Localization in Zigbee-based Sensor Networks

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***Abstract* – Localization in wireless sensor networks gets more and more important, because many applications need to locate the source of incoming measurements as precise as possible. Weighted Centroid Localization (WCL) provides a fast and easy algorithm to locate devices in wireless sensor networks. The algorithm is derived from a centroid determination which calculates the position of devices by averaging the coordinates of known reference points.**

To improve the calculated position in real implementations, WCL uses weights to attract the estimated position to close reference points provided that coarse distances are available. Due to the fact that Zigbee provides the Link Quality Indication (LQI) as a quality indicator of a received packet, it can also be used to estimate a distance from a node to reference points.

Index Terms: Sensor Networks, Zigbee, Centroid Localization, Distance Determination, Received Signal Strength Indicator (RSSI), CC2420, Link Quality (LQI).

I Introduction

The increasing miniaturization of electronic components and advances in modern communication technologies lead to the development of extreme small, cheap, and smart sensor nodes. These nodes consist of sensors, actuators, a low power processor, small memory, and a communication module. Nodes measure conditions of the environment, precalculate, aggregate, and transmit this data to a base station. Thousands of these nodes form a large wireless sensor network to monitor huge inaccessible terrains [Aky02,Kar03].

Processor performance and available energy of each sensor node are highly limited by its physical size. Therefore, intensive communication and computation tasks are not feasible. Thereby, algorithms in sensor networks are subject to strict requirements covering reduced memory consumption, communication, and processing time.

As a result of the stochastical distribution of all nodes in the deployment phase, a determination of the node's position is required. Determining the position of sensor nodes in wireless sensor networks represents a real challenge. To identify the exact coordinates of sensor nodes (also called unknown nodes or Unknowns) requires measuring a distance e.g., measuring time of arrival (ToA) or time difference of arrival (TDoA). Difficulties concerning time measurement results from synchronization of involved devices as well as the high mathematical effort to calculate the position. Measuring the received signal strength (RSS) offers a possibility to realize distance determination with minimal effort. Existing solutions based on measuring RSS do not produce very precise results.

A good localization algorithm should calculate a position as fast as possible and should be resistant to environmental influences as well as imprecise distances. A very good algorithm combining before mentioned conditions is the Weighted Centroid Localization (WCL) in combination with Zigbee.

The paper at hand is divided into five sections. The second section discusses the theoretical background and practical realization of measuring the RSSI and LQI in Zigbee devices. Next in Section III, the derivation and implementation of WCL is described. Our experimental results, we present in Section IV followed by the conclusion which closes this paper.

II RSSI and LQI as Distance Determination

II.I Received Signal Strength

Lots of localization algorithms require a distance to estimate the position of unknown devices. One possibility to acquire a distance is measuring the received signal strength of the incoming radio signal. The idea behind RSS is that the configured transmission power at the transmitting device (P_{TX}) directly affects the receiving power at the receiving device (P_{RX}). According to Friis' free space transmission equation [Rapp02], the detected signal strength decreases quadratically with the distance to the sender (Figure 1a).

$$P_{RX} = P_{TX} \cdot G_{TX} \cdot G_{RX} \left(\frac{\lambda}{4\pi d} \right)^2 \tag{1}$$

P_{TX} = Transmission power of sender
P_{RX} = Remaining power of wave at receiver
G_{TX} = Gain of transmitter
G_{RX} = Gain of receiver
λ = Wave length
d = Distance between sender and receiver

In embedded devices, the received signal strength is converted to a received signal strength indicator (RSSI) which is defined as ratio of the received power to the reference power (P_{Ref}). Typically, the reference power represents an absolute value of P_{ref}=1mW.

$$RSSI = 10 \cdot \log \frac{P_{RX}}{P_{Ref}} \qquad [RSSI] = dBm \tag{2}$$

An increasing received power results a rising RSSI. Figure 1b illustrates the relation between RSSI and the received signal power. Plotting RSSI versus distance *d* results in a graph, which is in principle axis-symmetric to the abscissa. Thus, distance *d* is indirect proportional to RSSI.

