Distance Measurement in Wireless Sensor Networks with Low Cost Components

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***Abstract*—Several ways to estimate the position of a Wireless-Sensor-Network (WSN) node have been discussed in the past years. Unlike in outdoor solutions where the Global Positioning System (GPS) could be used in most applications, a general solution for indoor usage has not been found.**

The few existing indoor localization solutions on the market are highly specialized and rely on infrastructure or on very expensive special designed hardware. Both - infrastructure and expensive hardware - do not fit well into most scenarios where WSNs are commonly used because of the adhoc characteristics and the large amount of nodes of such installations.

In this paper we present a solution to get a precise estimation of the distance between two nodes without the needs for special purpose chips or a redesign of already existent nodes. We use radio runtime measurement to calculate the distance between nodes and present algorithms to refine the measurements. A comparison with a professional solution which is available on the market is also presented.

***Index Terms*—Radio Runtime Measurement, Indoor Localization, Distance Measurement, Wireless Sensor Networks**

I. Introduction

A. Motivation

The indoor usage of WSN localization can be divided into two cases. In the first case the building is well defined and the WSN is designed especially for use in this building. In this case the deployment of special localization infrastructure like ultrasonic beacons is possible. The second case is the general case where nodes could move into unknown buildings. This case is met by rescue scenarios where the area of deployment is known only minutes before the deployment and infrastructure cannot be set up inside the buildings. For this general case all hardware has to be integrated into the nodes and only some anchors can be placed outside the building. We focus on this case in this paper.

Most localization systems for WSNs are using distance estimation techniques to calculate the nodes position. The distances can be gathered in several ways. For example estimated by received signal strength indicator (RSSI) or radio runtime measurement. Because the RSSI value in indoor deployments is influenced by many parameters, a distance estimation based on RSSI value is highly imprecise [1]. To use radio runtime measurement, normally special designed transceivers are used which often use wide spectrum or ultra wide spectrum techniques. To integrate these into an existing WSN a redesign of the whole platform is necessary which leads to high cost, additionally to the also high costs of the special purpose transceivers.

B. Contribution

In this paper we present a solution for radio based runtime measurement which can easily be integrated into existing WSNs with only minimal hardware modifications which does not lead to the need of a hardware redesign. We present an implementation on the MSB-A2 [2] WSN nodes. We address the problems of doing precise time measurements on the I/O pins of a microcontroller and taking care about the jitter which results from different clock sources of the microcontroller and the transceiver. So the contribution of this paper is a proposal for an easy to implement and precise solution for distance measurement in WSNs.

The paper is organized as follows: In chapter II we discuss and compare similar approaches. In chapter III we briefly introduce the techniques of radio runtime measurement with common microcontrollers and transceivers. We present our system design and some implementation hints in chapter IV. In chapter V we compare our solution with a professional measurement system which is available on the market and finally we give conclusions and an outlook in chapter VI.

II. Related Work

As the topic of RF based localization is researched since the beginning of the 20th century [3], there is a big amount of literature on this topic. Therefore we focus on publications covering the topic of RF based indoor localization in sensor networks [4].

To localize a WSN node in a network we need to know the distance of the WSN node to several anchor nodes. An anchor node is a normal WSN node in the network with an a priori known position. The distance measurement will be called ranging in this paper. There are several RF based methods to measure the distance between two radio stations. The following methods are used in our work.

A. RSSI-Based Approaches

The characteristic value for the power spectral density of a received signal is the RSSI value. A receiver derives this value from the measured incoming signal strength and signal amplification of the receiver part.

Electromagnetic waves lose power while being propagated through the air. In a theoretical setting the waves will propagate in a spherical form where the radius r of the sphere is the distance between transmitter and receiver. Because the performance of a real antenna and other physical effects the simple sphere formula does not give a good assumption for the distance. Harald T. Friis [5] proposes (1) for the estimated power at the receiver P_R in dependence of the gain of both antennas G_T and G_R and the wavelength λ.

$$P_R = P_T \frac{G_T G_R \lambda^2}{(4\pi)^2 r^n}, (n = 2 \text{ for open space propagation}) \quad (1)$$

In theory the distance between transmitter and receiver could easily be calculated with this formula if antenna gain, transmitting power and frequency are precisely known. Environment parameters like power loss in different transmission medias like air, concretes, steel, etc. are put into account with the constant parameter n. The estimation of n in real world scenarios can only be done by experiments in the selected environment. So a distance measurement with the RSSI value as a singular computation base is only reliable under laboratory conditions [1]. Although better models for distance estimation based on power loss have been developed, they are either too complex for an implementation on sensor nodes or they also lack accuracy.

