LOSNUS: Ultrasonic Indoor Locating for Numerous Static and Mobile devices

Gerhard F. Spitzer, Herbert F. Schweinzer

***Abstract*— In the past years a lot of research has been conducted in the field of ultrasonic location systems. Usually systems use time of flight measurement of the ultrasonic signal to determine the distance between transmitters and receivers. Mostly indoor location systems are used for tracking of mobile units. However, device location is getting growing importance in integration of numerous static sensor/actuator devices in WSN and in the evaluation of sensor array data. The high accuracy (≤ 10 mm) and a locating rate up to about 10 cycles/s of the ultrasonic indoor location system LOSNUS presented in this paper supports both locating of static devices and tracking of mobile devices. The principle of operation and the design of the transmitting system, realization elements of receiver nodes, and a location server calculating node locations by TDoA algorithms are presented in this paper. Clock error, quantization noise, and the influence of transmitter delay on echo suppression are crucial points discussed in detail.**

***Index Terms*— ultrasonic location system, indoor GPS, time difference of arrival, 1-bit correlation, time of flight**

I. Introduction

In the past years a lot of research has been conducted in the field of ultrasonic location systems [1-6]. Usually systems use time of flight (ToF) measurement of the ultrasonic signal to determine the distance between transmitters and receivers. Indoor location systems are mostly used for tracking of mobile units. However, the device location becomes growing importance in integration of numerous static sensor/actuator devices in WSN and in the evaluation of sensor array data. Location information can also be used for security and maintenance. The key features and crucial points of location accuracy of the ultrasonic location system LOSNUS (Localization of Sensor Nodes by UltraSound) are given attention, followed by a detailed description of the test system. For comparison location estimation with three different analytic time difference of arrival (TDoA) methods are presented in the measurement results.

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II. Related Work

A. Bat system

The bat system [2] is an active location system used for context-aware applications. A typical context aware application must know the location of moving equipment and users, as well as the equipment's capabilities and network structures. Small transmitters called Bats with a unique identifier are carried by users or are attached to moving devices. The receivers are placed at a known position near the ceiling. A single identifier is broadcasted by the base station and causes the corresponding Bat to transmit a short uncoded ultrasonic pulse. The receivers are reset by the base station via a wired network and record the time of arrival of the Bat's ultrasonic signal. The position of the object is determined by using a multilateration algorithm. Before a new measurement begins, the base station waits until the ultrasonic signal has died out in order to achieve correct distance measurements. The location accuracy is about 3 cm.

B. High Performance Privacy Oriented location system

In the "High Performance Privacy Oriented location system" of [1, 3] wideband transmitters are placed at known positions just below the ceiling, which transmit their coded signal simultaneously at well-defined times. The receiver is attached to a mobile device or worn by a user. Each receiver has knowledge of the transmitter positions and is able to detect the ultrasonic ranging signal. For each broadcast signal a unique gold code [7] is used. The receiver has knowledge of all used gold codes and is able to generate reference signals of the transmitted signals. The incoming signal is correlated with the reference signals and a large peak in the correlation sequence is interpreted as successful detection. For comparison the position is calculated with trilateration or pseudo trilateration. The ultrasonic signal structure makes a simultaneous transmission of the various broadcast signals possible, thus allowing high sampling rates. Additionally, it allows for the system's high noise immunity.

C. Cricket

Regarding privacy protection and data security, cricket [4] is a further decentralized system. It is a very economical system for mobile applications and can be easily installed. The system works with a random transmitted RF beacon for communication and the corresponding ultrasonic signal for range finding. The receiver named listener receives both signals and uses the difference in the arrival time to calculate the time of flight. The RF beacons are transmitted randomly, making them statistically independent and prevent persistent collisions. For the distance measurement a mono-frequent ultrasonic signal of 40 kHz is used and the position of the listener is determined by trilatation. The signal is very sensitive to echoes and multipath propagation. The achieved accuracy lies between 5 and 25 cm [5].

