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A comprehensive approach for optimizing ToA-localization in harsh industrial environments

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Abstract— **Real-life industrial environments pose a challenge for today's radio-based localization systems, as the radio channel is highly affected by the multiple interference present in the environment. Therefore, this paper presents a solution for generating Weighted Multilateration Position Estimation based on the RSSI (Received Signal Strength Indicator) for ToA (Time of Arrival) ranging measurements to enhance the fault tolerance, reduce the self-interference of the ranging system and finally enhance the accuracy of the position estimation. A coordinate descent algorithm for optimal anchor placement is demonstrated in this paper, which is based on results of 3D ray tracing. The applied 3D environment model is highly sophisticated, as it was generated by 3D laser scanning for gauging. In a final optimization step, power level adjustment is shown to further enhance the accuracy of the localization system. Concluding, a performance evaluation based on simulations, numerical optimization and experimental measurements in the industrial target environment will demonstrate the improvements of our comprehensive approach in terms of accuracy and robustness.**

Keywords-indoor localization, weighted multilateration, optimal anchor positioning, power management, self-interference

I. INTRODUCTION

Mobile node localization in harsh industrial environments is still a challenging topic for today's off-the-shelf localization solutions. The IEEE802.15.4a standard is a promising technology, due to new physical layer implementations based on Chirp Spread Spectrum (CSS) and Ultra Wideband (UWB). By utilizing a higher bandwidth, Time of Arrival (ToA) measurements provide a sophisticated approach, because the signal edge can be detected more precisely due to the inherently fine delay resolution. But the accuracy is vulnerable to the circumstances of the application scenario caused by the propagation effects of the signal, especially multipath fading and shadowing effects.

This paper demonstrates iteratively how to optimize the performance of ToA localization systems for applications pertaining real-life industrial environments. Therefore, the following optimization steps are executed:

1. Performance tests of a Chirp Spread Spectrum (CSS) ToA localization system specify the impact of the prevalent circumstances of the environment on the localization accuracy.
2. The combination of the two ranging methods - ToA and RSSI - is robust to dynamic changes in the environment, which occur by moving persons or stock. Therefore, a weighted multilateration method is applied.
3. Although geographic anchor node positioning has a major impact on the performance of localization systems, not many solutions for optimal anchor positioning are available. Therefore, a coordinate descent algorithm, described in this paper, makes several claims for finding an optimal geographical anchor distribution
4. A method for system calibration in terms of transmission power is shown to mitigate self-interferences.

In the end we demonstrate that the localization accuracy can be enhanced by more than 75% by applying the technologies evaluated throughout this paper.

The major scientific contribution of this paper is a comprehensive approach for optimizing the performance of indoor localization systems, as there are still no solutions available that deal with an application in harsh industrial environments. The work is part of a research project being carried out with Germany's largest steel fabricator ThyssenKrupp Steel Europe (TKSE). They will install the proposed solution to increase the safety of the factory employees in cases of emergency. The developed system is integrated in a gas sensor network, which consists of stationary and mobile equipment. Hence, not only factory employees, but also first responders profit from this solution, as they do not have to carry additional devices for navigating through the incident scene. The localization tag is integrated in the gas sensor, which has to be taken anyway. This solution for first responder navigation will lead to an increased self confidence and reduced time for reaching the incident scene, as industrial environments are often built in a convoluted and confusing manner.

After presenting related works in Section II, the application scenario is described in Section III, before the major contributions of this paper are presented:

- Performance evaluation of a ToA CSS-based localization system in a real-life industrial scenario (Section IV)
- Sophisticated modeling approach combining a 3D scenario model and ray tracing for deriving area-wide localization accuracy (Section V)

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- New localization scheme for ToA utilizing the RSSI for weighting the estimated distances (Section VI)
- New algorithmic approach for an optimal anchor node positioning (Section VII)
- Calibration of transmission power of anchor nodes for reducing self-interference effects (Section VII)

The paper then ends with conclusions and an outlook to future work.

II. RELATED WORKS

According to the description in [1], the problem of localization for wireless sensor networks is divided into three components: *distance estimation*, *position estimation* and *localization algorithm*. Furthermore, a detailed survey on different approaches and techniques for indoor localization is given in [2]. A comparison between different localization systems highlights the tradeoff between accuracy, complexity, robustness, scalability and costs. As a concluding remark, the authors state that future trends include a combination of distance estimation methods and optimal geographical anchor positioning.

In [4] ToA distance estimation methods for the IEEE 802.15.4a standard are proposed, which utilize the so-called Symmetrical Double-Sided Two-Way Ranging (SDS-TWR) protocol for non synchronized sensor networks. Further extensions are sought for a one-way ranging method [5], which delivers equivalent performance with a better scalability characteristic. But obviously ToA delivers very precise distance approximation only in Line-Of-Sight (LOS) conditions; in Non-Line-Of-Sight (NLOS) conditions, the performance decreases as the Time-of-flight is enlarged by the longer propagation path. Therefore, [6] presents a survey for handling ToA range estimations in NLOS environments.

[7] presents an error compensation scheme especially for CSS-based ToA localization systems. Here, measurements for the real system show good performance for non-multipath environments. For the evaluation of multipath environments, the authors utilize a simplified 2-ray-model.

In order to optimize the distance estimation, cooperative methods are needed. For instance, [8] presents an RSSI-based system utilizing the Link Quality Indicator (LQI) as a second metric for classification of the measurement. Furthermore, [9] proposes a weighting scheme for multilateration position estimation depending on the distance between mobile tag and anchor node.

It is also stated in the literature [2], that positioning of anchor nodes is a valuable task to optimize the performance of the localization system. [10] proposes a motion coordination algorithm to find the optimal anchor distribution based on the Cramer-Rao Lower Bound. In another approach, the algorithm RELOCATE is presented, which depends on minimizing the Position Error Bound (PEB) [11].

The authors of [12] propose the application of a genetic algorithm for optimal sensor placement. Furthermore, [13] presents an approach for optimal sensor placement for optimizing the network coverage based on the coverage of a single sensor node.

Transmission power control is also a crucial topic for wireless sensor networks [14], but an application to localization systems is - to the best of our knowledge - not present in the literature.

All presented related works have not been vested on realistic topologies and radio propagation models.