In practical scenarios, the ideal distribution of P_{RX} is not applicable, because the propagation of the radio

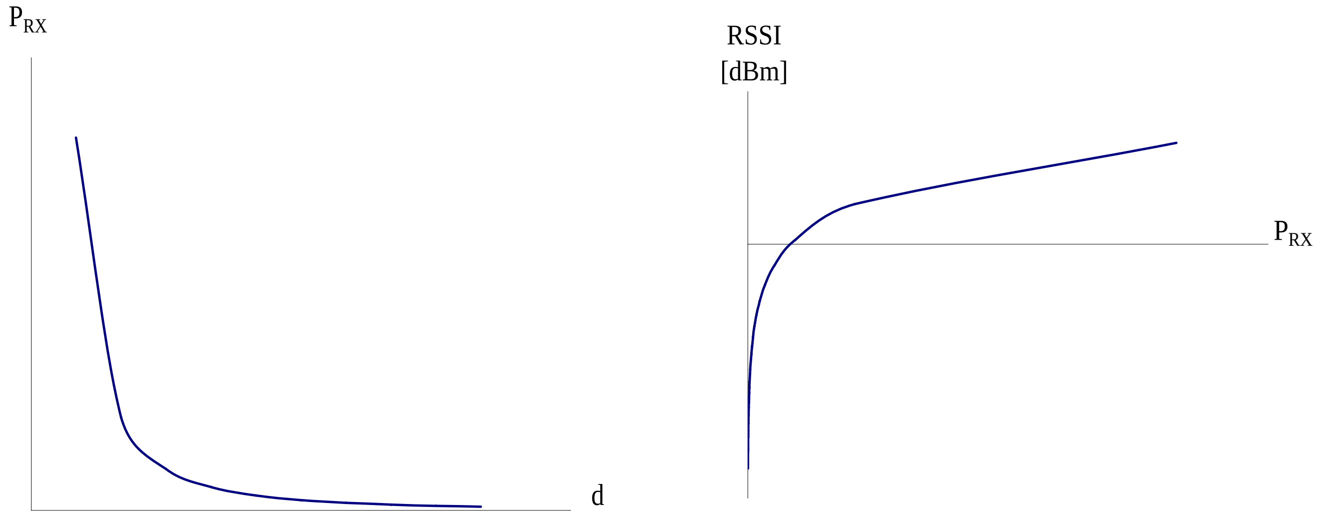

Figure 1: a) Received power P_{RX} versus distance to the transmitter b) RSSI as quality identifier of the received signal power P_{RX}

signal is interfered with a lot of influencing effects e.g.

- reflections on metallic objects
- superposition of electro-magnetic fields
- diffraction at edges
- refraction by media with different propagation velocity
- polarization of electro-magnetic fields
- unadapted MAC protocols
- inapplicable receiving circuits [Sri06]

These effects degrade the quality of the determined RSSI significantly. Thus in many applications, RSSI has a very high variance and low entropy (Figure 2).