B. Propagation delay

Electromagnetic radiation travels at the speed of light that is $c = 299792458 \frac{m}{s}$.

The time a radio signal travels between sender and receiver is called propagation delay or time of flight. If the propagation delay t is known, the distance d between sender and receiver can be calculated as shown in (2).

$$d = c \times t \quad (2)$$

To measure propagation delay between two radio transceivers we need an accurate time measurement in the magnitude of nanoseconds.

1) Direct Time of Flight measurement: The direct measuring method uses a timestamp t_1 that is the exact time of the signal leaving the transceiver of the sender and a timestamp t_2, which is the exact time when the signal arrives at the receiver. The propagation delay of the signal is $t = t_2 - t_1$.

The direct method is the difficult to implement, as highly accurate time synchronization between sender and receiver is necessary. Software based timing synchronization methods suitable for wireless sensor networks offer accuracy in the magnitude of microseconds [6], which is to imprecise to measure the propagation delay. Hardware based synchronization methods were not part of our research, as our goal was to use existing off the shelf hardware for our research.

2) Time difference of arrival (TDoA): Another approach to measure the propagation delay of radio signals is the TDoA method [7]. This method is based on a broadcast packet sent by the WSN node. Synchronized anchor nodes receive the packet and generate a timestamp of the arrival time. The timestamps are transferred to a data sink and can be used to calculate the possible position of the WSN node relative to the anchors. A key requirement for this method is a very exact synchronization of the anchor nodes, like it is needed for the direct method.

As our goal is to use the same hardware for the anchors as for the WSN nodes the TDoA approach was not suitable for our setting.

3) Round trip time of flight (RTOF): The RTOF method is also a well known method to measure the time of flight of radio packets [4]. The methods does not need hard time synchronisation within the network and is therefore used in this paper. The RTOF method is explained in detail in III-B.

C. Similar Approaches

Bahillo et al. describe a system which implements a RTT measurement method using standard 802.11 WLAN transceivers [8]. Although the approach is strongly related to our work, the main difference is that we do not need any additional hardware. Bahillo et al. use a custom printed circuit board (PCB) for time measurements while we use the embedded timer of a microcontroller. Our system can be applied to any sensor node of the MSB-A2 [2] family without any hardware changes. We also use a lower frequency band which has less resolution but better abilities towards multipath effects [9].

The nanotron company also uses a RTT based method to range with other members of the network. The company developed a complete transceiver that integrates localization functions in hardware [10]. Nanotron proposes the usage of a two way ranging method which focuses on minimizing the effects of frequency reference jitters between sender and receiver. They call it Symmetric Double Sided-Two Way Ranging (SDS-TWR). The basic strategy of this algorithm is to send a packet from A to B and back to A. After that, a second packet is sent from B to A and back to B. The two propagation delays are measured and averaged. That eliminates the effects of the different reference clock offsets between sender and receiver. This method consumes high bandwidth, because six packets have to be sent in their implementation for estimating one distance.

III. Time of flight measurements with common hardware

A. Propagation Time Based Measurements

The time a radio signal travels between transmitter and receiver is called propagation time or time of flight (TOF). If the propagation delay T_{TOF} is known, the distance d between transmitter and receiver can be calculated by multiplying the constant for speed of light c with T_{TOF}. In our case TOF is expected to be the magnitude of nanoseconds. To measure the T_{TOF} of a one-way propagation, the time difference between sending the signal at the transmitter and receiving the signal at the receiver has to be measured. The major challenge for this approach is the requirement of two accurately synchronized clocks and local times at the receiver and the transmitter [11]. In our case, where we want to keep the hardware complexity and therefore the costs as low as possible, this approach is less attractive.

B. Round trip time of flight

The round trip time of flight (RTT) method is the main measurement method for T_{TOF} used in this work. A WSN node A starts to measure the time T_{RTT} as the packet leaves the transceiver to B, when the reply packet from B arrives at the transceiver of A we measure T_{RTT}. The time node B needs to process the packet is called time to compute packet T_{TCP}.