D. Low Cost Indoor Positioning System

An economical alternative is the "Low Cost Indoor Positioning System" of [6]. This system uses 4 transmitters mounted in the corner of the ceiling which are synchronized with an RF signal (RF ping). Ultrasonic chirp signals of individual transmitters are shifted with precise timing in order to prevent any overlapping of the received signals. The determination of the position is made using trilateration, whereby one distance measuring is additionally carried out to compensate for any occurrences of a lost signal. Although this system is very economical it is slow and at the cost of a low sampling rate which strongly reduces the position accuracy of mobile objects.

III. Key Features of the US Locating System LOSNUS

The ultrasonic locating system LOSNUS is designed for indoor application where high accuracy is needed, e.g. wireless sensor/actuator networks in factory floors or tracking of mobile units. For locating, a permanent transmitter network which allows receiving of at least four different line of sight (LoS) signals at located devices has to be installed in every room. To enable 3D location measurement, the placement of the transmitters has to be arranged in a way that no more than 3 transmitters are in a plane. This is necessary because a time different of arrival method for locating is used. Locating happens periodically with a measurement rate up to 10 cycles per second. The broadcast signals of the individual transmitters are sent successively (Fig. 1) and the delays between individual transmitted frames are at least long enough that overlapping of LoS signals in any receiver location of the room cannot occur. One of the advantages of successively transmitted signals is the cost reduction of the transmitting system, as only one signal generator, one amplifier and a demultiplexer is necessary to control all transmitters.

The broadcasted transmitter signals consist of a nonlinear

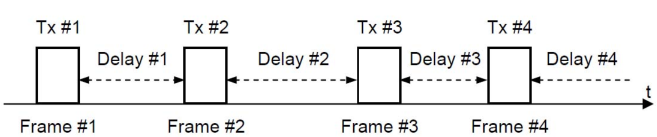

Fig. 1. Signal sequence: Ensures non-overlapping reception of line of sight signals and simplifies design of the broadcast system.

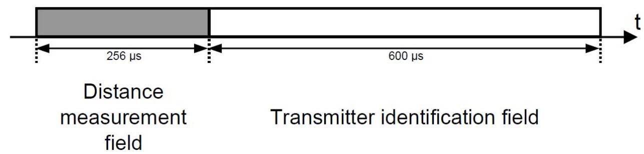

Fig. 2. Signal frame structure: A nonlinear coded chirp identical for all frames followed by an individual coded transmitter identification field.

chirp, which sweeps through a part of the available frequency band, and the transmitter coding for signal identification (Fig. 2). The same chirp signal is used for all transmitter signals to determine the time of arrival (ToA). This part of the signal can also be used in the receiver to restrict recorded data to valid frames, if the receiver correlates the incoming signal with a reference chirp and saves the data only when the correlation result is better than a predefined value. As the position of transmitter coding within the received signal is well-defined with respect to the chirp position, the correlation algorithm for the transmitter recognition is simplified to direct comparisons with the different coding references only. Transmitter coding allows relating the received signals to their individual transmitters. Therefore it is possible to distinguish between LoS signals and echoes which allow reducing the pause between back-to-back transmitting. Using this kind of transmitter identification simplifies the signal processing at the receiver node compared to e.g. gold codes as only one reference chirp needs to be correlated with the received signal.

The receiver node (Fig. 3) is divided into the analog circuit, digital circuit with microcontroller, application module, and wireless communication module. The received signal is conditioned before it is 1-bit quantized and stored in the microcontroller. The processing of the received data depends on the complexity and the task of the receiver node as well as the additional information needed to estimate the position, e.g. transmitter positions, delays between transmitted frames, transmitter identifications and sequence order. Sophisticated nodes with enough computer power can process all received data locally to calculate their own location. Simple nodes may not be able to calculate their position considering computer power or energy consumption. The introduction of a location server, which takes over the computation of the location, is an effective and cost-saving solution. The node sends the received data to the location server and receives the location in return.