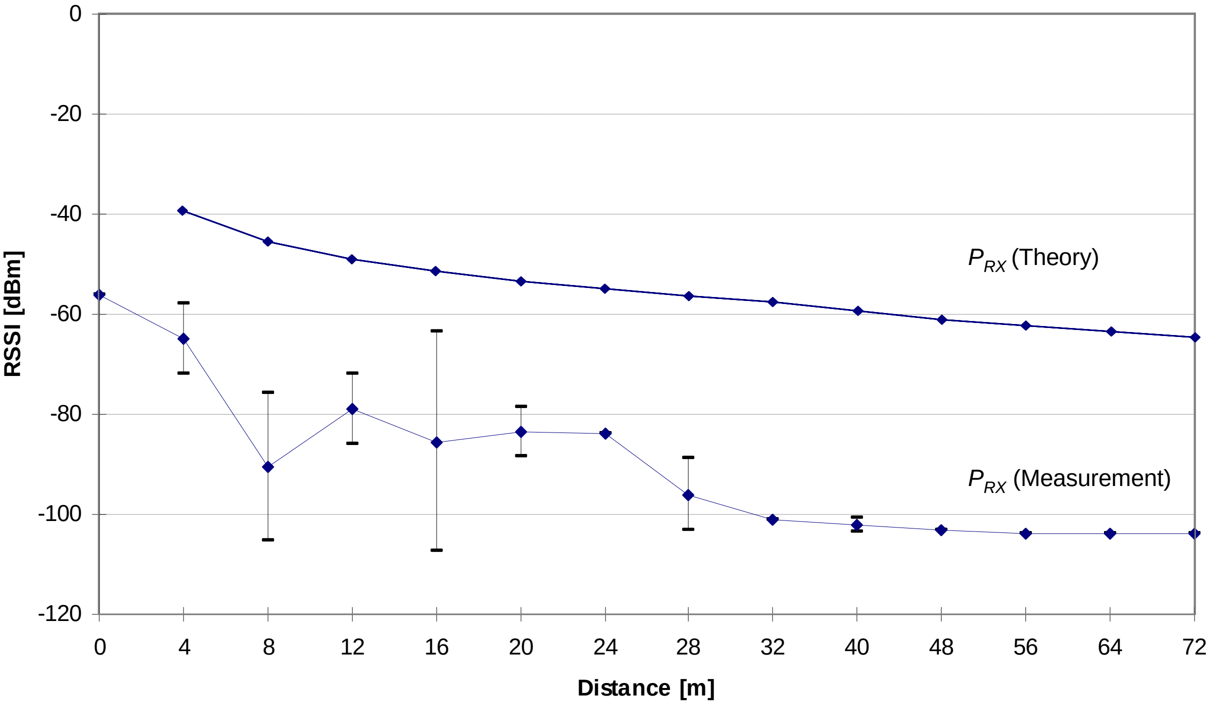

Figure 2: Received Signal Strength of a Chipcon CC1010 sensor node

II.II Link Quality

The before mentioned influences during transmission of radio packets reduce the quality of RSSI extremely. Thus, localization of unknowns becomes imprecise. Another method to determine the distance is based on the link quality indicator (LQI) of the transmission. It represents a number of required retransmissions to receive one radio packet correctly at the receiver.

In our laboratory, we measured the link quality indicator of the Zigbee-based devices (CC2420). The test scenario consists of two sensor nodes. One node serves as a reference device (beacon) and transmits packets continuously in a loop. The other one (unknown) logs the LQI of the incoming radio packets and forwards the LQI to the connected PC. During the measuring process, the position of the transmitting device was varied between 0 and 40m and was repeated 20 times. Each measuring process was performed with four different beacons.