The time of flight T_{TOF} can be calculated as follows

$$T_{TOF} = \frac{T_{RTT} - T_{TCP}}{2} \tag{3}$$

the distance between A and B can be easily calculated as

$$d_{RTT} = T_{TOF} \times c \tag{4}$$

Because T_{RTT} is only measured with the local clock of the sender, and T_{TOF} only with the local clock of the receiver, the major advantage of this method is that no time synchronization of the communicating partners is necessary and it can be done with standard hardware [12]. Nevertheless the challenge in this method is to get a very precise value for T_{TCP} and T_{RTT}. The faultiness of the distance measurement d_{RTT} using that method is described as

$$d_{RTT} = d + \epsilon_{RTT}^{LOS} + \epsilon_{RTT}^{NLOS} \tag{5}$$

by Bahillo et al. in [8]. This equation contains two error components ϵ_{RTT}^{LOS} for the error which appears when ranging in a line of sight setting and an additional error ϵ_{RTT}^{NLOS} when ranging in a non-line of sight environment. While a big factor in ϵ_{RTT}^{NLOS} are multipath effects, as described in [1], their negative impact can be reduced by using an empirical approach as described in [9]. The other source of error ϵ_{RTT}^{LOS} depends mostly on uncertainties and noise in the hardware. Especially jitter effects play a key role in the error component. In our work we concentrated on analyzing and eliminating the impact of ϵ_{RTT}^{LOS}. Lanzisera gives a detailed overview on performance limitations in [13].

C. Common Radio Transceivers in WSNs

Most radio transceivers used in WSNs like Chipcons or Atmels are low-IF (intermediate frequency) receivers. They have only a very small analog part where after some filtering the signal is put directly into one or more mixers to separate it from its carrier frequency and transform it to a much lower frequency. This lower frequency is called intermediate frequency.

The recognition and interpretation of signals is done completely in the digital part of the transceiver. If the data rate is known the bit frequency of the incoming data is detected while the preamble is sampled. The preamble is a stream of alternating bits.

D. When to Measure

For precise measurement of the TOF on a common microcontroller we need an appropriate signal as source for the time measurements. Most transceivers used in WSNs provide several sources like *first bit of packet*, *last bit of preamble*, or *last bit of packet* which are signaled through changing edges on a certain pin. All of these signals could be used while processing a packet. The preamble normally is an alternation of ones and zeros to provide bit synchronization to the receiving radio. So all indicators referring to the preamble like *first bit of packet* are not reliable. Because a packet could only be detected after bit synchronization and therefore the span between the incoming *first bit of the preamble* and the recognition of a packet is variable. A better approach is to use the sync word as an indicator, because it is sent directly after the preamble. Because the sync word directly follows bit synchronization, it has the lowest possible bit jitter.

In the rest of this paper we are using the *last bit of sync word* as event for all time measurements on sender and receiver.

E. Jitter effects

Understanding the jitter [14] effects occurring in our measurement was one of the biggest challenges in our work. While measuring we suffer from several points at which jitter effects influence the accuracy of our distance measurements.

There are two main sources for jitter in this work. The first source is the non-synchronous clock of the transceiver and the microcontroller. The second source is the unknown signal processing time of the transceiver itself. Jitter in our case means inaccuracies in the time measurement. Each single measurement jitters around a true value which we want to measure.

We assume the jitter effects to be gaussian distributed and validate this assumption in experiments. By repeating each measurement a certain amount of times we assume that the measured median value will get close to the true value.

F. Hardware Limitations

Nearly all modern microcontrollers provide a timer unit which could be used to measure time spans. To do measurements of very short time spans a high clock speed is needed. To measure the TOF of a radio packet we utilize the *last bit of sync word* pin of the transceiver chip to start a measurement on an outgoing packet and the same pin to stop the measurement on an incoming packet as described in section III-B. Included in the RTT is the time which the addressed node needed to compute the incoming packet and assemble the outgoing packet. This time could also be measured with the same pins from the transceiver and then transmitted to the requesting node. If these time spans are subtracted we get the raw transmission time of the two packets.