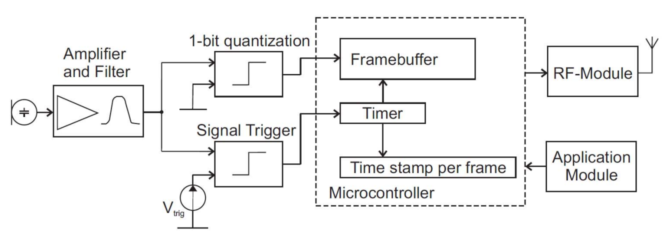

Fig. 3. Block diagram of a sensor node: The received signal is amplified and band-pass filtered before it is 1-bit quantized. The trigger unit, which suppresses signals with low amplitudes, starts data acquisition of US signal. Each US frame contains the bit stream of the received US signal and a time stamp. These US-frames and the application frames are sent via a RF-link to the locating server for further processing.

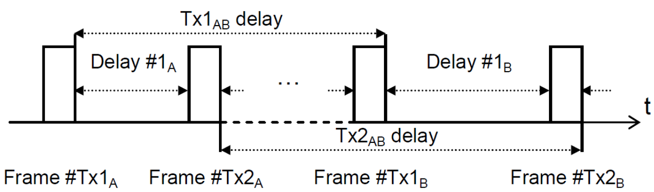

Fig. 4. Sequence of signal transmission: Every transmitter sends two frames with different transmitter coding. The different coding is indicated by the frame index A and B. The delay between two successive transmitted signals depends on the distance between the related transmitters and the signal length.

Node locations can be included in a concept of network security where attacker activities are limited to local areas [8]. This is a completely different situation because the node location has to fulfill the claim of being correct and not faked. Now, a location server is necessary providing a secure location procedure for nodes with encrypted location information [9] and acting as trusted authority where all the additional information for location computing is stored. In this case the node does not even know to which physical transmitter the received ultrasonic signal belongs. This makes it hard for an attacker to falsify location data even when a node is compromised. The pause between transmitted frames, transmitter identifications or sequence order can be varied to make it even harder for an attacker to tamper location information or to calculate the location.

The algorithm of calculating locations needs the following steps: First, a 1-bit correlation [10] is used to extract the time of arrivals. Afterwards, the ToA of one transmitter is subtracted from the ToAs of the other LoS transmitter signals. Further, the appropriate overall transmitter delays are subtracted from the time differences and then multiplied by the temperature compensated speed of sound to get the pseudo distances (distances with a common offset). The position of a node is estimated by using an analytic pseudo trilateration algorithm with four ToA [11]. The gained accuracy is typically better than 10 mm based on a sufficient knowledge of the transmitter coordinates.

IV. CRUCIAL POINTS OF PRECIZE LOCATING

A. *Clock calibration between transmitter and receiver*

System timing is overall defined by the common transmitter clock of the sequence. For receiver clock calibration a second locating sequence (Fig. 4) with a defined delay between the locating sequences is used. Different transmitter identifications allow distinguishing between echoes of the first transmission and the LoS signals of the second transmission of each transmitter. As the delays between transmitted frame pairs $Tx1_{AB}$, $Tx2_{AB}$, etc. are known they can be compared with the delays of the received frames pairs to calculate the clock drift of every receiver. The individual clock drifts are evaluated differently for static and mobile devices. For static devices an outlier of the clock drift means that the ToAs from that transmitter are not trustworthy and are excluded from the calculation of the position. For mobile devices a reference measurement of the mobile device in a stationary state is taken to calculate the clock drift. The clock drifts of the individual transmitters are averaged to compensate for disturbances in the sound propagation. Small variations in the calculated clock drifts from different transmitters of moving devices indicate a stationary state. The mean value and the standard deviation of common clock drifts of static devices are shown Table I. From each transmitter pairs 100 measurements are taken. More work has to be done to confirm that the variations in the clock drift can be used to compensate the movement of mobile devices in the location estimation.