III. TARGET SCENARIO: INDUSTRIAL PLANT

The investigated industrial scenario is depicted in Figure 1. The basement of an industrial production plant is used for energy supply for the upper production plant. Here, multiple boilers are heated with gas. Thus, a complex gas-pipe infrastructure is present.

As high temperatures are needed for the steel fabrication process, by-products of the combustion process like CO (carbon monoxide) may occur. In order to ensure the safety of the production plant and especially the factory employees, the area is flooded with CO_2 (carbon dioxide), if critical CO concentrations occur. As a result, sight is limited due to dispersed dust and condensation processes. Localization of employees, who were not able to leave the hazard zone in time, is absolutely mandatory, as the CO_2 extinguishing system also mitigates the oxygen supply. Thus, the rescue process can be optimized if localization is possible with a high degree of accuracy.

Figure 1: Industrial Application Scenario at ThyssenKrupp Steel Europe

As depicted in Figure 1, the construction of the scenario is convoluted and complex. The major challenge for an RF-based indoor localization system is to mitigate the interference caused by metallic water- and gas pipes.

The considered scenario consists of a *7m x 26.5m* supply unit in the basement. Eight fixed gas sensors equipped with RF modules are going to be placed in the scenario as anchor points. Additionally, reduced functional anchor nodes may be placed freely in the scenario. The exact number needed for granting the localization accuracy is described in Section VII.

As the structure of the scenario is very complex, we carried out a 3D laser scan to generate a digital image (depicted in Figure 3), which can be applied in the raytracing simulation for wireless network planning. In order to fulfill the network planning process with a high accuracy, exact gauging of the application scenario is mandatory in this case.

IV. ToA CSS-BASED LOCALIZATION SYSTEM

The following measurements are based on the Nanotron ToA Real-Time Localization System (RTLS) [15], which uses CSS technology and utilizes an 80 MHz channel in the 2.4 GHz band. The physical layer is standardized in IEEE 802.15.4a-CSS as an alternative implementation. The distance between two nodes is estimated by the SDS-TWR (Symmetrical Double-Sided Two-Way Ranging) protocol [4], which avoids the need for synchronous network nodes and also enhances the robustness, as the distance estimation is accomplished twice.

For position estimation, multilateration is used. With an anchor deployment of at least four nodes, position estimation is possible.

For the evaluation of the performance in the industrial environment, we installed four anchor nodes, which cover the half of the application scenario. Several positions in the scenario have then been evaluated in terms of localization accuracy.

Three exemplary results are shown in Figure 2. Obviously, the deviation is higher than expected from previous studies on ToA localization [10]. Due to the presence of metal, multipath fading clearly impacts the results. It can be seen from the measurements that the deviation varies from 5m to 1m accuracy. The variation of the position estimation is due to variation in the radio channel and the hardware of the receiver aperture. This effect has also been observed in previous studies for static measurement setups [5][7]. Through further evaluation of the measurements it has been clarified that connection losses are not the cause of fluctuating localization accuracy.

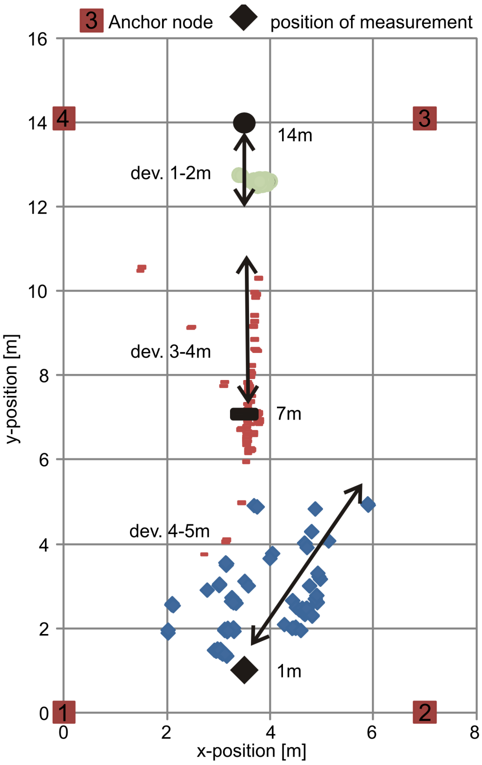


Figure 2: Influence of multipath fading on the localization accuracy for three exemplary measurement points in the industrial scenario

As performing measurements is very demanding work and especially because an evaluation of the entire scenario is not possible, a sophisticated modeling approach is described in the following section, which is capable of deriving the localization accuracy for the entire set. This step is mandatory, as the localization accuracy must be granted for safety-critical application scenarios.

V. MODELLING APPROACH

The goal of the modeling approach is a precise evaluation of ToA localization accuracy for the entire application scenario. Once this is achieved, the evaluation of different anchor positions and localization algorithms is possible without time-consuming measurements.

A. 3D Laser Scanning of the Application Scenario

In a first step we executed a 3D laser scan [16] of the entire scenario. This scan is highly precise with a maximum deviation of 0.1mm. The scan delivers so-called point clouds, which are the sample points of the laser.

B. CAD Modeling of the Scan Data

The sampling points of the laser scan are then imported into a CAD modeling tool, where the infrastructure can then be re-drawn manually. An automatic solution is not available for such complex scenarios. The resulting CAD model is depicted in Figure 3.

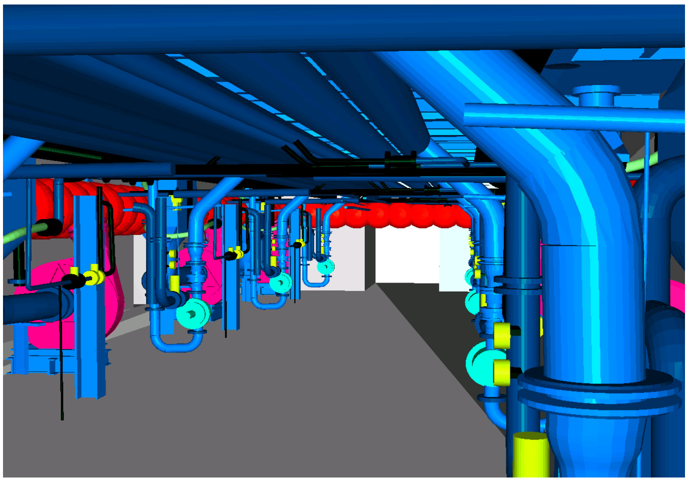


Figure 3: CAD model of the industrial scenario

C. Radio Channel Modeling based on a generated CAD Model

The 3D environment model is then imported in the Radiowave Propagation Simulator (RPS) [17], where it is parameterized with relevant material-reflection characteristics, e.g., for concrete and metal. In a second step, 134 nodes are placed at the possible anchor positions at the outer walls at a distance of

0.5m and a height of 1.8m. The evaluated scenario is divided into 0.5m squares for the receiver nodes.

