AWCL: Adaptive Weighted Centroid Localization as an Efficient Improvement of Coarse Grained Localization

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***Abstract*— Localization of sensor nodes is one of the key issues in Wireless Sensor Networks. It is a precondition for a variety of scenarios as well as geographic clustering and routing. A simple approach for coarse grained localization is Weighted Centroid Localization (WCL), which, unfortunately, comes with some drawbacks. Therefore, we present the "Adaptive WCL" (AWCL) algorithm that outperforms the linearly weighted WCL in terms of accuracy. Moreover, AWCL achieves similar accuracy as WCL using quadratic weights, but does not rely on complex calculations like quadratic WCL. The adaptive character of AWCL leads to a small localization failure for beacon communication ranges, exceeding the beacon distance.**

***Index Terms*— Localization, Optimization, WCL, Wireless Sensor Networks**

I. Introduction

Recent technological advances led to the development of tiny wireless devices, which are able to sense the environment, compute simple tasks and exchange data among each other. Interconnected assemblies of such devices, called Wireless Sensor Networks (WSN), are commonly used to observe large inaccessible areas [2]. For the majority of WSN scenarios the collected data needs to be combined with geographic information to make it useful. Moreover, localization in WSN is basis for geographic clustering [7] as well as geographic routing [1][3]. Due to existing limitations in terms of size and energy consumption, local positioning within the network is preferred over utilizing a commercial positioning system like GPS [6]. Therefore, a number of selected nodes know their exact position a priori or get it from common positioning systems. Then, all other nodes calculate their position with the help of these beacon nodes.

The variety of localization techniques ranges from high precision, commonly based on a set of linear equations, to low precision. Bulusu et al. divided location estimation into coarse grained localization and fine grained localization and proposed a coarse grained localization algorithm, which needs only a minimum of computation, called Centroid Localization (CL) [5]. In CL all unknown nodes calculate their position as the centroid of the beacon's position within their communication range, regardless of the distance or signal strength towards the beacons. This algorithm can be outperformed by the Weighted Centroid Localization (WCL), which uses the Received Signal Strength- or the Link Quality Indicator (LQI) respectively to quantify the beacons in range and emphasizes nearer ones [4]. Using a linear quantification the algorithm reaches the lowest localization failure, given as Euclidean distance between real position and estimation, if the beacons communication range is 96% of the beacon distance, so the beacons cannot interact with each other. This can be improved by using quadratic quantification, which is more complex in computation, but achieves its lowest failure at a communication range higher than the beacon distance.

In this paper, we present adaptive WCL (AWCL) as an improvement of WCL, which achieves a higher precision than the linear WCL with nearly the same complexity. Here, the measured LQI of beacons in range will be cut to a certain level, which gives more influence to the measured differences of LQI than to the nominal value. This algorithm provides a precision near to the quadratic WCL with linear complexity.

The remainder of the paper is organized as follows. In Section II the preceding CL and WCL algorithms, which build the basis for AWCL are explained. This leads to the description of the main idea of the proposed AWCL algorithm in Section III. After that the simulation environment and the used LQI model are discussed in Section IV. Section V deals with our results, we got through the simulations. Finally Section VI closes with conclusion and future work.

II. Related Work

The algorithm, that is proposed in the paper in hand, is designed as an enhancement of WCL which is again an advancement of the Centroid Localization, also called CL, which was published by Bulusu [5]. Therefore this Section shortly introduces both algorithms in the chronological order.

The basis of all presented approaches is a couple of sensor nodes, which are silhouetted from normal nodes by an inherent knowledge of there own position. These nodes will be called beacon nodes. They can be used by other sensor nodes for estimating their own position. Algorithms that are mentioned in this paper will be explained and have been analyzed for the special buildup of four beacon nodes which are arranged in the corners of a quadratic field.

A. *Centroid Localization*

The first and also simplest of the algorithms is CL. This one does not utilize the Received Signal Strength Indicator (RSSI), the LQI or any other parameter, indicating the distance between a beacon node and a normal sensor node, which will be referred to as unknown. The only kind of distance information used in CL is the binary information whether the unknown is in the communication range of a beacon or not. CL acts from the assumption, that each beacon has a circular area within it can communicate with other nodes. In Fig. 1, it is shown how the communication ranges of four beacons, arranged as described above, build up to thirteen intersecting areas within an unknown can be localized.