TABLE I
CLOCK DRIFT

	Tx1	Tx2	Tx3	Tx4	Tx5	Tx6
Mean Clock Drift (100) [ppm]	97.0	98.2	10.58	98.6	97.8	99.8
σ (100) [ppm]	15.14	17.08	14.58	15.89	17.03	15.95

B. *Influence of transmitter delay on echo suppression*

An echo is only of relevance when it disrupts a LoS signal at the receiver position. As described in chapter III the signals of different transmitters are broadcasted successive to permit overlapping LoS signals. The travel time of relevant echoes consist of the time of transmission pause (t_p), the ToF of the involved transmitter to the receiver (t_{ToF}), and the signal length (t_{sl}). The signal amplitude decays with 1/distance. Therefore the maximum amplitude ratio (r) between signal and echo is calculated with (1) assuming not being in the near field of the transmitter.

$$r \approx \frac{t_{LoS}}{t_{echo}} = \frac{t_{LoS}}{t_{LoS} + t_p + t_{sl}} \tag{1}$$

When using a 1-bit correlation algorithm, a correlation quality better than 75% which is sufficient for LoS signal detection is always reached when the ratio r is lower than 0.5 and mostly reached when the ratio is between 0.5 and 0.65 [9].

V. DETAILED DEFINITIONS OF THE TEST SYSTEM

A. *Transmitting system*

At the test application the actual transmitting system uses 6 wide band transducers (Polaroid 600) which are mounted on a wall (Fig. 5). The Polaroid transducer has a useable frequency range of 30 kHz to 70 kHz. Lower frequencies are preferred because the opening angle of the main lobe of the Polaroid transducer decreases with an increasing transmitted frequency (30 kHz: opening angle: ±15°; 60 kHz: opening angle ±11°). Therefore, lower frequencies offer a better room coverage. The controller of the transmitting system is a signal generator, which is able to transmit a preloaded sequence of precisely timed frames. Special attention was drawn to the signal generator clock, as this clock is the common time reference for all located nodes within the room (used to calibrate the clock drift of the receivers). The broadcasted sequence consisting of 6 different transmitting frames is less than 50 ms long. The

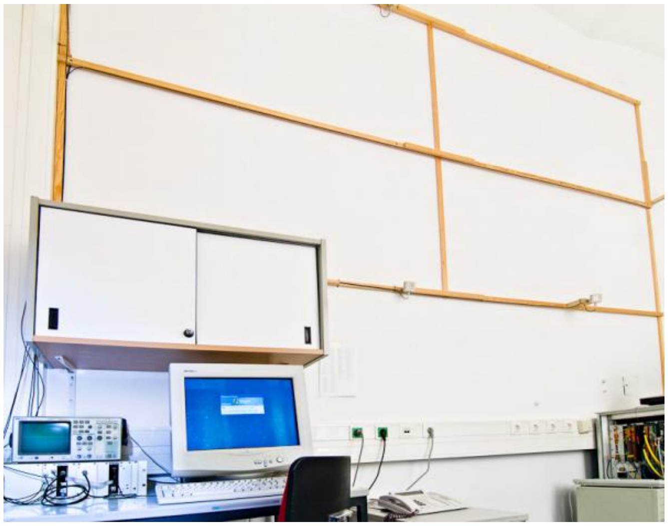

Fig. 5. Transmitting System: Wall mounted transmitters, which are controlled by the transmitter unit (bottom left) consisting of a preloaded arbitrary waveform generator (AWG), a high voltage amplifier, and a demultipexer. The PC is used to load new sequences into the AWG.

measurement cycle is composed of two sequences taking about 100 ms. Each transmitter is used twice with different transmitter coding and a constant offset to each other is used to calculate the clock drift. The delay between back-to-back transmitting frames is defined by the travelling time of the ultrasound signal from one transmitter to the next one plus the signal length.