The transmitters are equipped with dipole antennas transmitting at a transmission power of 0dBm at a center frequency of 2.45GHz and a bandwidth of 80MHz.

The simulation of the radio channel based on relevant node and receiver positions generates the impulse response for every receiver and transmitter, delay spread and RSSI distribution.

D. Derivation of Distance from simulated Impulse Responses

Based upon the results of the radio propagation simulation, the resulting localization accuracy is calculated. Therefore, distances from assumed anchor nodes to each receiver are calculated using the impulse response.

An example for the impulse response - captured in the application scenario (see Figure 4) - depicts the effect of multipath fading.

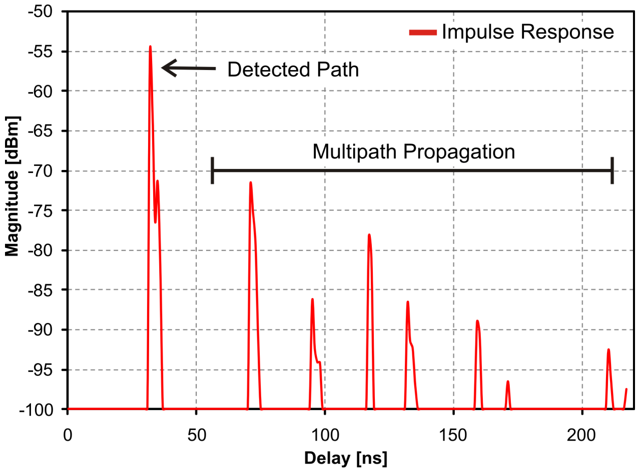


Figure 4: Exemplary impulse response in the application scenario

We assume that the receiver detects the path with the highest RSSI value and not necessarily the first incoming path. This reflects the behavior of the Nanotron system. The distance d_n between the anchor and the mobile node is then derived by the delay of the detected path and the speed of light as follows:

$$d_n = \tau_n \cdot c.$$

where τ_n is the measured delay and c is the speed of light.

E. Position Estimation

From the distances between anchor nodes and mobile nodes and the knowledge of fixed anchor positions, the position is estimated by multilateration [3].

The position is then compared to the real receiver position and the error in localization is quantified.

As the radio propagation results for 134 possible anchor nodes are available, investigations for different node constellations and localization algorithms can now be performed.

At this point it should be noted that the variation of the receiver aperture is neglected, as we want to base our calculations on the radio propagation characteristics. By doing so, the modeling approach is not restricted to a specific localization system, but moreover gives an insight into the behavior of different localization algorithms and node constellations.

VI. WEIGHTED POSITION ESTIMATION ALGORITHM COMBINING TOA AND RSSI MEASUREMENTS

Self-interference - in terms of distance measurements with a high deviation caused by influences on the radio propagation characteristics - can significantly harm the accuracy of position estimation. This effect is depicted in Figure 6. Distance measurements generated by anchor nodes in higher distance to the mobile tag, are often influenced by multipath fading and shadowing effects, and therefore harm the resulting localization accuracy. By using traditional multilateration, each estimated distance has the same significant impact on the position estimation, as no quality or weighting indicator is taken into account.

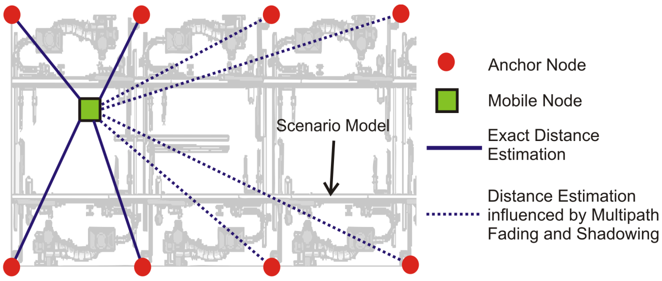


Figure 6: Effect of self-interference

The goal of this new approach is to weight the distance measurements accordingly to their quality, in order to reduce the influence of poor distance estimations. Therefore, the RSSI is evaluated as a quality indicator.

