Weighted Centroid Localization in Zigbee-based Sensor Networks

Jan Blumenthal**, Ralf Grossmann, Frank Golatowski*, Dirk Timmermann**
* CELISCA, Center for Life Science Automation
Friedrich-Barnewitz-Str. 8
University of Rostock
** Faculty of Computer Science and Electrical Engineering
Institute of Applied Microelectronics and CE
Richard-Wagner Str. 31
18119 Rostock-Warnemuende

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.**

Keywords **CC2420, Weighted Centroid Localization, Distance Determination, Link Quality (LQI), Received Signal Strength Indicator (RSSI), Sensor Networks, Zigbee.**

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 [1],[2].

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.

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
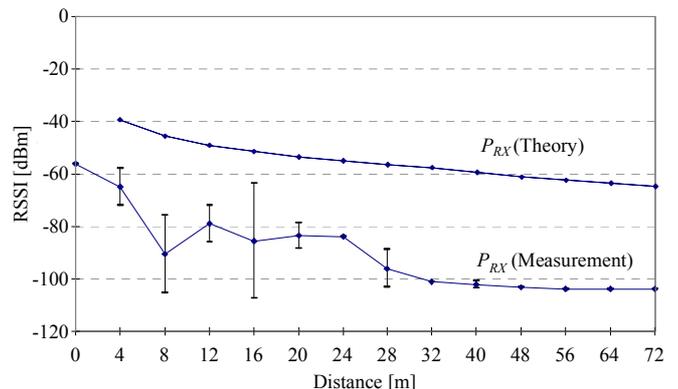

Figure 1: a) RSSI as quality identifier of the received signal power P_{RX} b) Received Signal Strength of a Chipcon CC1010 sensor node

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

A. 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 [6], the detected signal strength decreases quadratically with the distance to the sender.

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

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.

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

An increasing received power results a rising RSSI. 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 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 [10].

These effects degrade the quality of the determined RSSI significantly. Thus in many applications, RSSI has a very high variance and low entropy (Figure 1).

B. 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. According to IEEE 802.15.4, LQI is a characterization of the strength and/or the quality of a received packet. It must be proportional to signal level (RSSI), a signal-to-noise estimation or a combination of these methods and shall be a value between 0 and 255 [13]. In Chipcon's CC2420-based sensor nodes, RSSI is mapped directly to LQI [14].

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.

The determined LQI in our ideal outdoor configuration setup without any obstacles is visualized in Figure 2. 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 ($d=\{4;8\}$) [5]. These outliers may be caused by reflections at the ground or at walls and depends highly on the elevation of sender and receiver abive the ground level [12].