The transmitting frame is divided into a lead-in field (100 µs), a chirp coded distance measurement field (256 µs) and a transmitter coding field (600 µs) (Fig. 6). For transmitter identification three constant frequencies with a well-defined phase and position in respect to the chirp are used (Table II). The periodic time of the frequencies are chosen in the way that they are multiple of the 1µs sample time and furthermore they have a low cross-correlation in combination with the frequency changeover to the chirp. All constant frequencies start with a phase shift of zero which makes decoding of the transmitter identification easier, as the periodic time of each constant frequency can be calculated without any further information.

B. *Receiver node*

The receiver node for the test system is kept modular with an analogue circuit, a dual comparator, an Infineon XC-164 microcontroller, a temperature sensor application, and an Atmel ATZB-A24-UFL Zigbee module. The node parameters

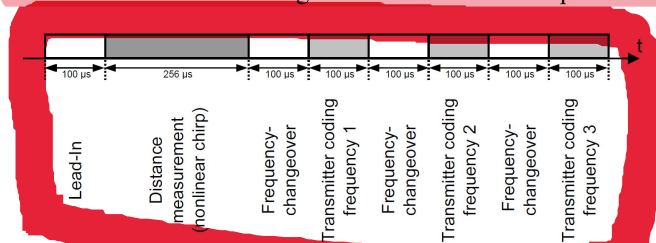

Fig. 6. Signal frame format: A lead-in time for transient effect of the transmitter. Afterwards the distance measurement realized with a nonlinear chirp, which is followed by the transmitter coding of three constant frequencies separated by frequency changeover.

are subject to changes and therefore the prototype node is not yet cost optimized. The analogue circuit consists of an electret microphone MEC-2000, an amplifier and an active band-pass filter. The electret microphone limits the useable frequency range of the Polaroid transducer to 30 kHz – 55 kHz, therefore some tests have been made with a new ultrasonic MEMS sensor from Knowles Acoustics. This sensor matches much better the response curve of the Polaroid transducer. However, more tests a necessary to evaluate this sensor. Afterwards, the received signal is processed through the analogue section (amplifier and band-pass filter) and 1-bit quantized by a comparator. This signal is fed into the synchronous serial interface of the microcontroller. A trigger signal commands the microcontroller to start with the recording of the signal at a sample rate of 1 MHz and adds a local time stamp which marks the beginning of the recorded frame. Although being the basic mechanism of frame recognition, the hardware trigger if applied alone can collect some data garbage. Thus, an analysis of the chirp contained in every frame decides about receiving a proper transmitter frame.

The incoming signal is evaluated with an online 1-bit correlation with a reduced time resolution of 4 µs. Every fourth bit of the incoming data is used in the correlation algorithm. Even though the correlation maximum has a high variation (Fig. 7) caused by the quantization error of the lower data rate and the shorter signal, it can be used to reject most of non valid frames. The full incoming data stream is stored in a 1968 bit long ring buffer (equal of around 2 ms of recording time). When the correlation result is equal or better 44 of maximal 64 (37.5%, where anti-correlation is defined as -100%) the data are copied from the ring buffer into the data frame and sent via the Zigbee communication module to the location server. In the location server the data are further processed and the location is evaluated. A temperature sensor has been added as sensor application. The temperature readings are used to compensate the temperature drift in the propagation of sound. The data from the temperature sensor is also send over the same communication channel. In the actual test state the Zigbee communication is under construction and sensor modules are communicating by wired serial links (Fig. 8).

TABLE II
TRANSMITTER CODING FREQUENCIES

Transmitter	Coding frequency #1	Coding frequency #2	Coding frequency #3
#1	30000	54945	30000
#2	34091	30000	39474
#3	39474	30000	44944
#4	54945	51546	54945
#5	42105	34091	39474
#6	51546	31915	54945
#7	54945	31915	30000
#8	54945	39474	46512
#9	36585	36585	54945
#10	30000	34091	54945
#11	36585	54945	34091
#12	42105	51546	44944

