Minimal Transmission Power vs. Signal Strength as Distance Estimation for Localization in Wireless Sensor Networks

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Abstract—**Autonomous localization of nodes in wireless sensor networks is essential to minimize the complex self-organization task consequently and to enhance network lifetime. Known techniques such as distance estimation based on received signal strength are mostly inaccurate and strong constrained. We propose a new method to measure a distance using the minimal transmission power between a transmitting node and a receiving node. The determined distance is very precise and has a low variance. It is therefore suitable for localization which is exemplary demonstrated for the approximate "Weighted Centroid Localization" algorithm.**

***Index Terms*—Localization, Distance Estimation, Signal Strength, Transmission Power, Wireless Sensor Networks**

I. Introduction

Hundreds of tiny electronic devices are able to sense the environment, compute simple tasks, and communicate with each other form a huge wireless sensor networks (WSN). Gathered information (e.g. temperature, humidity etc.) are transmitted in a multi-hop fashion over direct neighbors to a data sink, where the data is interpreted [1],[2]. With methods like self configuration and self organization, the network reacts to node failures. WSN enable new applications for timely detection of wood fire, monitoring of artificial dikes along a river, and "Precision Farming".

Due to the tiny desired node's size, the dimensions of the communication module and the battery are limited. Consequently, the smallest resource within a network is the available energy. Therefore, achieving a long lifetime of a sensor network requires low power hardware and slim as well as fast algorithms [3]. Beside the measuring task, every sensor node must be able to forward packets and to compute different subtasks such as data aggregation or checking received data using cyclic redundancy check (CRC).

After deploying a sensor network over an area of interest, sensor nodes initially have no position information. A node's position is very important, because measurements without a location where they were gathered are generally useless. Furthermore, node coordinates enable energy aware geographic routing.

Proposed algorithms can be classified into coarse grained methods, which approximate node positions, e.g. centroid localization [4],[5],[6]. On the other side, there are fine grained algorithms postulated, which calculate exact node position based on mathematical equations [7],[8]. Independently of the algorithm's type, all of these algorithms require additional input data to calculate a position. This input data can be received signal strength, neighboring node positions, signal time of flight between two nodes, or others. Unfortunately, measurements are noisy, dither, and have a relatively high standard deviation caused by environmental influences such as obstacles, deviations of transceivers, flection and interferences of waves, and other phenomens.

We will overcome some of theses problems by postulating a new technique to determine distances using minimal transmission power of the transceiver. In Section II, existing distance determinations and their characteristic are discussed. Then in Section III, we describe the "Weighted Centroid Localization" (WCL) algorithm that we need for further studies. Then, Section IV indicates some difficulties of signal strength measurements that we compare with the distance determination using minimal transmission power in Section V. This new technique is evaluated in a real environment using the WCL localization algorithm in Section VI. Finally, the paper ends with a conclusion in Section VII.

II. Related Work: Distance Determination

Assuming a random distribution of nodes over the area of interest, inter-node distances are initially unknown. Since most localization algorithms depend on this information, precise determination is essential. In sensor networks, a number of different techniques to determine distances are distinguished.

A. Neighboring Nodes

Algorithms working with neighboring information use the knowledge of the existence of remote nodes being aware their own positions. These algorithms assume that known neighboring nodes are located close to the local node and determine the local position by estimating out of all neighboring positions. Hence, distance *d* between two nodes is defined as a Boolean value. If *d=true*, the local sensor node is within transmission range of the remote sensor node. But a more precise information about the distance to the remote node is not possible. If no signal can be received, the local node is beyond the transmission range of the remote sensor node (*d=false*). Even though the entropy (*e=2*) is very small, because only binary values are distinguished, the precision of determined positions is more than acceptable [9]. It differs between 7% and 20% depending on the environment conditions and algorithm settings.

B. Signal Measuring

A more common method to determine a distance is based on measuring the received signal strength indicator (RSSI) of the received messages. In theory, power relations between an idealized transmitting pole (antenna) and a receiving sensor node behaves quadratically to a distance (1), well known as Frii's transmission equation [10].