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.
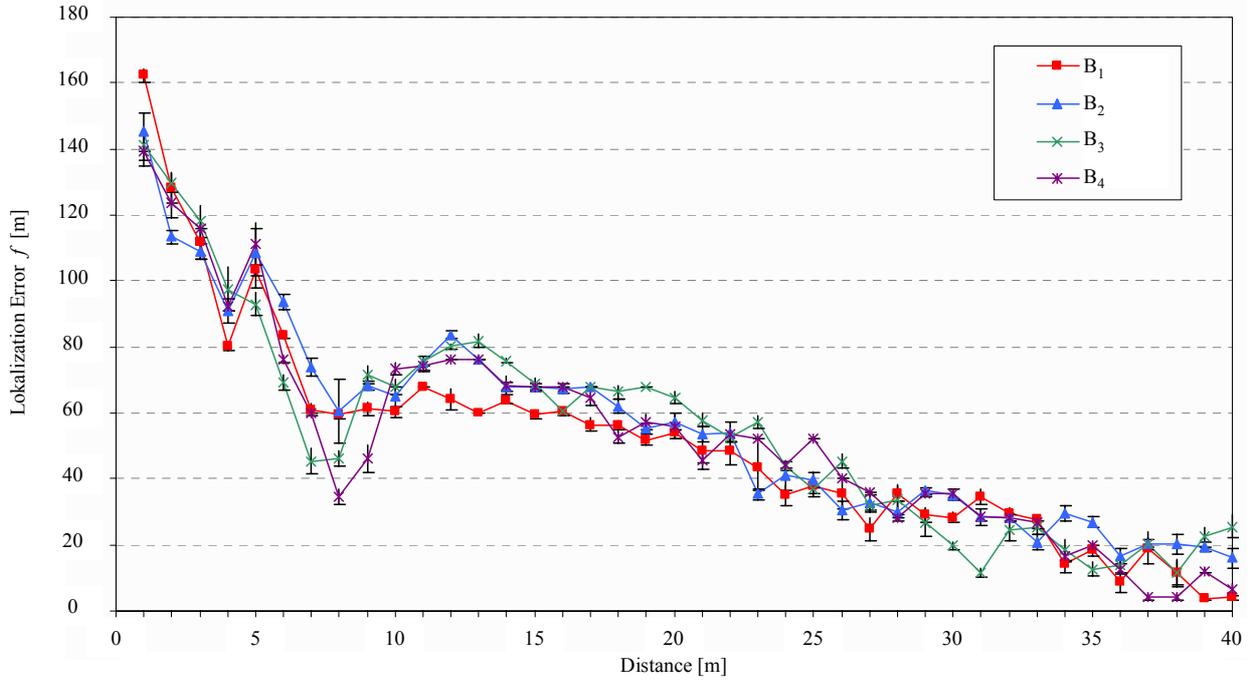
Figure 2: LQI vs. distance d between Zigbee-based sensor nodes $B_1..B_4$ and a coordinator node (CC2420DB) in 20 loops, ideal outdoor environment without obstacles, elevation h=20cm

Publicized algorithms such as CL use centroid determination to calculate their own position [4]. 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).

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

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

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).

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

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

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

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).

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

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
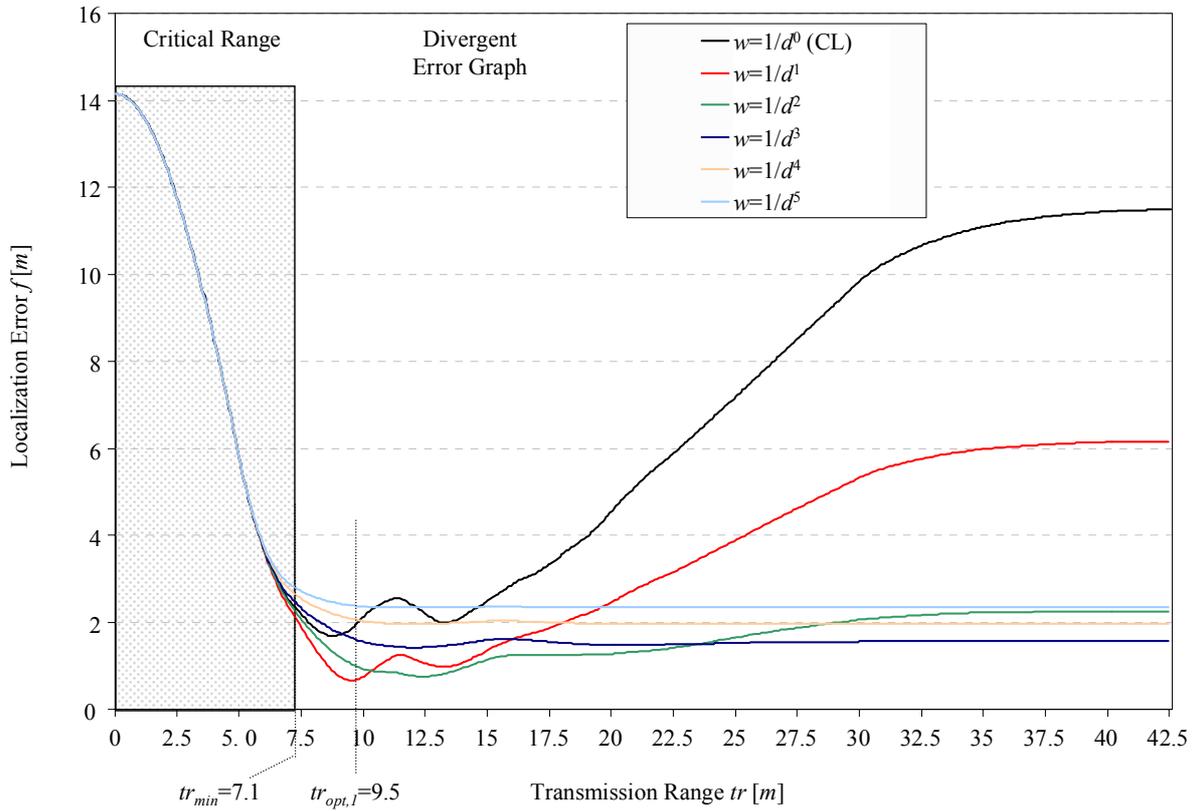
Figure 3: Simulation of the localization error versus transmission range tr with different weight functions in a full equipped sensor network enclosed by 4x4 beacons (dimension: 30mx30m, fq=10m).