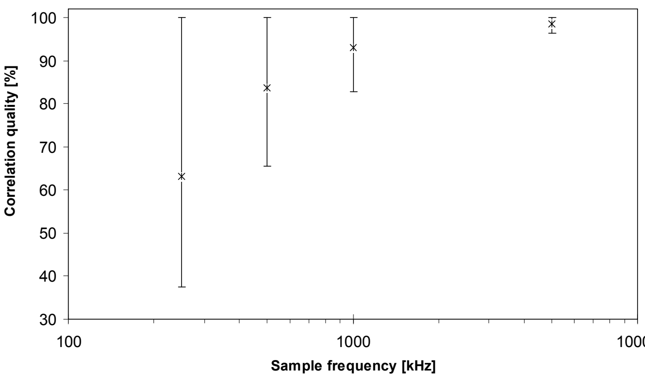

Fig. 7. Quantization error: The diagram shows the relation of the mean correlation quality depending on the sample frequency of 250 kHz, 500 kHz, 1 MHz, and 5 MHz. Two analog chirps with a length of 256 µs are shifted in 1000 steps within one appropriate sample periode and are afterwards 1-bit correlated. The ranges of the maxima of the correlation functions depending on the varying shift values are displayed in this diagram. The cross in the middle of each range shows the mean value of the correlation maximum. Anti-correlation is defined as -100 %.

C. Location server

Node locations are evaluated by a location server which also controls the transmitting sequence. First, the received frames are converted in a unique format and afterwards correlated with a 256 bit reference chirp. For every correlation peak which is bigger than 75 percent the ToA is calculated and the transmitter recognition immediately following the chirp is evaluated. Two methods are contrasted with each other: The transmitter coding field is compared with corresponding reference signals and at least 65 percent of the data bits must match. In the second method the periodic time of the constant frequency sequences within the transmitter coding sequence is analyzed (see Table II). The frequency is obtained by counting the rising slopes within the time window of the frequency and then dividing the number by the time difference between the last rising slope and the window start time. The frequency can be determined with an accuracy of ±2.2kHz and has a maximum standard deviation of 372 Hz of all evaluated frequencies. The advantage of this method is that reference signals are not necessary to extract the transmitter identification of the received frame.

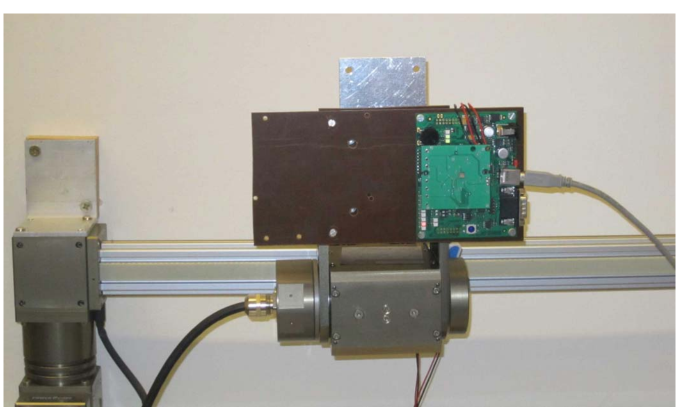

Fig. 8. Ultrasonic receiver node: The receiver node, consisting of an Infineon XC-164 microcontroller Evaluation board and a pluggable analog board, is mounted on a linear axis with 2 additional rotational axes. On the left hand side of the picture the drive and the gear of the linear axis are visible.

After that, the LoS signal arrival times are used to calculate the TDoA by subtracting the ToA of the first transmitter from the ToAs of transmitter two to twelve. A minimal uncertainty of ± 2 µs of the TDoA can be achieved. This uncertainty results from the asynchronous discretization of the analog signal with a sample frequency of 1 MHz. As the transmitted signals are broadcasted with given delays, these delays are subtracted from the TDoAs and then multiplied by the temperature compensated speed of sound and corrected by the clock drift (see chapter IV) in order to obtain the pseudo distances. Finally the location is estimated with a TDoA algorithm. Different TDoA methods [11], two analytic methods and a least square method, are compared in the paper.