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

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

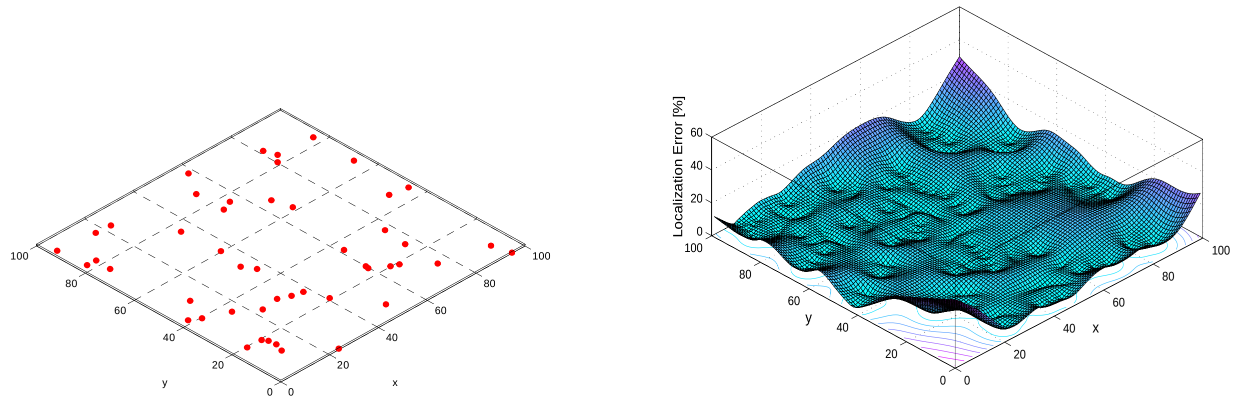
But in reality, ideal environment conditions are not met due to interferences, obstacles, flections, reflections, inhomogeneities of materials, and imprecise measurement methods. Systems relying on RSSI as input parameter tend to be quite accurate for short ranges if extensive post-processing is employed, but are imprecise beyond a few meters [11]. At short ranges, distance estimations with 2m averaged localization error at a maximum range of about 20m are feasible [12].

An improvement is presented in [11] where radio interferometry techniques are used to achieve an average localization error of 3cm and a range of up to 160m with a largest error of approximately 6cm. The downside of this approach is that it requires special features of the radio chip and strict timing accompanied by the high computational effort of the algorithm.

Measurement of a signal's "Time of Flight" (ToF) is a robust method to estimate distances, which is used e.g. by GPS. A difficulty in conducting such measurements is that a tight time synchronization of sender and receiver is required. Systems like Calamari [13] use a technique called "Differential Time of Arrival" (DToA) to avoid the complex time synchronization. They send out two signals travelling at different propagation velocities and quantify the difference in time of arrival. If both signal propagation speeds are known, a distance can be determined from this difference measurement. The majority of the proposed schemes require acoustic or ultrasonic sound technologies to determine a distance. Additionally, all schemas are combined with radio frequency transmissions as signalling technology. Raw difference measurements tend to yield average estimation errors of about 74%. Yet, quite good accuracies are achieved if the raw measurement values are post-processed with elaborated techniques like noise cancelling, digital filtering, peak detection and calibration. However, DToA systems inherently require an extra actuator and detector pair which increases cost, size, and energy consumption of a hardware platform.

C. Multihop Estimation

Another method to determine a distance between sensor nodes is the hop count along a message's path [14],[15],[16]. If no distance estimates between adjacent nodes are available, the smallest number of traversed hops is counted. To determine a hop count, a flooding is initiated by a sensor node *i* to other nodes. Each sensor node knowing its own position replys the request with hop count *0*. If a sensor node receives a reply, it forwards the reply with an increased hop count. Sensor node *i* collects all hop counts from remote sensor nodes with known positions and stores the minimal hop count to this sensor node. This minimal hop count represents a



a)

Figure 1. a) Sensor network with 60 uniform distributed beacons (solid points), b) Relative localization error of the „Weighted Centroid Localization" algorithm (WCL) in a sensor network with 100×100 sensor nodes and the same beacon distribution as shown in a)

distance. To determine the optimal hop count, the transmission range of sensor nodes must be adjusted such that each sensor node preferably reaches its direct neighbors only [17].