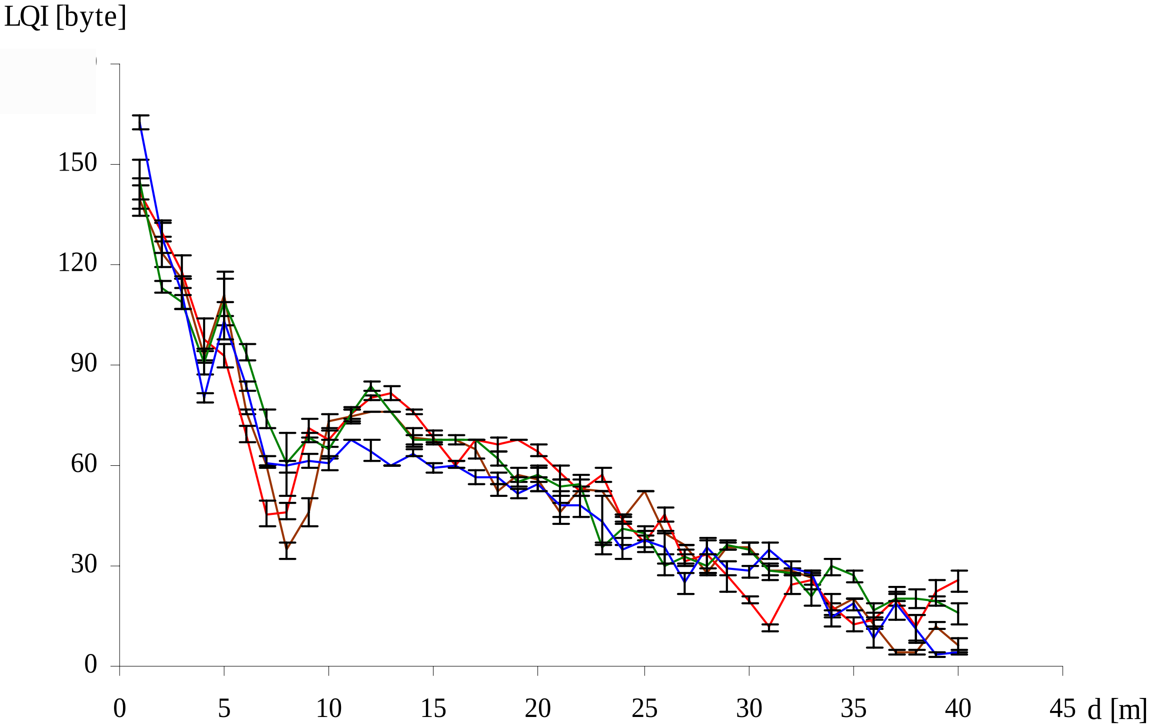

Figure 3: LQI vs. distance between two Zigbee-based sensor nodes (CC2420DB) in 20 loops

The determined LQI in our configuration setup is visualized in Figure 3. None surprisingly, the LQI of incoming radio packets decreases with an increasing distance. The graph satisfactorily shows the reproducibility of the distance determination. The LQI measurements at all four beacons show characteristic curves and offer an intense correlation between LQI and distance. Alike RSSI, systematic outliers based on channel effects are also noticeable ($d = \{4, 8\}$) [Gro07].

III WCL Algorithm

A sensor network with a total number of k nodes consists of u sensor nodes and b beacons ($b << u$). Beacons are equipped with more efficient hardware and localization system (e.g. GPS), whereby they are able to determine their own position. Furthermore, this position is assumed to be exact. Sensor nodes consist of minimal hardware and do not know their own position, initially. During deployment, sensor nodes and beacons are uniformly distributed over an area of interest.

Publicized algorithms such as CL use centroid determination to calculate their own position [Bul00]. In the first phase, all beacons send their position $B_j(x,y)$ to all sensor nodes within their transmission range. In the second phase, all sensor nodes calculate their own position $P_i'(x,y)$ by a centroid determination from all n positions of the beacons in range (3). The localization error $f_i(x,y)$ is defined as distance between the exact position $P_i(x,y)$ and the approximated position $P_i'(x,y)$ of a sensor node (4).

$$P_i'(x, y) = \frac{1}{n} \sum_{j=1}^{n} B_j(x, y) \tag{3}$$

$$f_i(x, y) = \sqrt{(x' - x)^2 + (y' - y)^2} \tag{4}$$

While CL performs only averaging the coordinates of beacon devices to localize blindfolded devices, WCL uses weights to ensure an improved localization. Starting from the calculation of the arithmetic centroid (3), the formula to determine the position with WCL is derived. Expressing the term n as sum of ones and the multiplication of B_j with ones, Equation 3 is expanded to the WCL formula (5).

$$P_i^{'}(x,y) = \frac{1}{\sum_{i=1}^{n} 1} \sum_{j=1}^{n} 1 \cdot B_j(x,y) \tag{5}$$

After replacing ones by weight functions w_{ij}, the final equation is formed.

$$P_i^{''}(x,y) = \frac{\sum_{j=1}^{n} \left(w_{ij} \cdot B_j(x,y) \right)}{\sum_{j=1}^{n} w_{ij}} \tag{6}$$

The weight w_{ij} is a function depending on the distance and the characteristics of the sensor node's receivers. Every application scenario requires a different weight due to changed environment conditions. In WCL, shorter distances are more weighted than higher distances. Thus, w_{ij} and d_{ij} are inversely proportional. As an approximation, the correlation is equivalent to the function $1/d$. To weight longer distances marginally lower, the distance is raised to a higher power of g. For a concentric wave expansion with a linear characteristic of the receiver and a uniform density of the beacons, we form (7).

$$w_{ij} = \frac{1}{\left(d_{ij}\right)^g} \tag{7}$$

d_{ij} = distance between beacon B_j and sensor node P_i, g = degree

The degree g has to ensure that remote beacons still impact the position determination. Otherwise in case of a very high g, the approximated position moves to the closest beacon's position and the positioning error $f_i(x,y)$ increases. Thus, a minimum of $f_i(x,y)$ exists, where g is optimal [Blu05].