The algorithm which can be performed on each unknown uses the location information of all beacons in its own range to calculate its position as the centroid as shown in (1). In this formula, $P_i(x,y)$ indicates the position of unknown i given by its two dimensional coordinates. The known position of beacon j is given by $B_j(x,y)$. The number of beacons which are within the communication range of the unknown node is indicated by m.

$$P_i(x,y) = \frac{1}{m}\sum_{j=1}^{m} B_j(x,y) \tag{1}$$

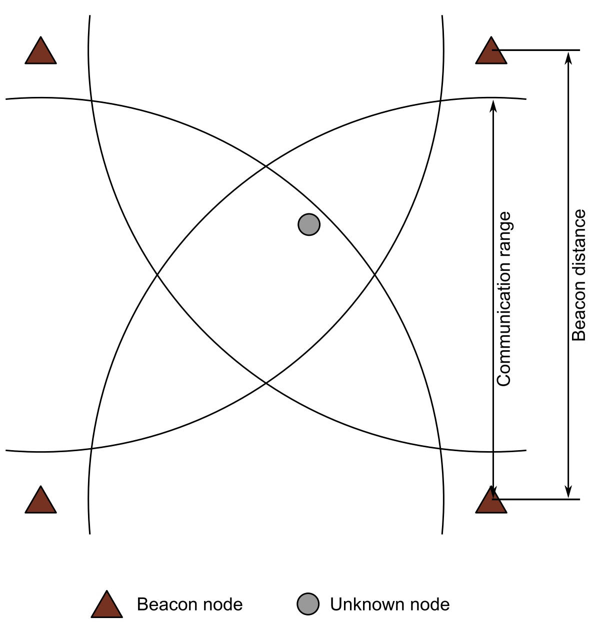

Fig. 1. Arrangement of 4 beacon nodes and 1 unknown node

Depending on the given calculation, a node which is situated within one of the intersecting areas will calculate its position at one single point, regardless of its exact position within the intersection area. For example, a node which is able to communicate to all of the four beacons will calculate its position in the centre of the arrangement. This behavior leads to a relative high localization failure, given as the Euclidian distance between the exact position of a sensor node and its calculated position. Blumenthal et al. showed in [4] that the averaged localization failure can not be less than 18% of the beacon distance for CL. This comes along with a maximum localization failure of 45%. This corresponds with the findings published by Bulusu in [5]. Blumenthal et al. also showed that the localization failure depends on the ratio between the beacon distance and the communication range. The cited values belong to an optimal transmission range of 87% of the beacon distance as it is illustrated in Fig. 1.

B. *Weighted Centroid Localization*

The low accuracy in location estimation of CL has motivated the development of WCL. WCL introduced the quantification of the beacons depending on their distance towards the unknown node. The aim is to give more influence to those beacons which are nearer to the unknown. As the RSSI as well as the LQI also increases with a decreasing distance it is selected as an appropriate quantifier.

The basic idea of WCL, published in [4], is to quantify each beacons position with a quantification function that uses the distance from an unknown node towards each beacon in range. The quantifier is described as shown in (2), where w_{ij} describes the quantification for beacon j used by node i. The distance between beacon j and node i is given by d_{ij} and g symbols a degree.

$$w_{ij} = \frac{1}{(d_{ij})^g} \tag{2}$$

Using this quantification the initial equation (1) has been expanded for WCL as shown in (3).

$$P_i(x,y) = \frac{\sum_{j=1}^{m}\left(w_{ij} \cdot B_j(x,y)\right)}{\sum_{j=1}^{m} w_{ij}} \tag{3}$$

An appropriate value for g was found in one. By the way, WCL with a degree of zero is equal to CL. Because WCL uses the distance only as a quantifier and does not try to find out the exact distance, it was proposed to use the LQI as a direct quantifier, without calculating the distance from the LQI. Therefore, equation (3) can be written as (4) by substitute the quantifier with the LQI measured between node i and beacon j noted as LQI_{ij}.

$$P_i(x,y) = \frac{\sum_{j=1}^{m} \left(LQI_{ij} \cdot B_j(x,y) \right)}{\sum_{j=1}^{m} LQI_{ij}} \quad (4)$$

The authors of [4] also showed in their experiments, that this is an appropriate translation of WCL for real world conditions.