III. Background: Weighted Centroid Localization

Weighted Centroid Localization is a coarse grained localization algorithm, which uses neighboring information and distance measurements. In WCL, 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 a localization system (e.g. GPS or Galileo [18]), whereby they are able to determine their own position. This position is assumed to be exact. In contrast to beacons, sensor nodes consist of resource-critical, low-cost hardware and do not know their own position. During deployment, sensor nodes and beacons are uniformly distributed over an area of interest (Figure 1a). After distribution, sensor nodes try to determine their own position. Weighted Centroid Localization is divided into three phases:

1. All beacons broadcast their exact positions $B_j(x,y)$ together with information on the current transmission power and the current round. All sensor nodes in transmission range of a beacon store the received positions of these beacons.
2. WCL determines a distance to each beacon position. Currently, two methods of distance determination are successfully evaluated – distance measurement based on RSSI and hop count determination. Both methods provide valid distance information d_{ij} between a sensor node i and a beacon j. In our demonstration application, we implemented the proposed method of distance determination using distance measurements based on minimal power transmission.
3. Finally, all sensor nodes calculate their approximative positions $P_i'(x,y)$ out of all n received beacon positions in range based on a centroid localization (2).

$$P_i'(x,y) = \frac{\sum_{j=1}^{n}\left(w_{ij} \cdot B_j(x,y)\right)}{\sum_{j=1}^{n} w_{ij}} \qquad (2)$$

To increase the precision, WCL optimizes the accuracy of the position using measured distances. But due to interferences, obstacles, and hardware restrictions, measured distances are inaccurate. Hence, distances are used only as additional input for the localization algorithm [19],[20]. Thus, distances must not impact the position determination very excessively. During localization, WCL considers beacons next to a sensor node more than remote beacons. In addition, the algorithm does not require very high precision of input values to converge. Therefore, WCL uses distance information only as a weight w_{ij}. Small distances to neighboring beacons lead to a higher weight than to remote beacons. Further, every coordinate of a beacon position obtains a weight depending on the distance $w_{ij}(d_{ij})$. Figure 1b briefly points out the localization error after weighting the coordinates (Figure 1b) in WCL.

IV. Preliminaries: Received Signal Strength Indicator

Reading the received signal strength indicator (RSSI) is supported by almost every transceiver's hardware. Transmitted signals are attenuated in the communication channel between sender and receiver. Thus, the RSSI determined by the receiver is lower then the emitted signal by the sender. This dependency can be described among others with the log-normal-shadowing model:

$$RSSI\left(d\right) = \left(P_T - PL\left(d_0\right) - 10\eta \log_{10}\frac{d}{d_0} + X_\sigma\right) \qquad (3)$$

P_T = Transmission Power
$PL(d_0)$ = Path loss for d_0
d_0 = Reference distance
η = Path loss exponent
X_σ = Gaussian random variable

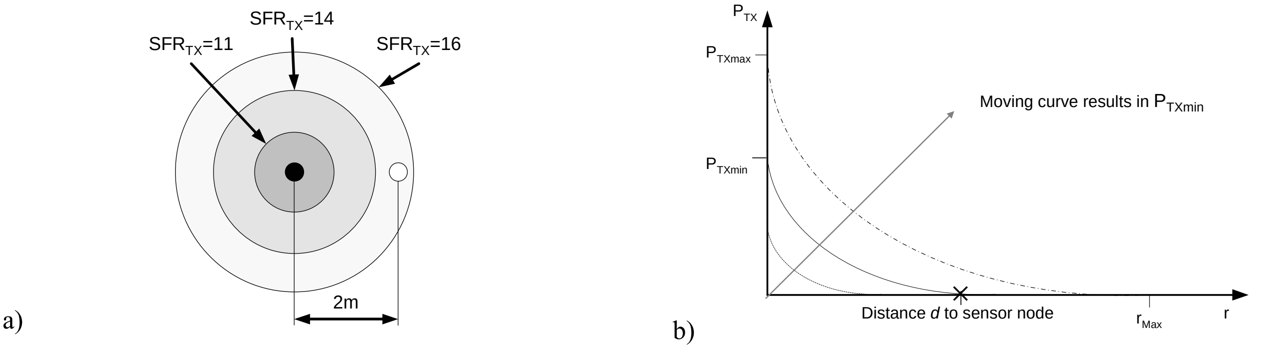


Figure 2. a) Determination of minimal transmission power by increasing the transmission power using SFR_{TX} successively. In this case, a message from the transmitting sensor node (solid circle) is received by the remote sensor node (blank circle) at a minimal transmission power of SFR_{TX}=16.
b) Correlation between transmission power P_{TX} and distance d according to equation (1). The solid line represents the minimal transmission power P_{TXmin} required to receive a message at the remote sensor node.