VI. Measurement results

Measurement results displaying an example of frame reception and standard deviations of TDoA measurements and clock drift correction by test series are shown in Table III. Six physical transmitters are used in two measurement sequences with different transmitter coding and a constant delay of 50 ms between transmitter pairs. The clock drift is calculated separately for every transmitter pair (considering the individual delays) and afterwards averaged over all transmitter pairs and used to correct the TDoA. Mean values over a series of 100 measurements are shown in the table.

An estimated location with standard deviation is shown in Tables IV - VI whereas Table IV shows the location of a single measurement, in Table V presents 100 pseudo distances averaged from each transmitter, and Table VI shows the average of 100 location estimates. In the location estimation three different TDoA algorithms are used for comparison. The analytic algorithm [11] uses 3 pseudo distances to calculate the location (refer to "analytic algorithm single" in Table IV - VI). Therefore, there are 15 different location estimates with 4 out of 6 transmitters possible. The mean value and the standard deviation of the gained locations are treated in two different ways. First, all 15 locations are averaged (multi-lateration), and second, from each location the length of the position vector is calculated and then the location from the shortest and longest position vectors are excluded

TABLE III
EXAMPLE OF A SINGLE AND AVERAGED MEASUREMENT

Pair	Tx	TDoA [µs]	Clock drift [ppm]	TDoA correct. [µs]	Mean (100) TDoA correct. [µs]	σ (100) of TDoA correct. [µs]
1	#1	0	100	0	0	0
	#7	-5		0.3	0.1	0.71
2	#2	854	120	854.8	855.9	1.25
	#8	848		854.2	855.9	1.22
3	#3	-1,446	100	-1,444.9	-1441.4	1.34
	#9	-1,451		-1,444.5	-1441.8	1.26
4	#4	-2,698	120	-2,696.2	-2,694.6	1.246
	#10	-2,704		-2,696.8	-2,694.6	1.306
5	#5	-1,987	100	-1,984.4	1,981.9	1.51
	#11	-1,992		-1,984.1	1,981.8	1.35
6	#6	384	100	387.6	389.1	1.465
	#12	379		387.9	389.1	1.37
Mean	-	-	106.7	-		

from averaging (shown in brackets in the table). The second algorithm (refer to “lin5 algorithm single” in Table IV - VI) is also an analytic algorithm but uses 4 pseudo distances. The fourth pseudo distance allows a simple computation of the position as the equation system is linearized. As only the pseudo distances of 5 transmitters are used in this algorithm, 6 combinations of location estimation can be generated with the additional sixth transmitter. The six locations are averaged twice, in the same way as the first method. The least square algorithm [12] is an enhancement of the lin5 algorithm which minimizes the square of the distance between the estimated positions and uses all 6 transmitters and pseudo distances as a multi-lateration.

The main influences on the results of the tables are given by variations of ultrasonic signal propagation, room positions of transmitters and their calibration. Signal propagation has the maximum impact on the accuracy of single measurements. Mean values of repeated measurements can be successfully calculated in case of static nodes which mainly reduces uncertainties while system calibration errors are still persisting.

TABLE VI
MEASUREMENT RESULTS
SINGLE MEASUREMENT

	Position			Standard deviation		
	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]
Analytic Algorithm single	1,807.0	-2,757.8	1,345.0	-	-	-
Analytic algorithm mean (15)	1,809.9 (1,806.7)	-2,749.7 (-2,756.8)	1,349.1 (1,345.1)	13.63 (0.89)	34.14 (3.74)	21.22 (3.45)
Lin5 algorithm single	1,807.1	-2,757.9	1,345.0	-	-	-
Lin5 algorithm mean(6)	1,807.2 (1,806.3)	-2,764.3 (-2,757.1)	1,347.2 (1,343.7)	2.74 (0.93)	13.46 (3.85)	6.81 (3.28)
Least square algorithm (6 Tx)	1,806.7	-2,755.1	1,345.6	-	-	-