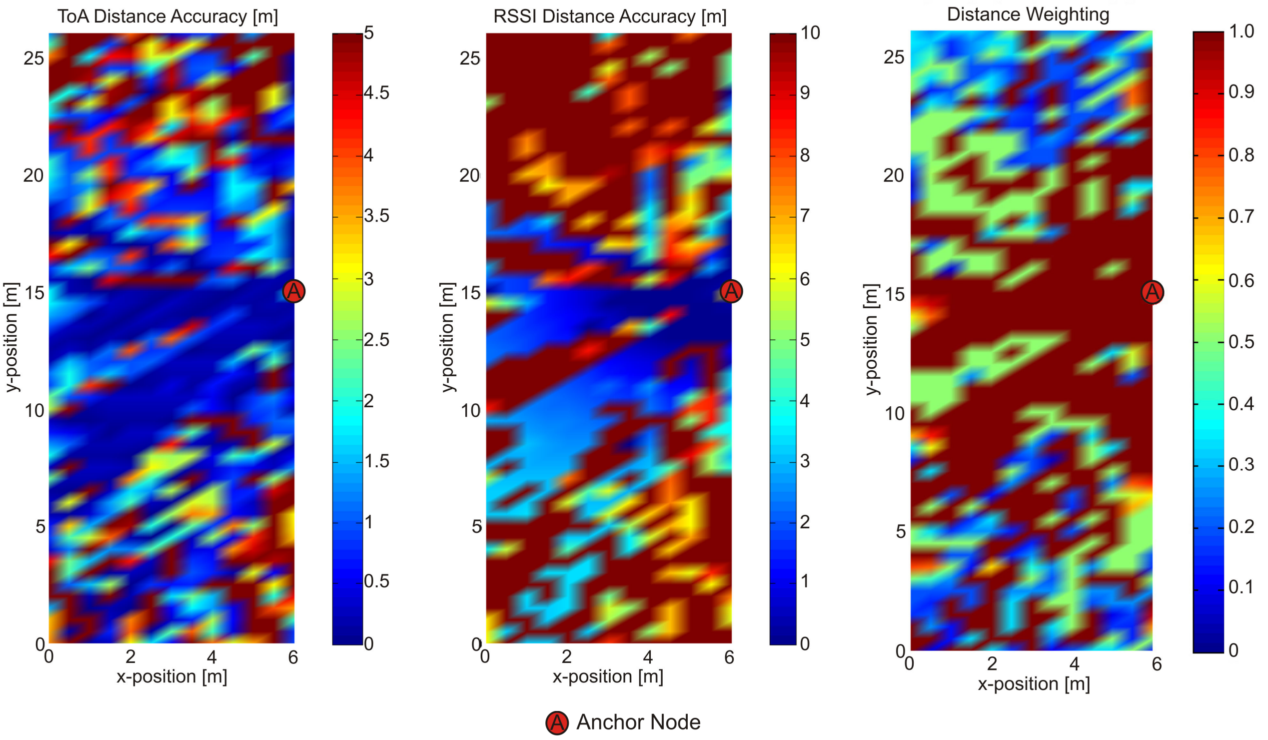
The principle is demonstrated in Figure 7. The deviation of the ToA distance estimation for one possible anchor node is shown in Figure 7a. It is obvious that some regions in the scenario are heavily influenced by shadowing and multipath fading effects. It is also visible that the ToA measurement expresses the propagation delay, which is influenced by multipath propagation.

Furthermore, Figure 7b depicts the RSSI distance estimation for the same anchor node. The regions, which are affected by multipath fading, also show high deviations. It can be seen that the RSSI is even more vulnerable to the radio propagation effects compared to ToA.

A. Calculation of weights:

The idea of the weighting approach is to evaluate both metrics: ToA and RSSI distances. A node which receives distance measurements from at least four anchors classifies this information by comparing the ToA distance estimation with the potential RSSI distance. Our experiments have shown that differences up to 100m are common for the worst case. The weight w_d for anchor d is therefore specified by the following equation:

$$w_d = \frac{1}{\left\lceil \frac{d_{RSSI} - d_{ToA}}{10} \right\rceil}$$



(a) (b) (c)

Figure 7: ToA and RSSI distance accuracy [m] and resulting distance weighting for one exemplary anchor node

where d_{RSSI} and d_{ToA} are the estimated distances of RSSI and ToA respectively. Assuming that w_d is in the range between

$$0.1 < w_d < 1,$$

measurements with high deviation are weighted low. If the difference between RSSI and ToA measurement is less than 10m, the distance estimation is rated high with a factor of 1. The weight is reduced if the difference between RSSI and TOA distance rises. Reducing w_d to zero is not leading to the desired result, as the multilateration might get unstable due to the geometric adjustment of the regarded anchors.

An example weight distribution is depicted in Figure 7c. By comparing the results of Figure 7a and b, the ToA distance values with a high deviation are rated low. It is also visible that a good RSSI distance estimation is correlated to a good ToA distance estimation and hence the weighting factor is near or equal to one. Comparing this approach to [9], a more adaptive weighting mechanism is defined, as this approach does not rely on the evaluation of fixed distances. Moreover, the scenario-specific radio propagation effects are also taken into account and the system is able to react dynamically to changes.

B. *Adaptation of Multilateration*

The position estimation using multilateration can be weighted accordingly to [9] and results in the following equations:

$$A = \begin{bmatrix} 2w_1^2w_2^2(x_1 - x_2) & 2w_1^2w_2^2(y_1 - y_2) \\ 2w_1^2w_3^2(x_1 - x_3) & 2w_1^2w_3^2(y_1 - y_3) \\ 2w_1^2w_4^2(x_1 - x_4) & 2w_1^2w_4^2(y_1 - y_4) \end{bmatrix}, x = \begin{pmatrix} x_1 \\ y_1 \end{pmatrix}$$

$$b = \begin{bmatrix} w_1^2w_2^2(r_1^2 - r_2^2 + d_{12}^2) \\ w_1^2w_3^2(r_1^2 - r_3^2 + d_{13}^2) \\ w_1^2w_4^2(r_1^2 - r_4^2 + d_{14}^2) \end{bmatrix}$$

where r_i is the distance between $Anchor_i$ and mobile tag, d_{ij} is the distance between $Anchor_i$ and $Anchor_j$, and (x_i, y_i) is the position of the anchor. The detailed derivation of multilateration can be found in [3]. The problem is still equivalent to the original solution $x = (A^TA)^{-1}A^Tb$ and can be solved if the rank is higher than 2.