This transmission time is far from being accurate. Several error sources have to be taken into account. First there is the jitter caused by the independent clocks of the microcontroller C_u and the transceiver C_t. This jitter is added in several stages of the measurement. If two independent clock sources are used the signal could only be sampled on a rising edge of our system clock source. This jitter J_c could be estimated as follows:

$$0 \leq J_c \leq \frac{1}{C_u} \quad (6)$$

The second form of jitter which is added is the jitter caused by the digital part of the transceiver. The transceiver transforms the waveform to a digital signal using a clock C_t. Because this clock is independent to the clock of the corresponding transceiver the rising edge for a detected bit could be delayed one clock cycle of C_t. This jitter J_t could be estimated as follows:

$$0 \leq J_t \leq \frac{1}{C_t} \quad (7)$$

Overall two timestamps are taken to calculate the TOF. Each timestamp N suffers from the jitter effects J_{tN} and J_{cN}. Two of the timestamps are used to calculate the time between the sending of the initial packet and the receiving of the ACK packet on the initiating node. These timestamps contain the jitters J_{t0}, J_{c0}, J_{t3} and J_{c3}. On the corresponding node also two timestamps are taken to calculate the computation time between receiving a packet and sending the first bit of the ACK packet. These timestamps contain the jitters J_{t1}, J_{c1}, J_{t2} and J_{c2}. The measured T_{RTT} is estimated as follows:

$$T_{RTT} = J_{t0} + J_{c0} + TOF_R + TOF_A + J_{t3} + J_{c3} + T_{TCP} \quad (8)$$

In (8) TOF_R is the TOF for the request packet and TOF_A is the TOF for the acknowledgment packet.

To calculate the estimated TOF_e the computation time has to be subtracted from R_t. Including jitters it could be estimated as:

$$TOF_e = \frac{T_{RTT} - (J_{t1} + J_{c1} + T_{TCP} + J_{c2} + J_{t2})}{2} \quad (9)$$

As introduced in (7) another kind of jitter occurs, which is sourced inside the transceiver and could hardly be measured. The time the transceivers digital part needs to recognize a bit can vary between on wave of the intermediate frequency and the bit length relating to the modulation, data rate and link quality. Because of the other jitters also occurring during measurements this jitter cannot be measured with common equipment and can only be assumed over a large number of measurements. Finally, we will estimate the TOF_e as the measured RTT decreased by T_{TCP} and an offset O_m which holds this bit jitter J_b.

$$TOF_e = \frac{T_{RTT} - T_{TCP} - O_m}{2} \quad (10)$$

Also included in the offset O_m is the propagation time of the signal in the analog part of the transceiver and the time to demodulate the signal in the digital part.

Additional to all of these error sources the clock drifts of the clock sources have also to be taken into account. Under normal circumstances the TOF of a packet is that small that the error sourcing from clock drift is minimal compared to the jitters.

The jitters could be minimized if the microcontroller and the transceiver are driven with the same clock source which would lead to a redesign of existing hardware if possible at all.

IV. Implementation

A. System Setup

For our reference implementation MSB-A2 sensor nodes are used. The MSB-A2 has an LPC2387 microcontroller [15] and a CC1101 radio transceiver [16]. The microcontroller has an ARM7 core and a 72MHz clock. The CC1101 is driven with a 26MHz clock and uses the 868MHz SRM radio band.

As the microcontroller runs a clock of 72MHz we expect a maximum time resolution of 13,89ns as shown in (11).

$$\frac{1}{72MHz} = 13,89ns \quad (11)$$

As the CC1101 runs with a lower clock than the microcontroller it has a different time resolution. This time resolution sets the theoretical accuracy limit for a single measurement to 11,53m as shown in (12).

$$\frac{c}{26MHz} = 11,53m; c = 299792459\frac{m}{s} \quad (12)$$

As operation system we are using the FireKernel microkernel [17]. The FireKernel is a multithreaded realtime system and supports several hardware features of the LPC2387. Along with the kernel we could also use a CC1101 driver implemented by the FireKernel developers.

B. Implementation Overview

Regarding III-F and with the knowledge about the exact clock rates of all relevant components we can calculate the estimated values for all error sources and take them into account. Only O_m remains inestimable because the bit jitter is independent from the clock rates. We have to measure O_m beforehand for every used transceiver and store it on a memory card.

To improve accuracy we have implemented a two way range measurement protocol which allows us to measure the TOF from node A to B and from node B to A in one cycle of our algorithm. First node A sends a ranging request (RR) to B which answers with a ranging acknowledge (RACK). In this step the TOF timer of A is started and B has measured the computation time and also started a TOF timer on sending out the RACK. A stops the TOF time on receiving the RACK and starts measuring the computation time immediately and sends out another packet to B (REACK). On receiving this packet B stops its TOF timer. The last step is to transmit the measured TOF and the computation time to node A. Node A has now two measured TOFs and the corresponding computation times. Because we normally have more than one of these measurements, we skip the last packet which only transmits the measured times to node A and piggyback those values in the RACK of the next step.

