqrt{\epsilon_r - \cos^2(\theta_i)}} \tag{3}$$

Here again, ϵ_r is the relative permittivity of the ground and θ_i is the angle of the incident wave to the ground in the reflection area.

Some variables in equation 2 might not be known directly, i.e. d_{dir}, d_{ind} and Δ_φ. But when h_t, h_r and d from Figure 1 are given, they can be calculated as follows:

$$d_{dir} = \sqrt{(h_t - h_r)^2 + d^2}$$
$$d_{ind} = \sqrt{(h_t + h_r)^2 + d^2}$$
$$\Delta_\varphi = \frac{2\pi \cdot (d_{ind} - d_{dir})}{\lambda}$$

In equation 3 the incident angle θ_i can be calculated as follows:

$$\theta_i = \arctan\left(\frac{h_t + h_r}{d}\right)$$

Now the mathematical toolbox is complete. This enables us to verify whether there is a chance to draw conclusions from measured RSSI values to spacial distances between transmitter and receiver nodes with our hardware. We will use the formulas to evaluate our measurements in section 5.

4 Testbed

4.1 Hardware Platform

For approving the practical application of the basics from section 3, we implemented a special testbed based on real-world WSN hardware and software. Therefore, we used SNoW^5 [15] sensor node platforms with MSP430 [16] microcontrollers and CC1100 [17] radio transceivers as senders and receivers.

The special advantage of SNoW^5 over several other nodes is its general purpose radio transceiver CC1100, which is not optimized for standard radio protocols like ZigBee, Bluetooth or WLAN. Instead, it allows versatile and deep going adjustments of transmission parameters for application specific and proprietary protocols. By using the various configuration options for fine-tuning the radio signals at the transmitters, we achieved a simple but still reliable distance calculation by RSSI measurement at the receivers. Depending on the radio setup, our measurements reflected the theoretical expectations very well and with little jitter. Table 1 shows the configuration space for our 192 accomplished measurement series.

As commonly done in various wireless localization systems, the known position of some static nodes along with their measured distance to a mobile one is used to estimate the mobile's position. However, depending on the desired precision and frequency, this localization process is not trivial and requires some computational power and real-time capabilities. Thus, our test application is based on the preemptive operating system *Smart*OS [18].

Parameter	Values
Base frequency [MHz]	433, 868, 915
Channel	0 (base + 0 Hz), 8 (base + 1.6 MHz)
Modulation	FSK, GFSK, OOK, MSK
Tx strength [dBm]	10, 7, 5, 0, -5, -10, -20, -30

Table 1. Testbed configuration space

4.2 Testbed Organization

In this subsection we describe the test setup for the three different sets of measurements we performed:

The *outdoor range measurements* were carried out in an open field area. As Figure 2 shows, the receiver nodes were arranged circularly around and with equal distances to the transmitter node. During the whole operation, the height was chosen constant and identical at $1.6\ \mathrm{m}$ above the ground to increase radio range while decreasing the impact of ground reflections. During the test, the transmitter iterated over all 192 combinations from Table 1, and broadcasted a certain amount of test packets in each configuration. For reliable configuration switching, an additional configurator node distributed the settings to all test nodes and verified the change. Finally, the complete test was repeated for several distances d ($2.5\ \mathrm{m}$, $5\ \mathrm{m}$, $10\ \mathrm{m}$, $20\ \mathrm{m}$, $30\ \mathrm{m}$, $40\ \mathrm{m}$, $50\ \mathrm{m}$, $60\ \mathrm{m}$, $70\ \mathrm{m}$, and $80\ \mathrm{m}$) between transmitter and receivers.