C. *Results and Evaluation*

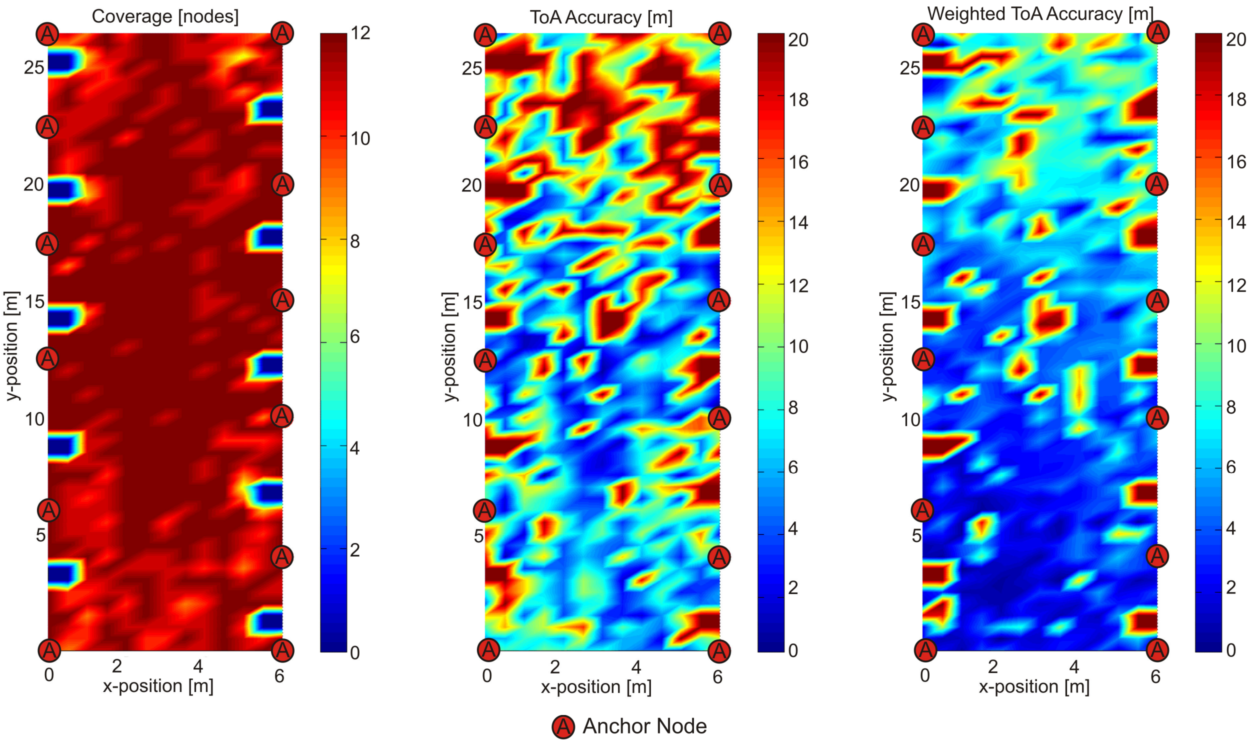
The results of the performance evaluation - accomplished by using the modeling approach described in Section V - are depicted in Figure 8.

We divided the scenario into discrete squares of 0.5m. The position error for one square is described by

$$PE = \sqrt{(x - \hat{x})^2 + (y - \hat{y})^2}$$

where x, y is the real and $\hat{x}, \hat{y}$ is the estimated position.

The Mean Position Error (MPE) for the whole scenario can be derived by the following equation:



(a) (b) (c)

Figure 8: Evaluation of a 12 anchor node scenario (a) Number of nodes in range (b) Accuracy of ToA Localization (MPE=8.445m) and (c) Accuracy of weighted ToA (MPE=5.067m)

$$MPE = \frac{\sum_{i=1}^{n} PE}{n}$$

In a first step, 12 nodes are naively distributed in the scenario. It can be seen from the coverage plot in Figure 8a that the setup provides good connectivity from 10 up to 12 nodes in range at an assumed transmit power of 0dBm. Furthermore, it is obvious that some parts of the scenario are not covered due to the constructional influence of the plant. Figure 8b shows the calculated accuracy of ToA and Figure 8c the Weighted ToA method.

Comparing the result with the Weighted ToA approach, it can be seen that the weighting enhances the performance with a gain of more than 35% in this anchor setup. It should be noted at that point that the maximum PE is restricted to 20m. By comparing this value to the size of the scenario, localization is not possible if the MPE is assumed to be higher.

Obviously, ToA does not perform as well in industrial scenarios as expected from previous studies. The results are even worse compared to the experimental measurements of Section IV as more nodes are in range, which cause self-interference.

In the next step, the effect of self-interference is analyzed in more detail. Obviously, by adjusting the transmission power level of the anchor nodes, the size of the coverage regions can be influenced. Hence, anchor nodes can be restricted to a local area of influence, if the transmission power is reduced to a minimum.

Figure 9 quantifies the effect of self-interference and shows the impact of the transmission power on the performance of ToA localization without weighting. Assuming the same anchor node constellation, the accuracy is decreased if the transmission power of the anchor nodes is enhanced. A local minimum is visible for a low transmission power of -27dBm.

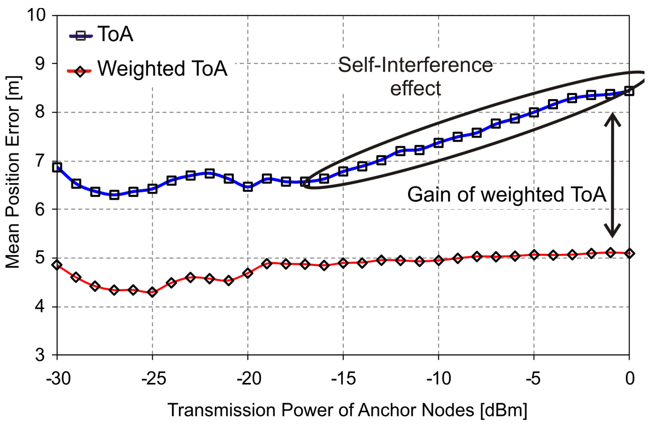


Figure 9: Effect of self-interference for varying transmission power

The Weighted ToA approach shows a linear behavior if the transmission power and therefore the grade of self-interference is enlarged. Again, a local minimum is reached at a low transmit power level, but the influence of higher transmit power and thus corrupted distance measurements is mitigated due to the distance weighting.

Thus, it can be concluded that a simple extension can enhance the performance and the robustness of a ToA localization system immensely just by taking into account RSSI measurements, which are available with the reception of a ranging packet.

VII. OPTIMAL ANCHOR PLACEMENT

As a next optimization step, we analyze an optimal geographical positioning of anchor nodes. The optimized anchor deployment is based on the evaluation of impulse responses calculated for every possible anchor and receiver position. In this specific scenario, 134 possible node positions are assumed at the outer walls with a distance of 0.5m. Several tests have been carried out for choosing the optimal anchor constellation such as:

- Choose anchor nodes with highest coverage
- Choose anchor nodes with the lowest mean delay spread, as the ToA localization is vulnerable to multipath fading
- Choose anchors with the highest LOS area in the scenario
- Choose the predefined positions of (gas-) sensors

These simple approaches are not leading the optimal anchor positioning, as the geometric alignment is not optimal for multilateration in most cases.

Thus, our approach takes into consideration the calculation of the mean position error for the whole scenario including all positions where the mobile entity can be located. This is a more generalized approach compared to [11], which assumes the position optimization for fixed agents.