position and the positioning error $f_i(x,y)$ increases. Thus, a minimum of $f_i(x,y)$ exists, where g is optimal [3].

To determine the optimal g, we simulated a full equipped sensor network of the dimension 30mx30m enclosed by 4x4 beacons. Hence, the beacons are grid-aligned and have a distance to each other of fq=10m. Figure 3 demonstrates the graphs of the localization errors depending on the transmission range tr 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.

Mostly, distances are measured indirectly by other quantities. The determination of distances out of the measured LQI values requires an appropriate transfer function. In theory, this is equivalent to a rearranged equation (1). But in practice, environment influences such as unpredictable reflections, interferences and obstacles as well as unknown electronic transfer elements within the transceivers impact the measured data enormously. Hence, calculating distances

using simple models will result in faulty distances with at least offset errors and scaling errors.

Due to using distances only as additional weights, the Weighted Centroid Localization (WCL) is featuring a very high robustness against scaling errors. In comparison with the least squares method (LS) – an optimal mathematical solution to solve over-determined linear equations – the WCL algorithm results in smaller localization errors in. As Figure 4 visualizes, only correct scaling leads to a smaller localization error in comparison to the weighted centroid localization. In all other cases, WCL yields smaller errors.
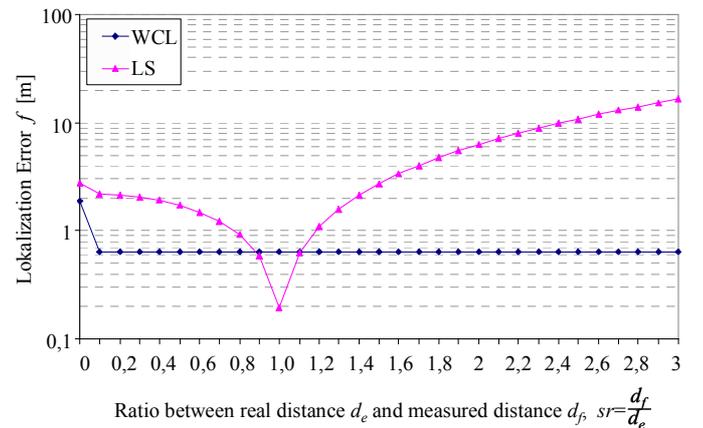

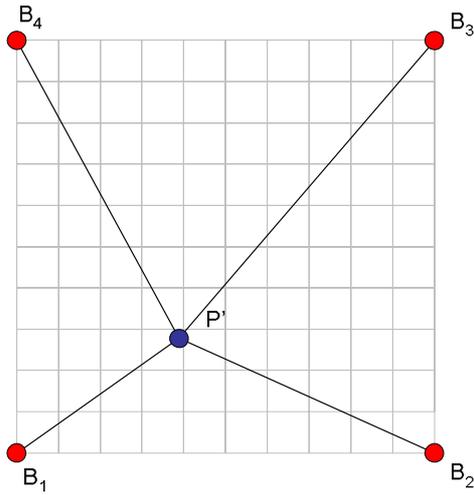Figure 4: Localization error vs. scaling ratio of WCL and Least Squares.