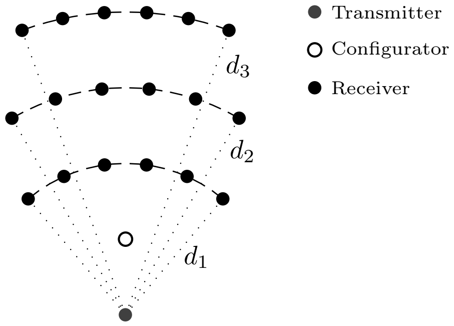

Figure 2. Test setup for separate measurements at distances d_1, d_2, and d_3 respectively

The *indoor range measurements* were performed within a corridor and followed the same measurement procedure and test setup as the outdoor range measurements. Here, the selected distances d were $2.5\ \mathrm{m}$, $5\ \mathrm{m}$, $10\ \mathrm{m}$, $15\ \mathrm{m}$, and $20\ \mathrm{m}$.

The *indoor height measurements* were performed in a typical office environment. This time we did not alter the ground distance d between transmitter and receivers but the height h_t of the transmitter (→ Figure 1) while leaving the receivers fixed.

5 Results and Analysis

In this section we evaluate the measurements we performed. Therefore we use the theoretical models described in section 3. In the following figures the function graph named P_r relates to equation 1 and the function graph $P_{r,g}$ to equation 2.

5.1 Outdoor Range Measurements

The antenna gain plays an important role in the Friis equation 1, but is hard to determine. However, an adjustment of this gain factor is needed for real-world environments, since the assumption of an antenna as isotropic radiator with gain $G_t = 1$ is not applicable. Figure 3 shows one of our outdoor range measurements. Here, the antenna gain parameters have been adapted so that the modified function graph has the least mean error to the measured RSSI values. This correction allows us to compute the transmitter-receiver distance from measured RSSI values. The measured values follow the progression of the function graphs. Up to 20 m distance $P_{r,g}$ hardly differs from P_r, beyond 20 m the values follow $P_{r,g}$.

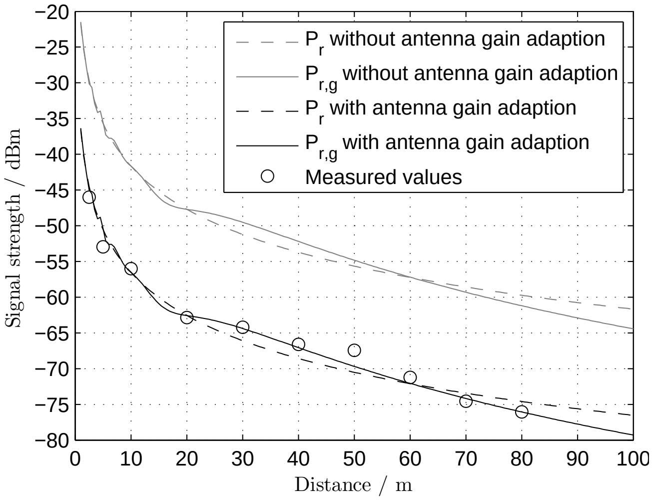

Figure 3. Outdoor range measurement: 915 MHz - Channel 8 - MSK - 10 dBm

Besides the gain factor, the radio base frequency directly influences the Friis equation as well. Though our radio hardware was optimized for 915 MHz, we additionally configured the nodes for 433 MHz. Figure 4 shows the differences. For short and mid-range distances the expected significant degradation of the resulting RSSI values could not be observed. However, distances beyond 50 m suddenly produced 100 % packet loss rate.

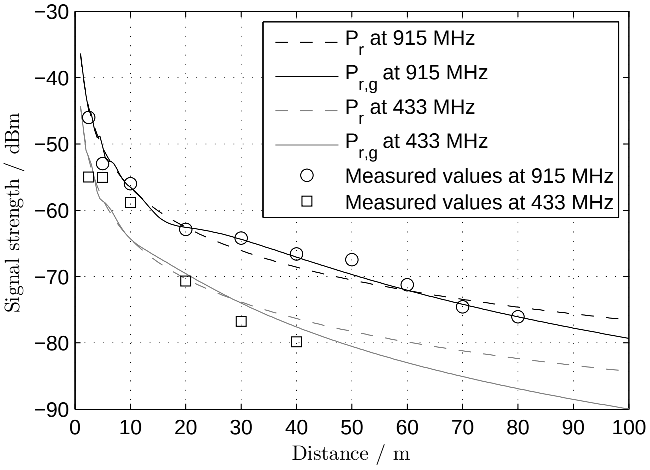

Figure 4. Outdoor range measurement: Measured signal strengths from same node with different base frequencies