It was also shown in this publication that using a linear weighting of the distance, that means a degree of 1, the averaged localization failure is at least 6.5%. This has been achieved using a transmission range of 95% of the beacon distance. At the same time the maximum localization failure is 18% of the beacon distance.

III. Description of AWCL

Although WCL overcomes the original CL in several aspects, i.e. the achievable localization failure is smaller and the quantification makes the localization more robust against imprecise transmission ranges, there are also some disadvantages. The most important one is its dependency on the communication range or rather the ratio between communication range and beacon distance. Several experiments with real sensor nodes showed that it is quit difficult to achieve the optimal communication range presented in Section II.B. Therefore it is one aim to make the location estimation more independent from the ratio between communication range and beacon distance. On the other hand the optimal transmission range for linear WCL is given as 95% of the beacon distance. That means, beacons are not able to communicate with each other in such an arrangement. In our opinion, it would be more useful to use an arrangement where each beacon is able to communicate with its neighbors. In that case the beacons could be used for example as a backbone.

The influence of the optimal communication range can be demonstrated by a simple example. Imagine an unknown node within an arrangement of four beacons as shown in Fig. 1. Provided that the correctly adjusted communication range leads to a tuple of LQI values as shown in Fig. 2, the unknown node would calculate its own position as illustrated. If all beacons would, for any reason, provide higher LQI, the calculated position would be nearer to the center, also shown in Fig. 2. In the other case, that the LQI is lower – even an LQI of 0 can be measured in spite of an existing connection – the calculated position would be more in the outer field as shown in Fig. 2. This occurs even though the variation of the LQI value is the same for all beacons and the differences between the measured LQI values is the same in every case.

The basic idea of AWCL is to compensate too high LQI values and give more influence to the differences between the LQIs instead of the nominal values. If the LQI of all measured beacons in range exceeds a specific threshold, we propose to decrease the measured values by a part of this gray fraction. As it was shown in the example, if all beacons in range provide relative high LQI values, the influence of one beacon's LQI becomes relative low. Therefore, AWCL first identifies the beacon with the lowest LQI. Then, all beacons in range must have an LQI, which is equal or greater than this value that can be seen as a gray fraction. Now, the measured LQI of all beacons will be reduced by a part of this minimum LQI. After this reduction, the linear WCL will be performed as usual. As it is illustrated in the example (Fig. 2), the amount of this reduction part plays an important role and has to be chosen carefully. The example gives an idea of what happens, if the whole gray fraction will be eliminated.

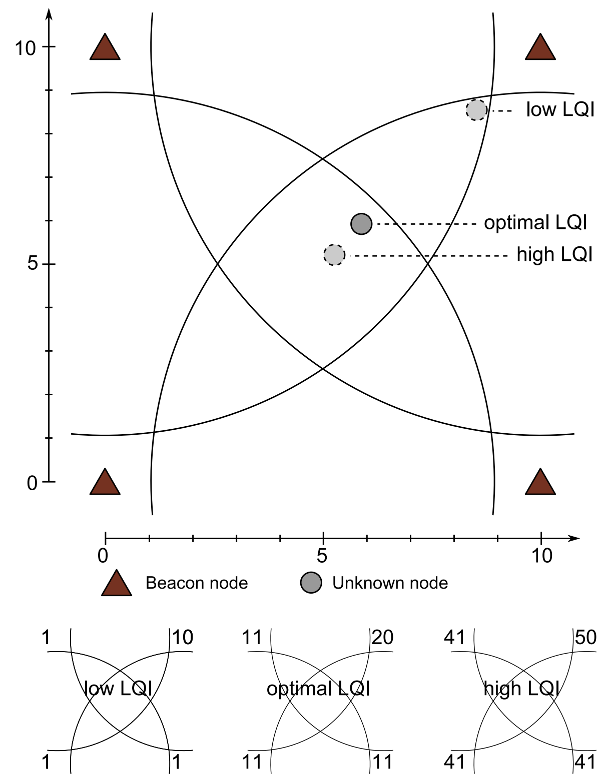

Fig. 2. Illustration of the influence of a well adjusted transmission range: optimal adjustment leads to the LQI values shown in the middle and the localization shown above. Lower or higher adjustments lead to different LQI values and differing localization.