Figure 5: Setting of outdoor test localization.

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.

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

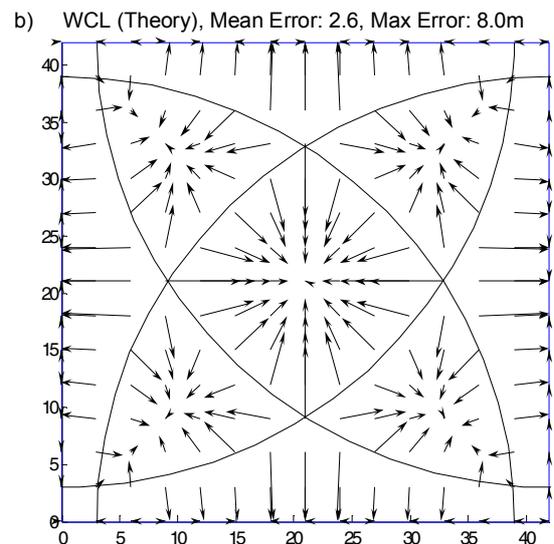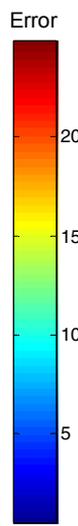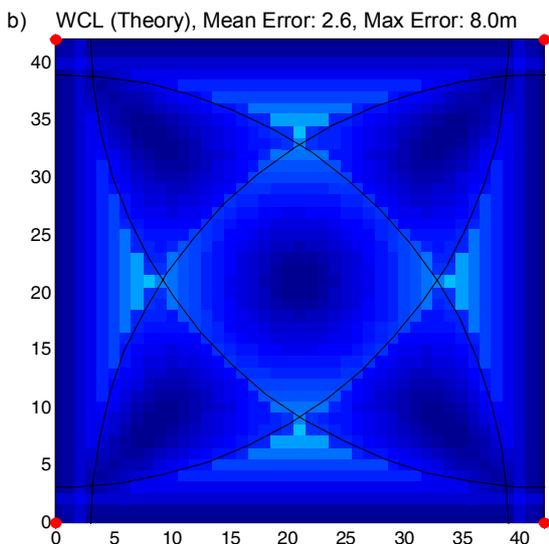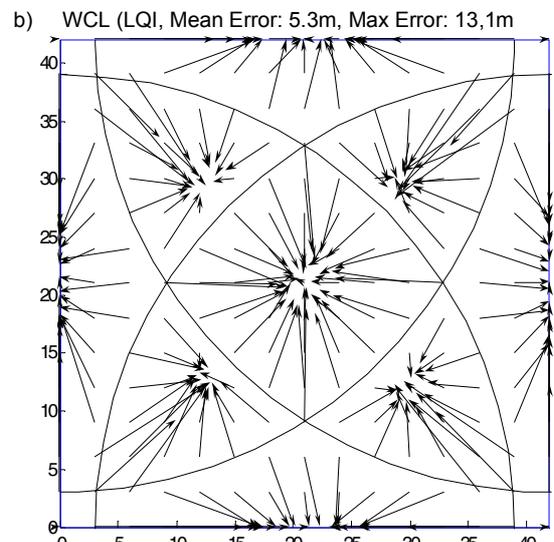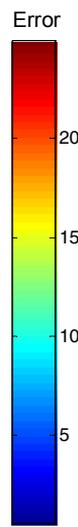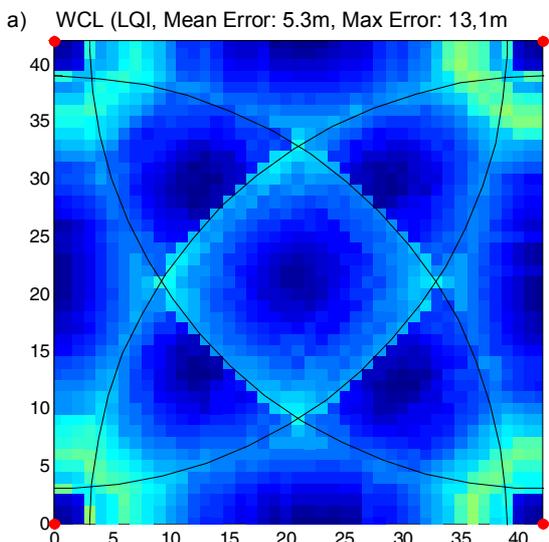Figure 6: Top view and error vectors of localization errors using Weighted Centroid Localization (WCL) based on a,b) Link Quality Indicator (LQI) in Zigbee-based devices (CC2420) c,d) theoretical model with exact distances in a sensor network of 43mx43m