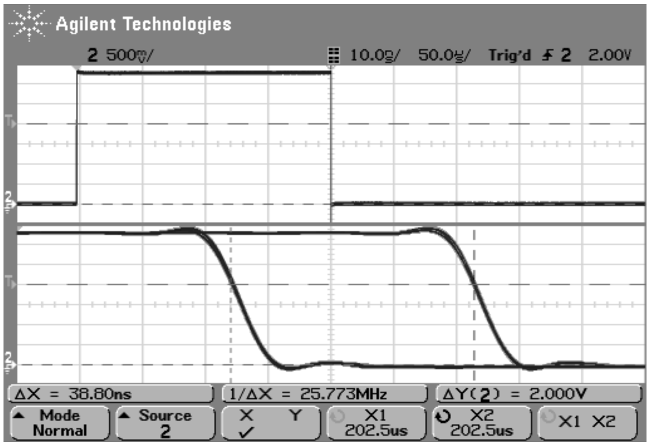

Fig. 1. The jitter of the transceiver while measuring the end of sync word pin. The origin of the jitter is the 26 MHz clock of the transceiver.

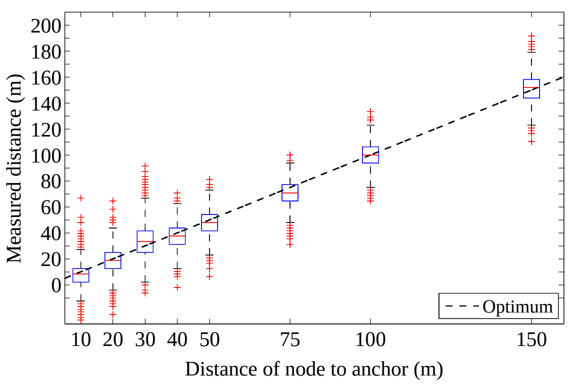

Fig. 2. The box plot shows the accuracy of outdoor measurements under line of sight conditions. The whisker length is 1.5 times of the interquartile distance.

V. Evaluation

A. Evaluation of the jitter presumption

First we estimated by experiments if our assumptions about the error sources and the error distribution were correct. The experiments showed that the jitters where assumed correctly and they are equally distributed. Fig. 1 shows the transceiver jitter measured with a digital storage oscilloscope (DSO). The upper half of Fig. 1 shows the output of the *packet status* pin, which is high as long as the packet is processed and transmitted by the transceiver. The lower half shows the falling edge of the same signal in high resolution measured over multiple transmissions. The experiment shows that the signal pin of the transceiver seems to jitter around one transceiver clock, as we expected.

B. Measuring O_m

Prior to an outdoor evaluation experiment we must find the offset of each transceiver as described in III-F. The measurement of the offset O_m is done by three different nodes which are located in a reference distance of 10m to an anchor node. The whole distance measurement process is carried out by all three nodes and the time of the process is measured in CPU cycles the process needs. We repeat this process 8000 times to gain representative values. The distribution of measured cycles is shown in Fig. (3). Due to our reference distance of 10m we expect a TOF of 76,61ns. This time equals approximately 6 CPU cycles of our 72MHz driven microcontroller as shown in (11). One can easily see there are several peaks in each histogram plot shown in Fig. (3). We chose the highest peak of each histogram as offset value O_m of each corresponding node. The value of O_m is stored in a memory card on the node and reused with each start of the node. The distance between the histogram peaks can be explained by the different clock sources of the transceiver and the microcontroller.

The time offset O_m is much higher than the actual TOF we want to measure which is a drawback in our system. As the distance between anchor and sensor node shrinks it becomes harder to distinguish between noise in the measurement and the actual measured time. We also do not know whether O_m depends on environmental parameters like temperature or humidity, however our experiments so far suggest that this is not the case and that O_m just depends on the transceiver itself. It might be possible to lower the offset O_m by changing some transceiver parameters, but we could not prove this due to a lack of documentation of the internals of the transceiver.