The level of reduction has a recent impact on the precision, which can be achieved. Furthermore, the ratio between beacon distance and the beacon's communication range has a strong impact, which was already shown for WCL. With the help of some simulations, presented in the subsequent Section, we identified the optimal combination of communication range, beacon distance and cut percentage and we also identified a cut percentage that performs generally good. The reduction of a part of the minimum LQI leads to the situation that the level of reduction is permanently adapted to the local situation, which gives the algorithm its name. The new equation for position calculation, derived from (4) can be noted as in (5) like a combination of LQI reduction and WCL localization, where q is a reduction factor between 0 and 1.

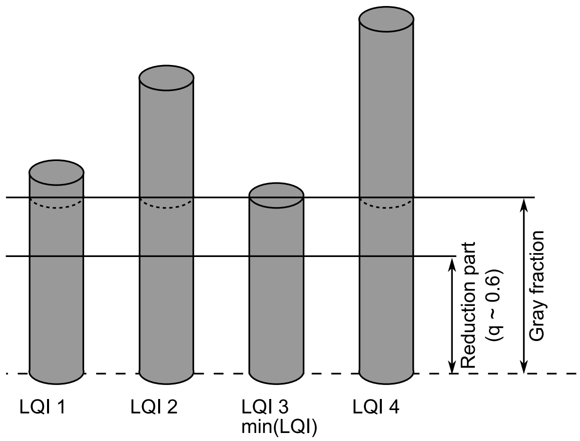

Fig. 3. Illustration of the gray fraction and the reduction part used in AWCL

$$P_i(x,y) = \frac{\sum_{j=1}^{m}\left(\left(LQI_{ij} - q \cdot \min\left(LQI_{i,1..m}\right)\right) \cdot B_j(x,y)\right)}{\sum_{j=1}^{m}\left(LQI_{ij} - q \cdot \min\left(LQI_{i,1..m}\right)\right)} \quad (5)$$

For a better understanding of the used terms like reduction part and gray fraction, Fig. 3 gives a visual idea of the LQI and the used terminology.

IV. Simulation and LQI Model

Previous work, i.e. WCL [4], treated the LQI or the RSSI only as a substitute of the distance between the node and the beacon in range. Therefore, the calculations, done in that work, directly used the distance instead of the LQI. The AWCL, in contrast, needs the LQI to perform the reduction as described in the previous Section. Using a kind of LQI makes simulations also more realistic, because translating distances into LQI implies also a discretization like it is done on real devices. Therefore, we used the model given by (6) for simulating an LQI between 0 and 255, depending on the distance d and the selected beacon's communication range R_c. The LQI aims to be similar to real LQI values that have been found in our experiments.

$$LQI = \begin{cases} 255 & for\ d = 0 \\ \left(\ln\left(\left(\frac{R_c}{100 \cdot d}\right)^2\right) + 10\right) \cdot 25 & for\ 0 < d \le R_c \\ 0 & for\ d > R_c \end{cases} \quad (6)$$

For our simulations we assumed a quadratic field with 4 beacons, one in each corner, like it is already shown in Fig. 1. Then, we placed an unknown node on each possible position in the field with a granularity of 100 x 100 different positions. For each position, the estimated position was calculated and compared to its real location. Furthermore, the average as well as the maximum localization failure over all positions were calculated as percentage of the beacon distance. We varied the communication range from 1 to 200% of the beacon distance and the reduction part from 0 to 100% of the minimum LQI.