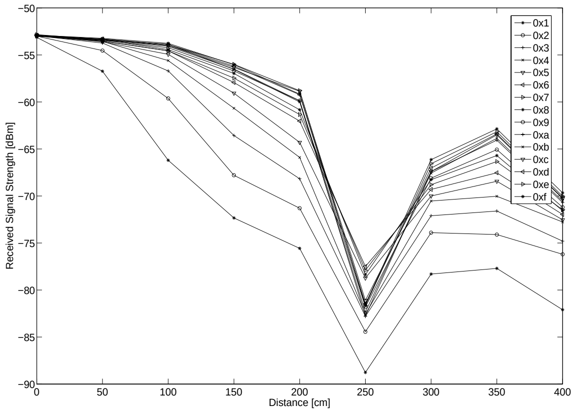


Figure 3. RSSI over distance characteristics between two sensor nodes on a straight line in our meeting room (output power levels are listed as register values; Variances were very small and thus are not shown here)

To get an idea of the RSSI characteristics, we measured the RSSI on a straight line at different distances (1cm ≤ d ≤ 500cm, Δd=50cm) in our meeting room with Chipcon's C1010 evaluation modules [21]. The room had a size of 7×5 meters. All modules were placed on the carpet. At every distance d, the signal strength was measured with 15 different output powers as illustrated in Figure 3. The characteristics approximately correlate with the expected signal path loss curves to be obtained from (3). An increasing output power level at the sender results in an increasing RSSI at the receiver. Reflections in the room produced high outliers, e.g. at 250cm. The outliers were independent of the different power levels. Summarized, relations between RSSI and distances are only qualified for localization with further enhancements.

V. A New Technique: Transmission Power Levels

In our new approach, the distance is determined out of the minimal transmission power which is required to send a message to another sensor node. In microcontrollers, the transmission power P_{TX} cannot be adjusted directly. Instead, the transmission power is controlled via special function register (SFR_{TX}). Sensor nodes knowing their own position (beacons) transmit their position with a stepwise increasing transmission power in range $SFR_{TXmin}..SFR_{TXmax}$. Figure 2a demonstrates a sensor node knowing its own position (solid circle). This node transmits a message containing its position and transmission power. In case of transmission power SFR_{TX}=11 and SFR_{TX}=14, the target sensor node (blank circle) is not able to receive the message. But if transmission power SFR_{TX}=16, the target node (blank circle) receives the message and stores the transmission power as distance. The sensor node saves only the smallest sufficient transmission power, messages with higher transmission powers are discarded.

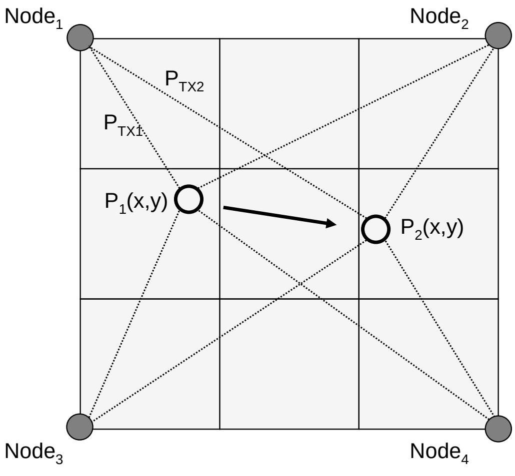


Figure 4. Moving sensor node (blank circle) from P_1(x,y) to P_2(x,y) in an array of 3×3 tiles

As described in (1) and visualized in Figure 2b, transmission power P_R and d are quadratically related. To determine a linear distance, (1) must be rearranged. The relationship between P_{TX} and SFR_{TX} strongly depends on the hardware conditions and must be adapted respectively. The transfer function H_{TX} of a transmitter, according to the specifics of a npn transistor, is assumed as $H_{TX} = SFR_{TX}^4$. Thus, P_{TX} is approximately defined as:

$$P_{TX} \approx SFR_{TX}^4 \tag{4}$$

To finalize (1), we consider the transfer function of the transmitter H_{TX} and a constant scaling factor k representing the gain of the antennas. Inserting (4) into (1) results into (5) to determine a linear distance between two nodes.