To determine the optimal g, we simulated a full equipped sensor network of the dimension 30mx30m enclosed by 2x2 beacons. Hence, the beacons are grid-aligned and have a distance to each other of fq=30m. Figure 4 demonstrates the graphs of the localization errors depending on the transmission range and 6 different weight functions. The weight functions only differ in the degree g. The simulation satisfactorily shows several minima of the localization error depending on the transmission range and the degree. The smallest minimum of the localization error exists at tr=10 and a weight function w=1/d. Thus, a very small transmission range and a degree g=1 produces best localization results. But, in other configurations e.g., tr=30m, a degree g=3 yields in best results. Therefore before starting the localization process, an intensive analysis of the adjusted transmission ranges and the dimensions of the network are necessary to get smallest localization errors.

IV Outdoor Experiences

We verified our theoretical analysis based on LQI as distance measurement and weighted centroid localization to determine the position of sensor nodes. The WCL algorithm was implemented on the CC2420 development kit (CC2420DK) provided by Chipcon, which primarily includes five development boards (CC2420DB) and the required software to program the boards.

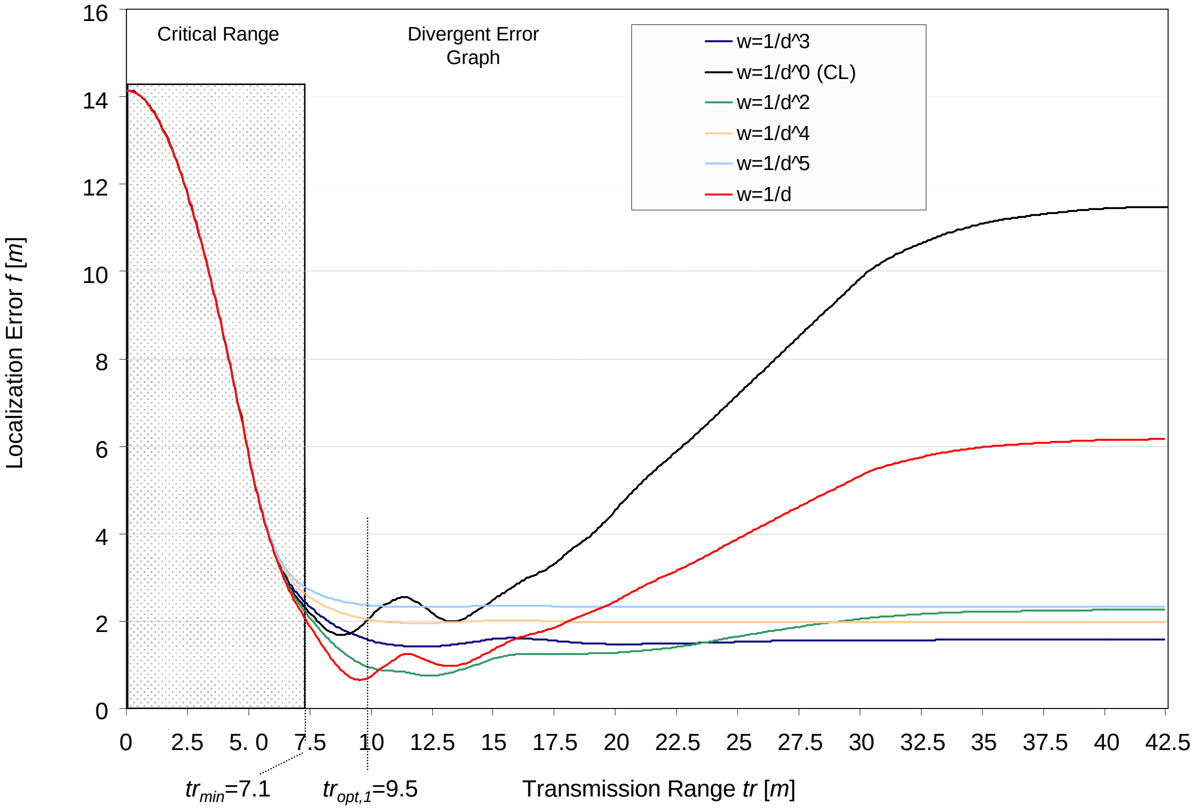

Figure 4: Simulation of the localization error versus transmission range *tr* with different weight functions in a full equipped sensor network enclosed by 2x2 beacons (dimension: 30mx30m, *fq*=10m).