V. Simulational Results

In our simulations we used the described LQI for simulating WCL as known from [4] as well as the described AWCL. Both algorithms have been simulated for a linear weighting of the LQI, i.e. q in equation (2) gets the value of 1, and for a quadratic quantification, i.e. q was chosen as 2. For these four cases we varied the communication range and in the case of AWCL also the reduction part as described in the preceding Section. Considering the subsequent findings and graphics, it is important to know how nodes have been handled during the simulations, which could not be located due to the fact that they have been out of the communication range of all beacon nodes. Such nodes exist for a communication range smaller than 71%. If a node could not be located, its position was chosen as the point of origin, i.e. the x-coordinate as well as the y-coordinate have been set to zero. Therefore the calculated localization failure could not exceed 141.4% of the beacon distance. That means all values which are given for a communication range smaller than 71% are only qualitative and could be scaled in any order, depending on the treatment of not locatable nodes.

A. *Proof of Comparability*

Our first focus concerning the simulational results has been the comparability to other work, i.e. the findings of [4] as described in Section II.B. Fig. 4 shows the localization failure as percentage of the beacon distance against the communication range for linear WCL. As it can be seen in the graph, the smallest averaged localization failure of 5.5% could be found for a communication range of 96%. The maximum localization failure for this communication range could be identified as 18%. These values are very similar to those that have been found in previous work, cited in Section II.B. The small difference concerning the averaged localization failure

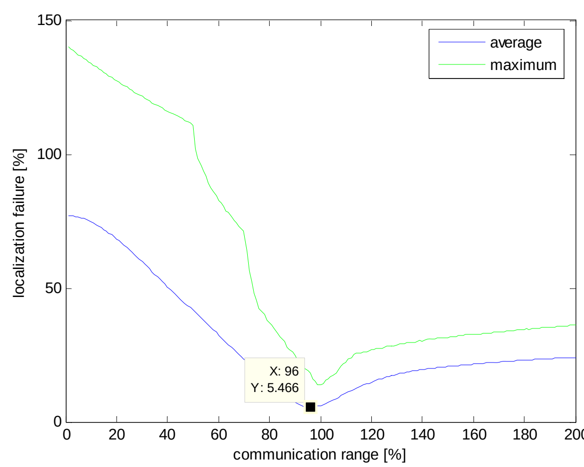

Fig. 4. Localization failure over the communication range for linear WCL

can be traced back to the discretization of the distance, by using LQI instead of the distance. However this result shows that the chosen simulation environment as well as the LQI model leads to comparable results.

B. *Improvements for linear WCL*

Our simulations turned out, that the introduction of the reduction part in AWCL leads to an improved localization. Having a look at the optimal communication range of WCL, shown as 96% in the previous Section, a small improvement of the averaged failure can be achieved using the correct reduction part. As illustrated in Fig. 5, reducing all measured LQI values about 30% of the minimum LQI leads to a smaller averaged localization failure than without reduction. In this case the reduced averaged localization failure is only 4.9%. The graph also shows that reducing too much would lead to a worse result.

As it is shown in Fig. 4 and Fig. 5 the achievable localization failure depends on both the communication range and the reduction part. Therefore, as it was described earlier, we varied both in our simulation. Fig. 6 shows the localization failure over the communication range, varied from 0% to 200%, and the reduction part, varied from 0% to 100%. It is identifiable, that the reduction has only a small influence if the communication range is relative low, i.e. about 90%. The more important result that is shown in this figure is that AWCL has the potential to hold the localization failure on a low level for higher communication ranges. Readily identifiable, for higher communication range, AWCL reduction leads to a failure much less than WCL without reduction.

To find the best possible improvement that can be achieved using AWCL, we calculated the point of the smallest failure. We found out that the smallest average failure of 4% of the beacon distance can be achieved with a communication range of 105% and a reduction part of 55%. With this configuration a maximum localization failure of 10.7% was reached. That means both, the average failure as well as the maximum failure, could be improved. Fig. 7 shows WCL and AWCL with a reduction of 55% over a varying communication range. This illustration does not only show the mentioned failure values for these constellations, it also shows that for lower ranges AWCL leads to a small impairment compared to WCL. But for a higher communication range both, the averaged failure as well as the maximum failure, is significantly lower using AWCL with the chosen reduction part.