$$\begin{aligned} P_{RX} &= k \cdot SFR_{TX}^4 \left(\frac{\lambda}{4\pi d} \right)^2 \\ \rightarrow d &= SFR_{TX}^2 \sqrt{\frac{k}{P_{RX}} \left(\frac{\lambda}{4\pi} \right)^2} \\ d &\sim SFR_{TX}^2 \end{aligned} \tag{5}$$

In dynamical systems with mobil nodes as visualized in Figure 4, a node's position must be recalculated from time to time. Therefore, it is necessary to determine the new correct minimal distance. If the blank sensor node is moved from position $P_1(x,y)$ to $P_2(x,y)$, the minimal transmission power representing the distance $\overline{Node_1 P(x,y)}$ increases from P_{TX1} to P_{TX2}. Thus, the minimal transmission power according to node 1 and 3 increase while they decrease for node 2 and 4.

To keep track of the periodically repeated distance estimation, we sum up all beacon transmissions of one sequence from $SFR_{TXmin}..SFR_{TXmax}$ in rounds. To enable receiving sensor nodes to distinguish beacons from different rounds, a beacon message contains a round number that is increased from one round to another (Figure 5a). Thus, all sensor nodes consider a minimum of the perceived transmission power within one round in

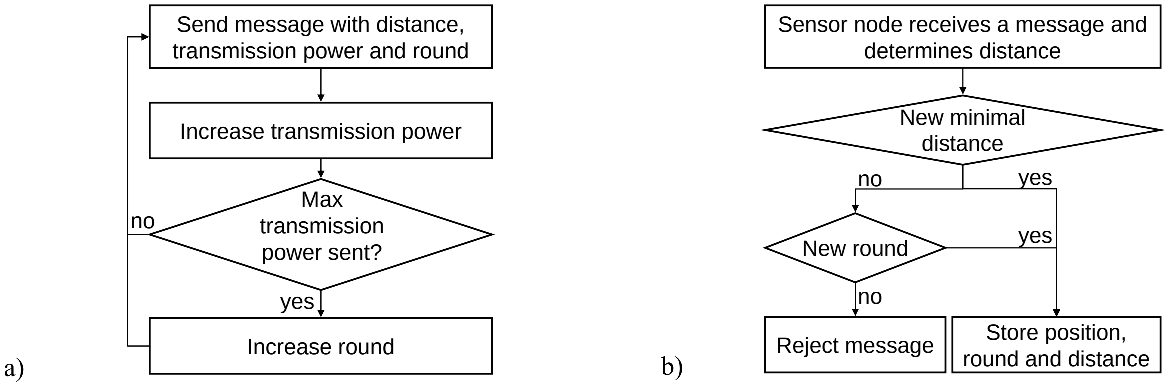


Figure 5. a) Flow diagram of a sensor node transmitting own known positions b) Flow diagram of sensor node receiving messages with positions from remote sensor nodes

order to quantify a distance to the transmitting sensor node (Figure 5b). In each round, a new distance estimate is generated.

VI. Experimentation

We implemented a demonstration application using embedded sensor boards (ESB) of the scatterweb project [22] to verify the distance determination based on minimal transmission power. Our application consists of beacons knowing their own position and sensor nodes. These sensor nodes do not know their own positions. Hence, they have to determine the position, e.g. with the algorithm “Weigthed Centroid Localization”.

The minimal transmission power scheme described in Section V is now used to determine the weight $w_{ij}(d_{ij})$. The weight $w_{ij}(d_{ij})$ requires a distance d_{ij} (6) and a degree g which defines the weight of a distance and amounts to g=3 as proved in [17].

$$w_{ij}(d_{ij}) = \frac{1}{\left(d_{ij}\right)^{g}} \qquad (6)$$

We measured the minimal transmission power from a beacon to a sensor node by stepwise increasing the distance between both nodes. Figure 6 visualizes the measured min. transmission power (y-axis) over the distance (x-axis). At each step, the empirical distances were measured forty times to determine the variance besides a meaningful averaged distance. The graph shows that measuring minimal transmission power has a low variance and a high resolution.

After measuring, we squared the measured SFR_{TX} to get a linear Equation (7) using (4). Now, we determined m by linear regression $f(x)=mx+n$.