TABLE V
MEASUREMENT RESULTS
MEAN OF 100 PSEUDO DISTANCES PER TRANSMITTER

	Position			Standard deviation		
	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]
Analytic algorithm single	1,807.0	-2,754.8	1,346.1			
Analytic algorithm mean (15)	1,806.9 (1,807.0)	-2,755.3 (-2,755.2)	1,345.9 (1,345.9)	0.34 (0.08)	0.97 (0.35)	0.66 (0.32)
Lin5 algorithm single	1,807.0	-2,755.1	1,346.0			
Lin5 algorithm mean(6)	1,807.0 (1,807.0)	-2,755.0 (-2,755.1)	1,345.9 (1,346.0)	0.07 (0.02)	0.34 (0.10)	0.17 (0.08)
Least square algorithm(6 Tx)	1,807.0	-2,755,2	1,346.0			

T.ABLE IV
MEASUREMENT RESULTS
MEAN OF 100 LOCATION ESTIMATES

	Position			Standard deviation		
	x [mm]	y [mm]	z [mm]	x [mm]	y [mm]	z [mm]
Analytic algorithm single	1,807.0	-2,754.9	1,346.1	1.75	10.76	4.90
Analytic algorithm mean (15)	1,806.8 (1,806.9)	-2,755.5 (-2,755.4)	1,345.6 (1,345.6)	0.65 (0.29)	2.02 (1.12)	1.60 (1.19)
Lin5 algorithm single	1,807.0	-2,755.1	1,346.0	0.59	3.05	1.66
Lin5 algorithm mean(6)	1,807.0 (1,806.8)	-2,754.9 (-2,753.9)	1,345.9 (1,345.6)	0.08 (0.68)	0.36 (2.81)	0.19 (2.39)
Least square algorithm(6 Tx)	1,807.0	-2,755.2	1,346.0	0.53	2.80	1.68

Position calculation based on single measurement (Table IV) delivers comparable results of the three algorithms if frames of 6 transmitters are received. However in case of the Analytic and the Lin5 algorithms, an exclusion of the two extreme positions is advantageous. If only frames of 4 transmitters are received, the Analytic algorithm can only be applied, if receiving 5 frames, the Lin5 algorithm also.

Calculating positions on base of averaged values of time differences significantly improves the results of single measurements (Table V). The three algorithms applied with or without exclusions deliver position coordinates which are very close together with differences of about ±0.1mm. However, the standard deviations are differing between 0.1mm and 1mm. The Lin5 algorithm displays a smaller deviation which can be explained by already using 4 time differences in position calculating and averaging afterwards only few different position results. In this case, both the Analytic algorithm single using 3 pseudo distances and the Lin5 algorithm single using 4 pseudo distances deliver comparable good results.

In Table VI results of an alternative approach are given. Location estimates are individually calculated from pseudo distance of the locating cycles and averaged afterwards. Mean values of positions can be continuously improved by this method. The example of calculating the Analytic algorithm single using 3 pseudo distances shows this improvement. The mean of 100 locations delivers about the same results as in Table V, although the standard deviation of the y-coordinate exceeds 10mm which shows a strong dependency on the variation of the data. The standard deviations display the “stability” of the algorithm. Here, the least square delivers similar results as the Lin5 single and the Lin5 mean shows an eye-catching dependency on excluded location estimates.

To sum up, mean results of 100 locating cycles of the three algorithms are very close together. Considering a signal reception of four to six frames, the Analytic algorithm is well suited for all these cases. Thus, the application of the Analytic algorithm seems to be a good choice overall.

VII. CONCLUSION

This paper has reported on the key feature and the design goals of the ultrasonic location system LOSNUS. The crucial points: receiver clock calibration and influence of transmitter delay on echo separation are discussed in detail. Measurements results of an estimated location are presented with tree different TDoA algorithm for comparison. Future work includes completing the new receiver node, setting up the ZigBee network and developing a method of motion compensation of mobile devices in the location estimation.

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