A. Algorithm Description

The developed algorithm is a coordinate descent algorithm, where the MPE is optimized for changing anchor position until convergence. Before the algorithm is started, relevant raytracing data like node positions, impulse responses and RSSI distributions are calculated. The behavior of the algorithm can be divided into 7 steps:

1. Initialize anchor positions:
    - Initialize anchor positions which are optimal for a manual network setup (equidistant positioning)
    - Assume transmission power as minimum

If sensors are integrated in anchor nodes, we assume that sensors are positioned at dedicated points in the scenario to meet the requirements of the monitoring application. Thus, we assume two types of nodes: *Anchors* and *Sensor Anchors*.

2. Calculate the MPE for the whole set by calculating position estimation of multilateration based on distance estimation from the mobile entity to the anchor.
3. Change Position of $Anchor_i \rightarrow Anchor_{i+1}$
4. Calculate and compare MPE with previous calculated. If lower, assume current constellation as optimal
5. Repeat 3.) and 4.) for number of installed anchor nodes until convergence
6. Enhance the transmission power for each anchor node by 1dBm and start recalculation. This procedure is called Transmission Power Level Adaptation (TPLA) throughout this paper.
7. End, if no MPE optimization is achieved and highest transmit power is reached

Figure 10 depicts the flow chart of the developed coordinate descent algorithm.

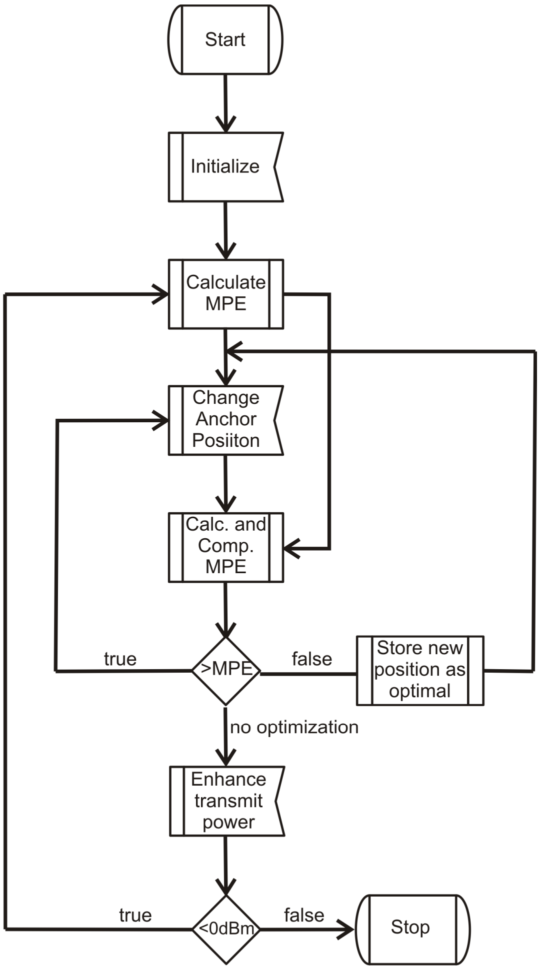
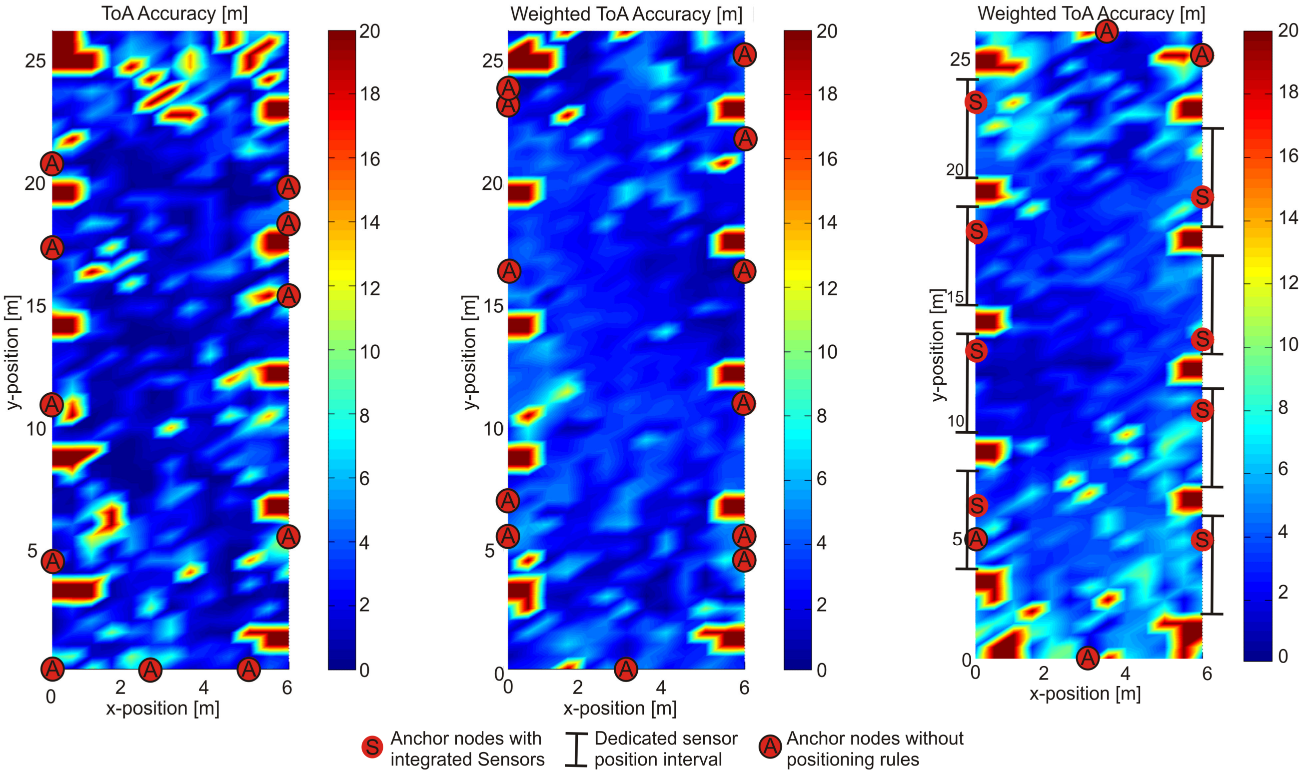


Figure 10: SDL flow chart of coordinate descent algorithm for anchor positioning

The authors want to note that the Transmission Power Level Adaptation (TPLA) delivers more accurate results also for ToA localization. In this optimization step, the transmission power level is adjusted for the whole set, whereas in Section VIII the transmission power is adjusted for each anchor node individually.