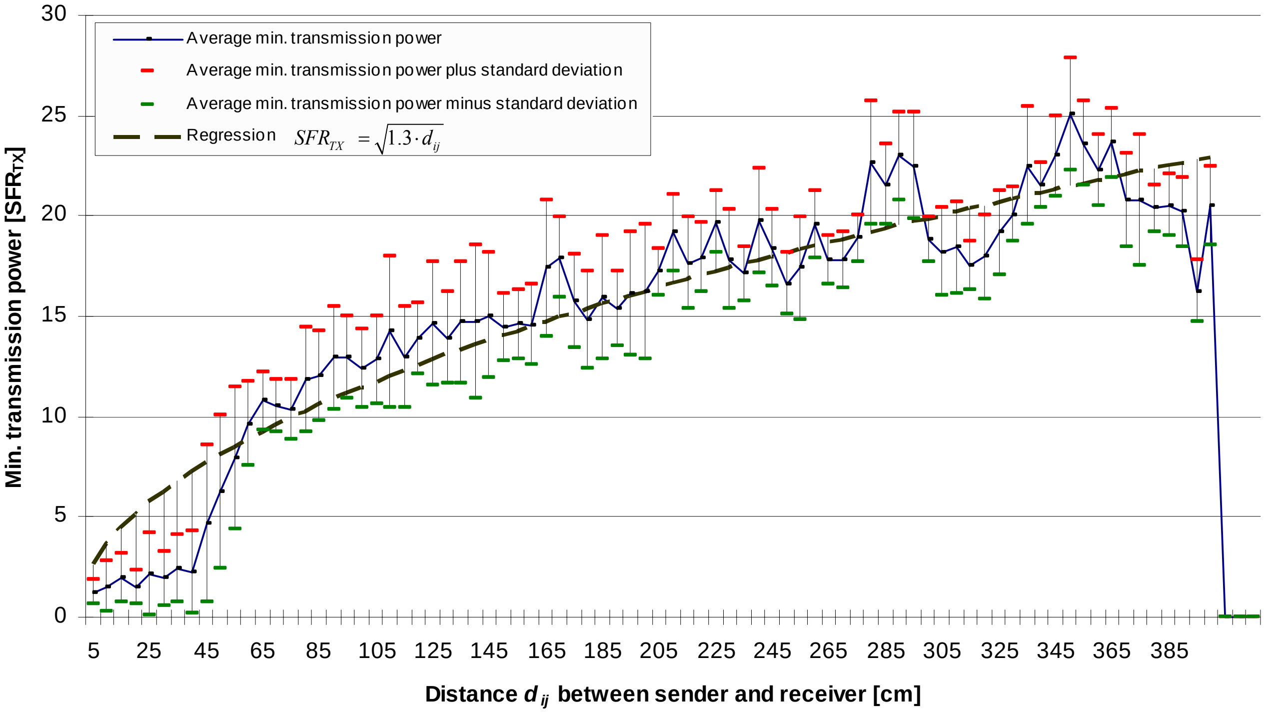


Figure 6. Minimal averaged transmission power SFR_{TX} over distance required to transmit messages between a beacon and a sensor node

$$SFR_{TX}^2 = m \cdot d_{ij} \tag{7}$$

In our configuration, the scaling factor results in *m=1.3* and *n=0*. Now, we rearrange (7) and obtain equation (8) which is similar to Equation (5).

$$d_{ij} = \frac{SFR_{TX}^2}{1.3} \tag{8}$$

To determine a correct transmission power SFR_{TX}, Equation (9) can be used for ESB sensor boards.

$$SFR_{TX} = \sqrt{m \cdot d_{ij}} \tag{9}$$

After these considerations, we evaluated our proposed distance estimation method on a demonstrator using WCL algorithm. This demonstration application consists of four sensor nodes with pre-defined positions (beacons) and was recorded on video. The video can be downloaded from the link in [23].

VII. Conclusion

In this paper, we presented a new approach to determine a distance between sensor nodes using minimal transmission power. The determined distance has a high resolution and a small variance compared to received signal strength that we also studied in this work. The distance's determination process was empirically proved in a demonstration application. The localization error achived a very high precision between 5%-15% compared to the real position with an approximated position algorithm.

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