C. Outdoor Evaluation

To evaluate the accuracy we first carried out some outdoor experiments to prove the general fitness of our system. The experiment was carried out in a region with low radio activity which was verified beforehand using a portable spectrum analyzer. The band we operate in is the 868MHz SRM band, which was completely unused by third party devices in our outdoor experiment. We used one anchor node and three portable nodes which were placed in different distances to the anchor node in a line of sight scenario. Each node was placed in a height of four meters above the ground to get the optimal radio performance. The maximum distance we could measure in this setting was 150m as for 200m the packet loss became to high to gain representative values. For each distance the measurement was conducted 10000 times for each node. Incomplete measurements due to packet loss or implausible results, such as distances bigger than the radio range were dropped by the software, nevertheless between 8000 and 9000 successful measurements remained for each distance. The measured values were stored on a SD memory card on the sensor node and later examined using Matlab. Fig. 2 shows a box plot of the measured values of one node, the middle of each box represents the median of the values, the vertical borders of the box show the lower and upper quartile of the measured values. The results of the other nodes are similar to the presented values.

It is shown in Fig. 2 that an average accuracy of 3m could be achieved if the median value out of 10000 single measurements is chosen, which is very promising.

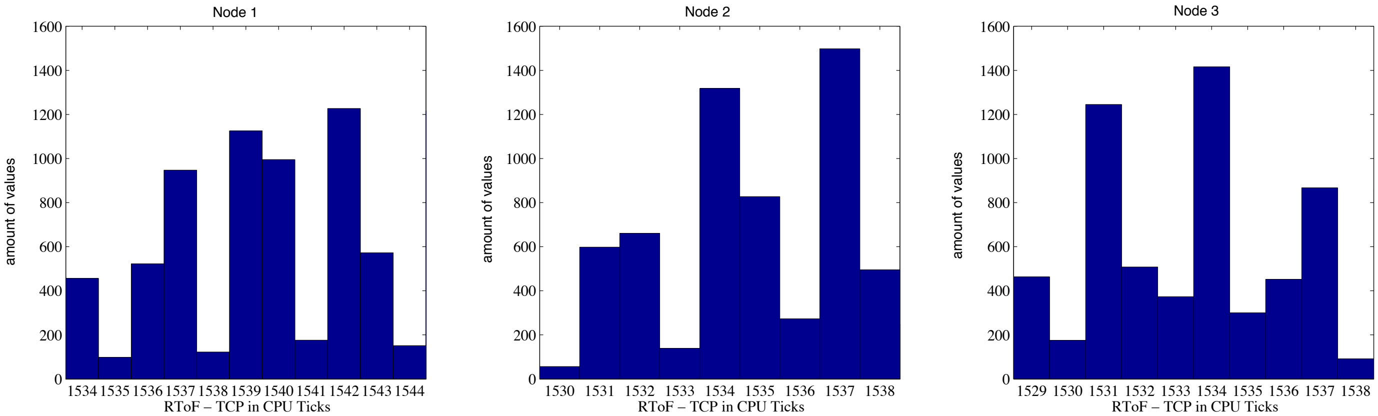

Fig. 3. The measured RTOF including O_m of three nodes used in the evaluation

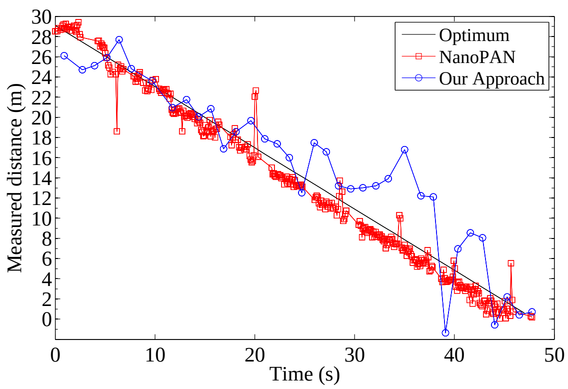

Fig. 4. Accuracy comparison between Nanopan 5375 range measurements and our system. Indoor measurement on a 30m long corridor.