B. Predefined Sensor Positions

The system architecture foresees the integration of anchor nodes into gas sensors. These gas sensors have to be placed at predefined distances to the optimal measurement point. As 8 gas sensors are going to be placed in the specific scenario, the coordinate descent algorithm is modified in the sense that these anchor nodes are only able to change their position



(a) (b) (c)

Figure 11: Resulting position deviation after.(a) ToA anchor node position optmization (MPE=2.956m) (b) Weighted ToA anchor node position optimization (MPE=2.876m) and (c) Weighted ToA position optimization including fixed intervalls for sensor positioning (MPE=3.772m)

within a predefined interval, which is defined at 2m around the optimal gas sensor position.

C. Results and Evaluation

The results of the performance evaluation demonstrate that an optimal anchor node distribution strongly affects the performance of the localization system. For a further evaluation, the behavior of ToA and Weighted ToA are compared for optimal anchor node positioning.

The MPE plot for the entire scenario - depicted in Figure 11 - shows the behavior of an optimal node constellation with TPLA for 12 nodes. The MPE is nearly equal for ToA and Weighted ToA (cf. Figure 12 for the exact values), but ToA shows higher deviations compared to Weighted ToA. There are still some positions with a maximum deviation of 20m, which means that localization is not possible in these cases. Weighted ToA moreover shows a smooth behavior without a high number of outliers.

Figure 11c shows the deployment in case of anchor nodes are integrated in gas sensors. A dedicated placement interval is given for each sensor anchor. Comparing the resulting MPE to the free anchor distribution, the accuracy is decreased by around 1m, although the geographical anchor node distribution is similar to Figure 11b.

Figure 12 depicts the behavior for a varying number of nodes with and without TPLA applied for calculated anchor positions.

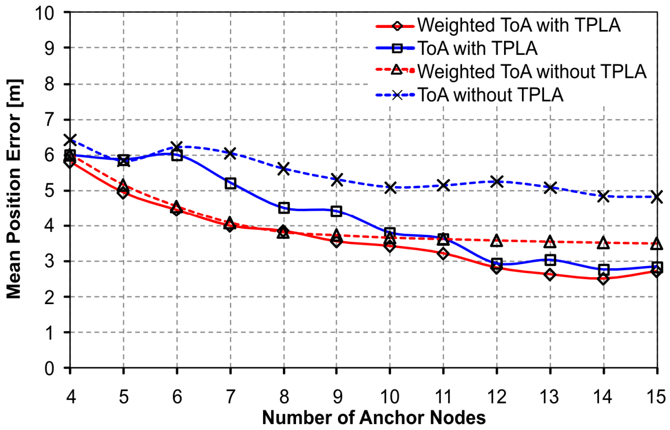


Figure 12: Comparison of MPE for ToA and Weighted ToA for optimal anchor positioning with and without TPLA (transmission power level adjustment)

First we will discuss the results without TPLA. Comparing the results of ToA and Weighted ToA, the MPE shows an improvement of around 1.5m if more than 5 anchors are deployed. In the cases of 4 and 5 anchor nodes, the deviation is smaller as the distance weighting affects the performance if additional measurements are available. An interesting case is the optimal positioning for Weighted ToA. The curve shows a logarithmic behavior for an increasing number of nodes and seems to reach a bound for the MPE, which is not significantly enhanced for more than 10 nodes.

In the next step, the positioning algorithm is executed with TPLA. Comparing the curves of ToA, TPLA mainly affects the performance, as self-interference is reduced. In the deployment case of up to 6 nodes, TPLA does not affect the performance as the anchors have to transmit with a high transmission power for covering the entire scenario. But if the number of deployed anchors is enlarged, TPLA has huge influence. In the case of 12 anchor nodes, the MPE is enhanced by more than 2m.

It can be seen by comparing the curves of Weighted ToA, TPLA also enhances the MPE, but in this case not as significantly as compared to ToA, as Weighted ToA reduces the self-interference effect by the adapted position estimation. Furthermore, if a high number of nodes is deployed, TPLA can further enhance the performance, e.g., by 1m in the case of 13 anchors being deployed.

If a high number of anchor nodes is deployed in the scenario, ToA and Weighted ToA show equal behavior with TPLA. Hence, if the power level is adjusted, the effect of self-interference is reduced and therefore ToA shows improved localization accuracy compared to a fixed power level of 0dBm.

As TPLA reduces the effect of self-interference, we examine a power level adjustment for each anchor node based on the assumed anchor positions in the next section.

VIII. INDIVIDUAL TRANSMISSION POWER ADAPTATION

The previous sections have shown that the accuracy of the localization is mainly affected by self-interference effects. In order to minimize these effects, an accurate transmission power level adjustment for each anchor node is meaningful.

The optimal transmit power evaluation is accomplished by an equal coordinate descent algorithm as described in Section VII, but in this case the anchor positions are assumed to be fixed and the transmit power is varied between -40dBm and 0dBm.

A. *Individual Power adjustment for each Anchor Node*

As depicted in Figures 13 and 14, Individual Transmission Power Level Adjustment (ITPLA) for each anchor node enhances the accuracy of position estimation as the self-interference effect is reduced.

ITPLA is applied on the anchor positions depicted in Figure 11 for ToA localization. The optimization is depicted in Figure 13. Obviously, an accurate power level adjustment enhances the localization accuracy, but is also restricted to the bounds of the optimal anchor positioning. This is why the curves for ToA with TPLA and ITPLA show the same behavior; although another 0.5m gain is visible for ITPLA.

In the next step, ITPLA is applied on the Weighted ToA constellations. A similar effect can be seen compared to the previous findings. The curves show an equal behavior, but the accuracy gain is lower as the Weighted ToA approach is more robust against self-interference effects. An optimal deployment can be achieved with 14 anchor nodes in this scenario reaching an MPE of 2m.