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 [7][8]. 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 5a illustrates the principal test environment. The beacons are placed in squared grid with edge length of fq=43m. 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 third raster point within a grid of 43mx43m. After the estimation process, all localization errors are compared with the exact positions.

The beacons B_i ($i\in\{1;2;3;4\}$) are configured as router and their tasks is to broadcast their own positions to the field with an optimal transmission range tr=39 adjusted by setting appropriate transmission power [9][11]. 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 results of the localization process as colored top view and as error vectors. An error vector starts at the exact position and ends at the estimated position calculated by WCL. Each localization error shows the average of all 20 loops. Compared to the theoretical model with an averaged localization error of 2.6m in a grid-aligned sensor network (fq=43m), the localization error increases only to 5.3m using measured LQI as distance estimation. Hence, the averaged localization error is equal to 12% to the beacon distance (fq). The reason of doubling the error is caused by the discrepancy between the theoretical decreasing graph and the measured graph as exemplarily compared in Figure 1 and Figure 2.

V. Conclusion

This paper has summarized basic theoretical und practical facts concerning the analysis of RSSI measurements.

Furthermore, the WCL algorithm and robust behavior against scaling errors of distance measurements has been explained. its error behavior und its is illustrated. Finally, first localization results using Zigbee nodes in outdoor environments 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.

REFERENCES

[1] Ian F. Akyildiz, W. Su, Y. Sankarasubramaniam, and E. Cayirci, "A survey on sensor networks", *IEEE Communications Magazine*, pp. 102-114, August 2002.
[2] H. Karl, A. Willig, "A short survey of wireless sensor networks", TKN Technical Report TKN-03-018, Berlin, October 2003.
[3] 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.
[4] 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.
[5] Ralf Grossmann, "Localization in Zigbee-based wireless sensor networks", Technical Report (German), University of Rostock, Institute MD, April 2007.
[6] T. S. Rappaport. *Wireless Communications: Principles and Practice*. Prentice-Hall Inc., New Jersey, 1996.
[7] IEEE 802.15.4 specification, Mai 2003 http://standards.ieee.org/ getieee802/download/802.15.4-2003.pdf
[8] ZigBee specification v1.0, http://www.chipcon.com/zigbee/members_ only.cfm, Dezember 2004.
[9] Patwari et al, "Relative Location Estimation in Wireless Sensor Networks", August 2003.
[10] Kannan Srinivasan† and Philip Levis, "RSSI is Under Appreciated", In Proceedings of the Third Workshop on Embedded Networked Sensors (EmNets 2006).
[11] 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
[12] J. P. Linmartz's, "Wireless Communication", Vol. 1, Baltzer Science Publishers, ISSN 1383 4231, Amsterdam, 1996.
[13] S. C. Ergen, " ZigBee/IEEE 802.15.4 Summary", http://pages.cs.wisc. edu/~suman/courses/838/papers/zigbee.pdf.
[14] Texas Instruments, "2.4 GHz IEEE 802.15.4 / Zigbee-ready RF Transceiver", http://focus.ti.com/lit/ds/swrs041b/swrs041b.pdf, 2007.