On each CC2420DB, the Zigbee stack is installed, which supports up to 240 application objects inside the application framework layer. Within one of these application objects, the positioning algorithm is implemented. This architecture provides a comfortable design of application within wireless sensor networks. Traditional solutions like CC1010 without standardized protocol stacks require deep knowledge about physical channel, data packaging, discovering networks, retransmission etc. whereas Zigbee provides all these features inherently and simplifies the development process of applications rapidly.

According to Zigbee, one distinguishes three types of logical devices: the coordinator, the router, and the end device. Depending on the kind of logical device type, different tasks are processed [IEEE03, Zig04]. In case of beacon nodes, which are configured as router, the current position is transmitted in a specific time interval. The sensor node (unknown), the required coordinator, receives packets and saves the beacon's coordinates as well as the appropriate LQI to an internal structure. After receiving a specific number of packets from beacons, which are in range, the localization algorithm is executed.

Starting from a general network, which consists of b beacons and u unknowns, we consider only a part of four beacons and one unknown node, initially. Figure 5 illustrates the principal test environment. The beacons are placed in squared grid, which edge length is *fq*=10m. While the test period, the coordinates of the beacon devices are not changed. The unknown acts as coordinator. Its position is assumed to be unknown. The software tries to estimate the position based on the weighted centroid localization (20 times). This estimation process is repeated at each second raster point within a grid of 10mx10m. After the estimation process, all localization errors are compared with the exact positions.

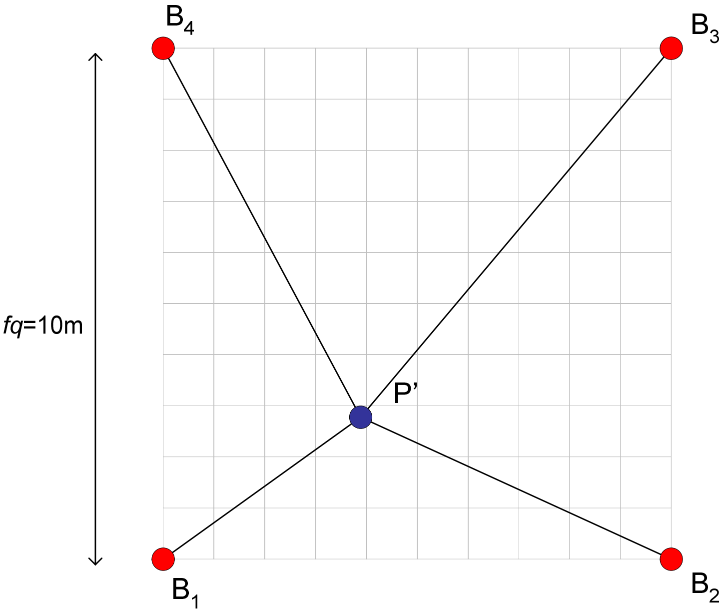

Figure 5: Setting of outdoor test localization

The beacons B_i ($i \in \{1;2;3;4\}$) are configured as router and their tasks is to transmit their own positions. The coordinator *P'* processes incoming packets and determines the link quality indicator (LQI). After a successful reception of several beacon positions and the corresponding LQI, the unknown estimates its own unknown position. The estimated position is sent to the serial interface and is logged on a mobile computer.

Figure 6 illustrates the result of the localization process. The plotted vectors represent the location errors. It starts at the exact position and ends at the estimated position calculated by WCL. Each localization error shows the average of all 20 loops. Based on a weakness of WCL algorithm, the localization error increases if the node moves from the center to the borders of the considered area [Pat03, Rei06].