Table I depicts the resulting transmission power of anchor nodes for different node constellations after application of ITPLA. The transmit power is mostly remaining very low, which can be justified by the findings of Figure 9, where a local optimum for position estimation was found at around -27dBm. Some strong anchor positions are configured with higher transmission power. This effect is again an anchor weighting.

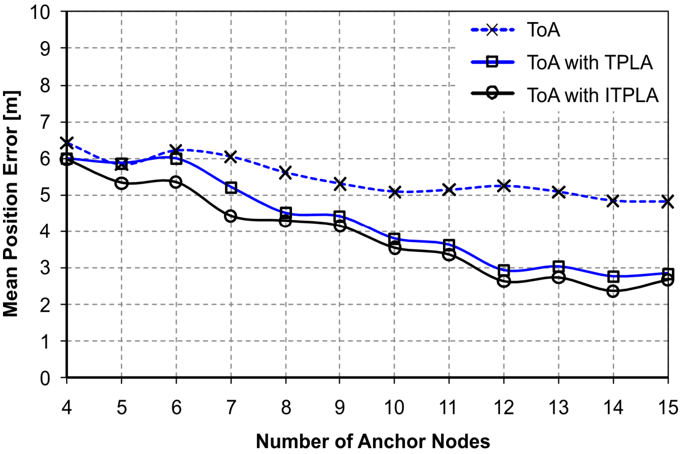


Figure 13: Power level adjustment for ToA anchor nodes

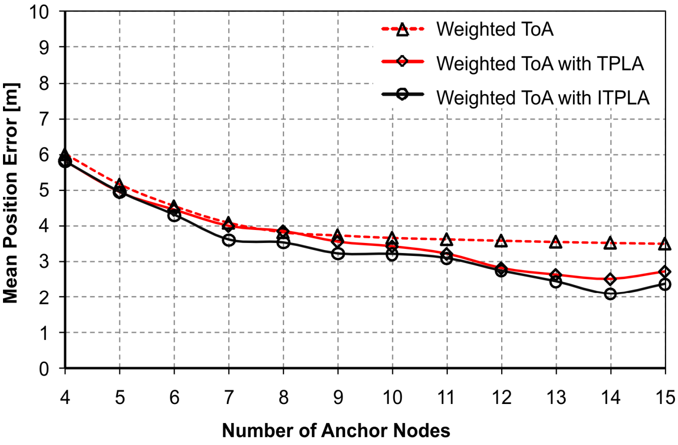


Figure 14: Power level adjustment for Weighted ToA anchor nodes

TABLE I. ADJUSTED TRANSMISSION POWER [DBM] FOR WEIGHTED TOA CONSTELLATIONS

Num. of Nodes	Power Adjustment for Node n [dBm]														
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*
N=4	0	0	0	0											
N=5	0	-7	-25	0	-1										
N=6	-20	-4	0	-12	-13	-27									
N=7	-35	-28	0	-22	-19	-1	0								
N=8	-28	-29	-24	0	-26	-23	-10	-15							
N=9	-31	-27	-28	-27	0	-22	-28	-19	-27						
N=10	-29	-6	-32	-3	-33	-32	-31	-27	-27	-29					
N=11	-29	-25	-34	-26	-23	-26	-27	-29	-1	-29	-27				
N=12	-31	-31	-27	-29	-31	-30	-25	-25	-30	-30	-33	-33			
N=13	-31	-30	-29	-26	-27	-33	-28	-32	-31	-30	-18	-35	-32		
N=14	-36	-33	-27	-28	-33	-31	-23	-32	-24	-34	-33	-30	-33	-37	
N=15	-33	-35	-39	-30	-35	-10	-28	-31	-33	-34	-36	-31	-19	-27	-33

IX. CONCLUSION AND FUTURE WORKS

This paper presents a comprehensive approach for enhancing the accuracy of a ToA-based localization system without making in-depth system modifications. After defining the effect of self-interference, our first proposal - *weighting ToA distance estimations with the RSSI* - has shown performance improvements especially in the industrial application scenario. Furthermore, an optimal anchor placement can mainly enhance the localization accuracy. We have shown that an optimal distribution saves anchor nodes even with granting high localization accuracy. We have also shown that power management is a critical task for localization networks, as a wrongly calibrated anchor node harms the accuracy caused by self-interference effects. The resulting MPE and the gain related to the initial 12 node anchor constellation are depicted in Figure 14. Weighted ToA is always superior compared to ToA in all optimization steps, although transmission power adjustment enhances the accuracy of ToA clearly. By applying all optimization steps, we have shown that a gain of 75% compared to naïve ToA is possible.

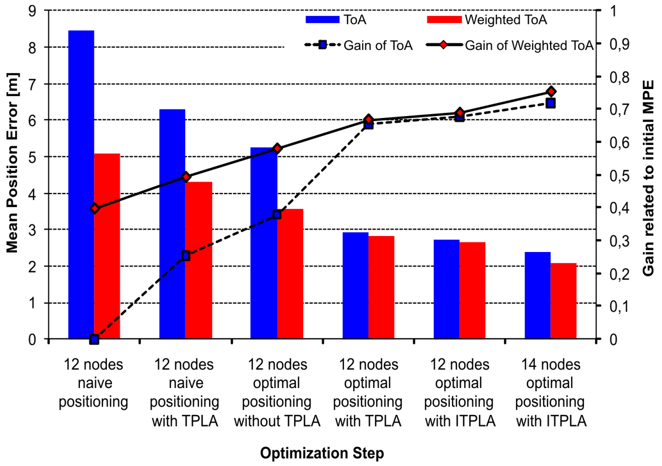


Figure 14: Summary of MPE for different optimization steps and quantification of the gain related to the initial anchor node distribution using ToA

Our future works regard the development of a dynamic transmission power adjustment procedure to recalibrate the localization system according to changing environments or node constellations. Furthermore, a genetic algorithmic approach for optimal anchor node positioning could enhance the performance with less computational costs. It is also intended to evaluate *Multidimensional Scaling* for replacing the traditional multilateration approach.

The procedure for ITPLA bases on the evaluation of the entire scenario. It is not purposeful to regard measurements for the entire scenario to calibrate the system. Hence, in a future step we will evaluate how many measurement points in the scenario are needed to gain comparable results.

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