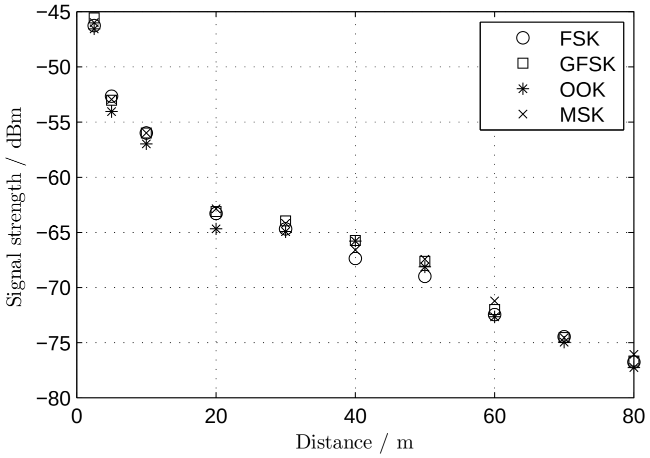

Figure 5. Outdoor range measurement: Comparison between different modulations at 915 MHz

Another interesting but not obvious factor is the different characteristics of identically constructed and configured nodes. Figure 6 shows, that each node requires an individual calibration regarding its antenna gain factor to produce suitable measurements. In large WSN installations, this adaption process might be quite complex but finally yields consistent data over all nodes for accurate localization.

Finally, we compared the following signal modulation formats: FSK, GFSK, OOK, and MSK. However, no considerable influences were detected as Figure 5 documents.

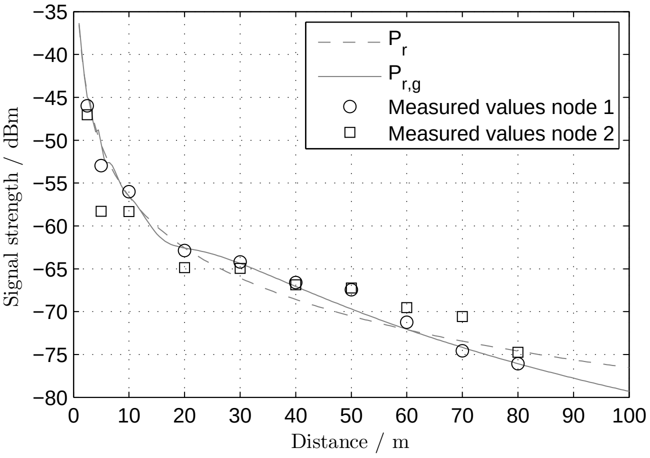

Figure 6. Outdoor range measurement: Measured signal strengths from different nodes with equal configuration at $915\ \mathrm{MHz}$

5.2 Indoor Range Measurements

Next, we will address our experiences from indoor range measurements. Most notably, we were not able to confirm that radio signals with higher transmission strength are more susceptible to interferences in (narrow) indoor environments. Multipath effects, in particular, could not be observed as the comparison for $10\ \mathrm{dBm}$ and $-10\ \mathrm{dBm}$ with in other respects identical configuration shows in Figure 7. Except for their offset, both resulting measurement series exhibit virtually the same characteristics. Since the RSSI values are unfortunately not very precise for distances above $5\ \mathrm{m}$, a large number of static nodes within the infrastructure of a localization system might be required.

5.3 Indoor Height Measurements

For typical indoor use of an RSSI based localization system additional circumstances like the relative height of sender and receiver as well as obstructing objects, e.g. office table or chairs, need deeper examination. Two outliers can be recognized in Figure 8.