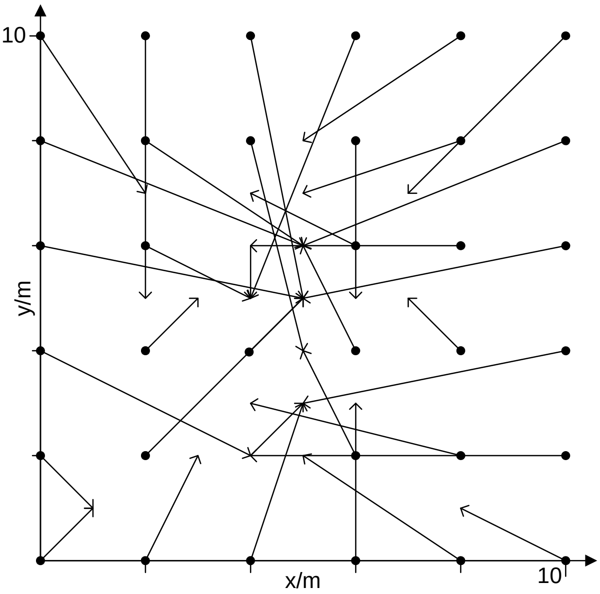

Figure 6: Localization error of WCL using Link Quality Indicator (LQI) in Zigbee-based devices (CC2420)

V Conclusion

This paper has summarized basic theoretical und practical facts concerning the analysis of RSSI measurements. Furthermore, the WCL algorithm und its realization with Zigbee is illustrated. Finally, first outdoor tests are presented.

Although the positioning algorithm does not yet provide the desired results very exactly, the presented localization algorithm in combination with a Zigbee offers lots of advantages. The most important advantage is the simplified implementation process due to already defined fundamental functions within the provided protocol suite of Zigbee. The low complexity, the fast calculation, and the minimal resource requirements recommend WCL as localization algorithm in wireless sensor networks.

VI References

[Aky02] Ian F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, “A survey on sensor networks”, IEEE Communications Magazine, pp. 102- 114, August 2002.

[Kar03] H. Karl, A. Willig, “A short survey of wireless sensor networks”, TKN Technical Report TKN-03-018, Berlin, October 2003.

[Blu05] Jan Blumenthal, Frank Reichenbach, Dirk Timmermann, “Position Estimation in Ad hoc Wireless Sensor Networks with Low Complexity“, Joint 2nd Workshop on Positioning, Navigation and Communication 2005 (WPNC 05) & 1st Ultra-Wideband Expert Talk 2005 (05), S.41-49, ISBN: 3-8322-3746-1, Hanover, Deutschland, 2005.

[Bul00] N. Bulusu, J. Heidemann, and D. Estrin, “GPS-less low cost outdoor localization for very small devices”, *IEEE Personal Communications Magazine*, 7(5):28–34, October 2000.

[Gro07] Ralf Grossmann, “Localization in Zigbee-based wireless sensor networks”, Technical Report (German), University of Rostock, Institute MD, April 2007.

[Rapp02] T. S. Rappaport. *Wireless Communications: Principles and Practice*. Prentice-Hall Inc., New Jersey, 1996.

[IEEE03] IEEE 802.15.4 specification, Mai 2003 http://standards.ieee.org/getieee802/download/802.15.4-2003.pdf

[Zig04] ZigBee specification v1.0, http://www.chipcon.com/zigbee/members_only.cfm, Dezember 2004.

[Pat03] Patwari et al, “Relative Location Estimation in Wireless Sensor Networks”, August 2003.

[Sri06] Kannan Srinivasan† and Philip Levis, “RSSI is Under Appreciated”, In Proceedings of the Third Workshop on Embedded Networked Sensors (EmNets 2006).

[Rei06] Frank Reichenbach, Jan Blumenthal, Dirk Timmermann, “Improved Precision of Coarse Grained Localization in Wireless Sensor Networks”, 9th Euromicro Conference on Digital System Design (DSD 2006), pp. 630-637, ISBN: 0-7695-2609-8, Dubrovnik, Croatia, September 2006