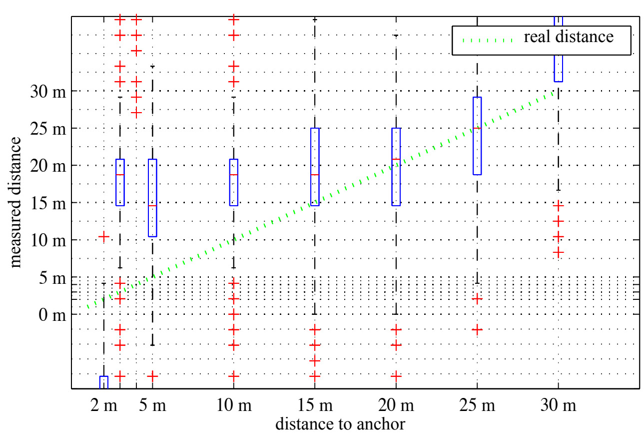

Fig. 5. Indoor measurement with saturation effects

D. Indoor Evaluation

For a more practical evaluation we set up an indoor experiment where we walked along a 30m long corridor in our university. We did the same measurement with a professional ranging measurement system from Nanotron, the Nanopan 5375 RF module mounted on the same WSN platform [10]. As shown in Fig. 4 our system behaves similar to the reference system. To compare the two systems in a real word scenario we did a walk through our office and measured the distance between an anchor and a sensor node. The result was comparable to the results of the comparison system. As shown in Fig. 4 our system gets more inaccurate if the distance between sensor node and anchor shrinks below 11.53m because we hit the theoretical limit of the transceiver time resolution as shown in (12), furthermore the transceiver of the receiving node is likely driven into saturation when the distance is too short which leads to high inaccuracies. We implemented a possible solution for the near field-problem which is described in V-E.

One major drawback is that our system uses a relatively high bandwidth. To achieve a single ranging the reference system uses the radio channel for around 6ms. To compensate the jitters in our system we have to do 20 ranging cycles which blocks the air for around 30ms. This does not influence the accuracy comparison, because the accuracy of the reference system is not increased significantly with more measurements.

E. Near-Field Evaluation

As mentioned before, the overall accuracy of our system decreases as the distance between sensor node and reference node shortens below 11.53m. The reason for this behavior arises out of a trade-off between higher accuracy and measurement stability as we want to establish connections between the sensor nodes even in shadowed areas, especially in indoor environments. Thus, we operate the transceiver with maximum output power. The drawback of this solution is that the analog digital converter (ADC) of the transceiver is driven into saturation for the line-of-sight (LOS) component of the signal and so the signal cannot be demodulated, whereas the reflected parts of the signal, which always occur in indoor environments, have a lower power density and can be demodulated easier. Since the reflected signal, having had to travel a longer distance to the receiver, arrives a moment later than the direct signal, the measured TOF is higher and thus the determined distance.

A first approach to mitigate the near-field problem was done by automatically adjusting the output power of the involved