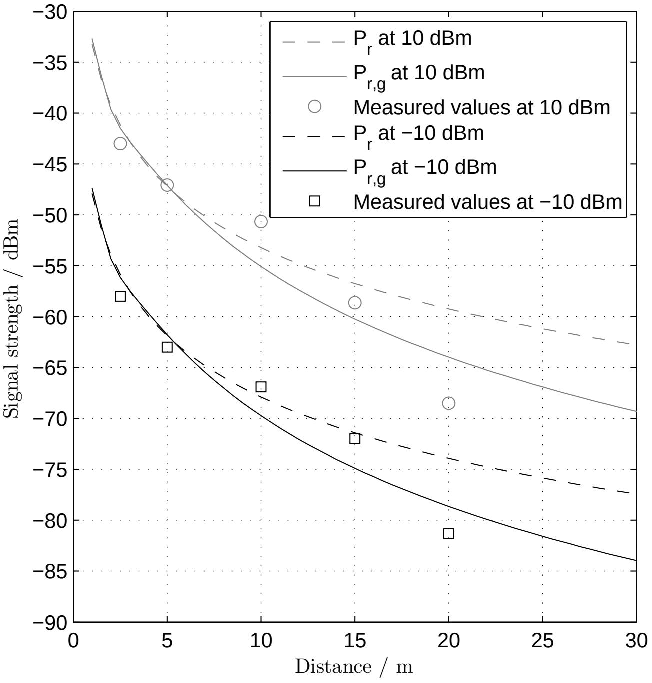

Figure 7. Indoor range measurement: 915 MHz - Channel 8 - MSK

The first one around $1.0\ \mathrm{m}$ is bound to the presence of a table between transmitter and receivers obstructing radio signal propagation. The second one around $2.4\ \mathrm{m}$ results from the transmitter being too close to the ceiling. According to Lymberopoulos et. al., the antenna orientation should be changed to improve the measured RSSI values in such cases. The values at other heights correspond well to the theoretical prediction. In general, the proximity to any objects causes deterioration of measurement values.

5.4 Further Thoughts

When implementing an RSSI based localization system, the measurements of the RSSI values should be linked up with a measure of dispersion considering a single or more packets. The number of packets not only depends on the used hardware components (e.g. synchronization issues between microcontroller and radio), but also on the environmental influences (e.g. a highly dynamical system). Another beneficial technique is monitoring the RSSI value with a sensitivity threshold for unreliable distance measurements to recognize outliers, and exclude them from position estimation.

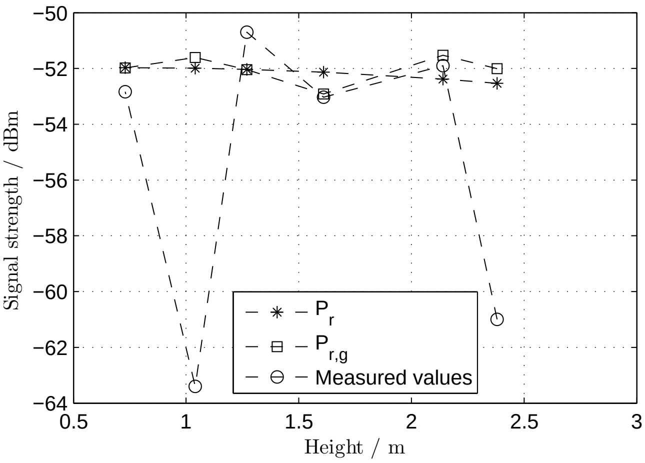

Figure 8. Indoor height measurement with receivers at a fixed height of $0.75\ \mathrm{m}$

6 Conclusion and Outlook

In this paper we summarized the theoretical basics of a propagation model for radio signals at free space. We also described our corresponding real-world testbed in detail before presenting and analyzing the RSSI measurement series. By choosing suitable parameters, the outdoor experiments closely follow the theoretical free space propagation model with ground reflection. However, node-specific calibration is required before relating RSSI values to spatial distances. In indoor environments, significant deviations from the used theoretical models could be observed with increasing transmitter-receiver distance. Obstructing objects causing reflection, diffraction, or scattering even lead to much higher differences compared to the ideal radio propagation model.

For further research we intend to use our achieved results to design two RSSI based localization systems for indoor and outdoor use. The self calibration of deployed sensor nodes is desirable, too. Finally, the communication protocol as well as centralized and distributed position estimation algorithms are scope of our current research.

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