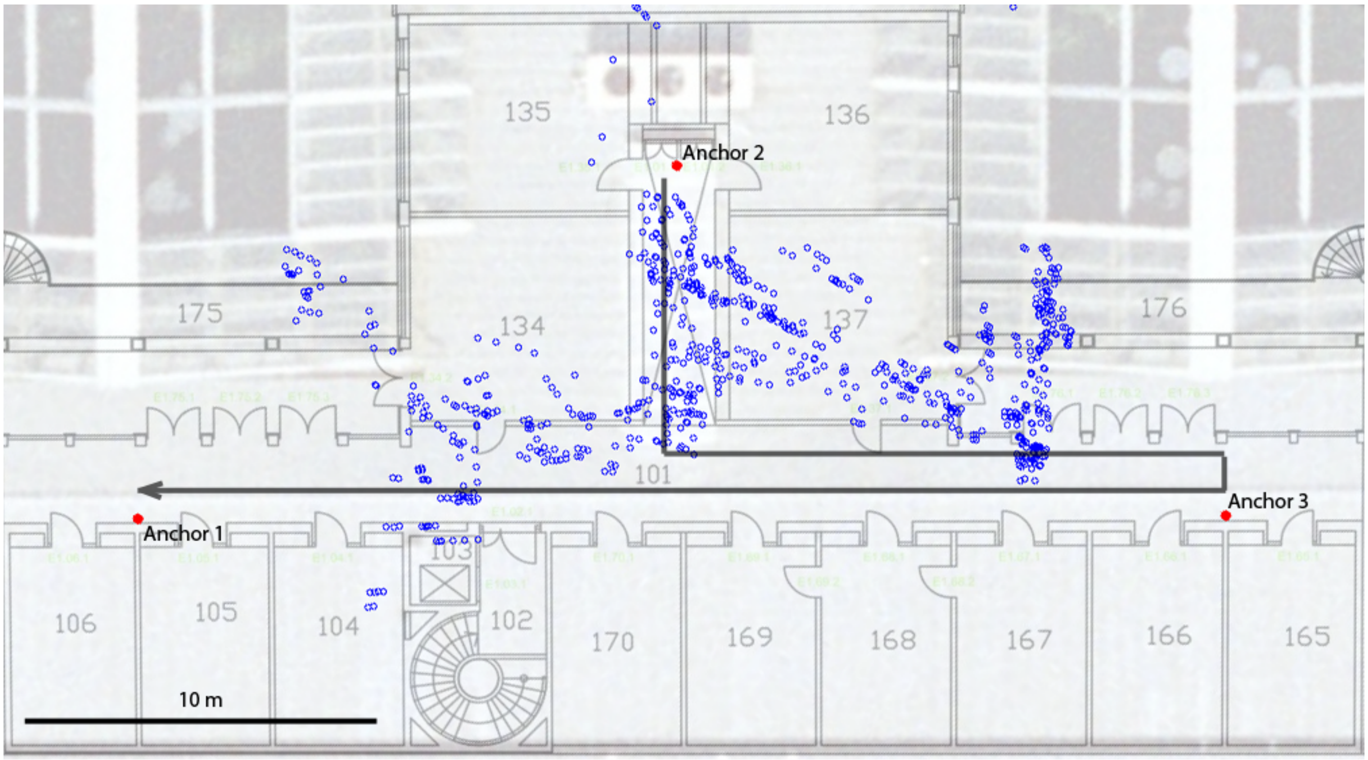

Fig. 6. Results of an indoor localization experiment

sensor nodes via exchange of radio packets. Unfortunately, our solution needed the exchange of 10 packets at least, too many packets to perform a single measurement in sufficient time for locating moving objects.

As a second approach we used a hitherto hardly known feature of the CC1101 transceiver which allows us to manually adjust the attenuation in the receive section. Therefore, the RSSI value is already readout and evaluated while receiving the preamble of a packet. Modifying the register FIFOTHR of the CC1101 transceiver while receiving a packet lets us manually readjust the attenuation in three steps (6dB, 12dB, 18dB), hence lowering the resulting level of the LOS signal to be demodulated. This solution limits all modifications to the receiver while the sending node still can use maximum transmission power and no additional information exchange is required. After enabling this feature the localization accuracy of our system increases significantly, especially in indoor situations where the distance to the reference nodes is likely to be small. This can be seen by comparing Fig. 4 with Fig. 5. Fig. 5 shows massive deviations with up to 50m if the distance to the anchor gets smaller than 10m. In 4 it is shown that the near-field deviation is not bigger than 10m when we dynamically adjust the attenuation of the receiver.

F. Localization Experiment

As a first localization experiment we used three reference nodes to estimate the position of one mobile node moving along a given path in our office building. The actual path (black line) and the position of the anchor nodes (the red dots) can be seen in Fig. 6. We used the AML [18] algorithm for this experiment which delivered better results than normal trilateration. Blue dots mark the estimated location of the mobile node. Throughout the experiment more than 12000 measurements were conducted and only 168 measurements were invalid. The deviation to the real path lies between 4m and 7.5m whereas the dispersion of the position with 7.5m turns out to be quite acceptable in contrast to the measurement resolution of the hardware.

As can be seen in Fig. 6 the results worsen if the node gets closer to anchor 1 and 3. A possible reason for this behavior is the decreased performance of our system in the near field as described in V-E and the not ideal layout of the anchor nodes with reference to the actual path of the mobile node. Furthermore, the points plotted represent unfiltered raw data and could be significantly improved by using some sort of Kalman filter or particle filter [19] [20].

In the future we also plan to carry out more experiments with additional anchors to cover a larger area and to achieve a higher localization accuracy with more sophisticated localization algorithms.

VI. Conclusions and Outlook

Our experiments showed that our proposal has some great advantages to common methods for range determination in WSNs without special hardware, especially to RSSI based methods. We also showed that we can compete with special hardware which is used in several installations today. We propose our work as a generic solution for range measurements in existing WSNs or WSNs where the use of special hardware is not possible.

Drawbacks of our solution are the high use of bandwidth which blocks actual communication between the sensor nodes. Due to the high bandwidth use and repeated radio communication the method has a very big energy footprint.

More sophisticated statistical approaches are needed to lower the used bandwidth by fewer ranging packets which would also be used to overcome the high energy use of the ranging method.

In a first approach we will implement our method on a hardware where both transceiver and microcontroller use a shared clock source and therefore eliminate some of the core jitter effects.

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