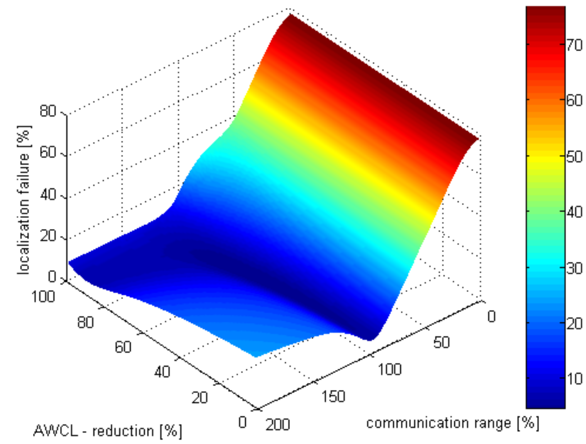

Fig. 6. Averaged localization failure over the reduction part and the communication range. Reduction leads to a smaller failure for a larger communication range.

In addition to this over all performance it is also from high interest, where most of the improvements take place in the described environment. In the following two figures, vectors are pointing from the real position of a simulated unknown node to the position calculated by the node itself. With respect to the clearness only a part of the calculated vectors are displayed. Fig. 8 shows the error vectors for WCL. One can see that there is a high concentration in the centre and also four other points of concentration near to the corners. Having a look at Fig. 9 one can see the influence of the LQI reduction

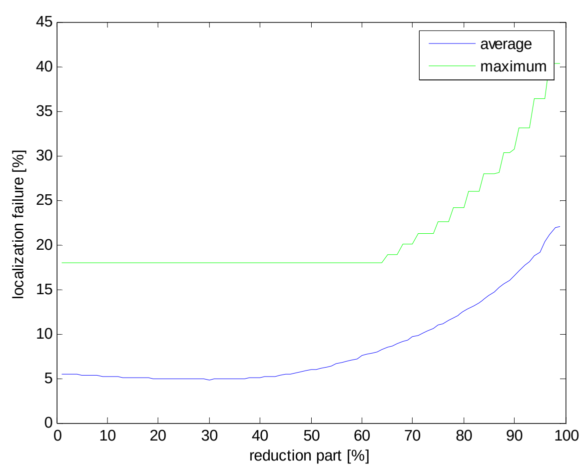

Fig. 5. Localization failure over the reduction part for a fixed communication range of 96%

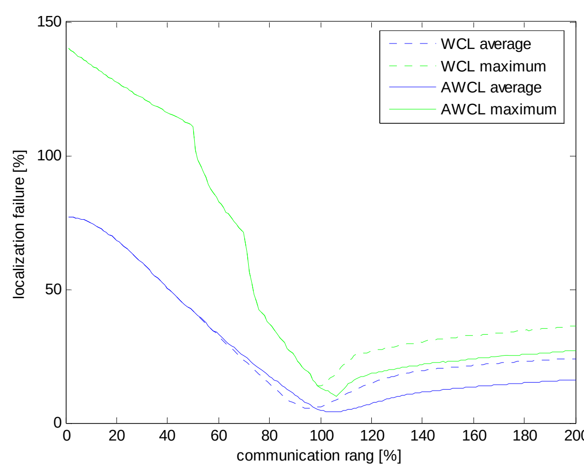

Fig. 7. Localization failure over the communication range for linear WCL and linear AWCL with a reduction part of 55%

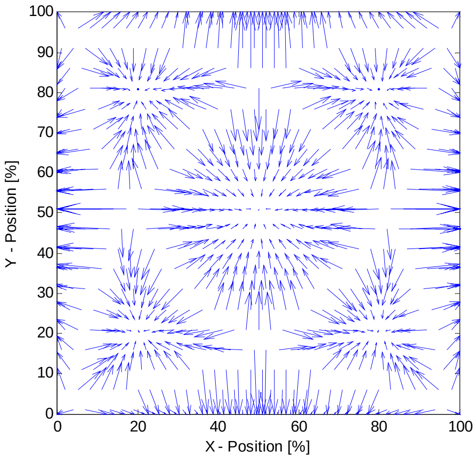

Fig. 8. Failure vectors, pointing from the real position to the estimated one, calculated with WCL and a communication range of 96% of the beacon distance

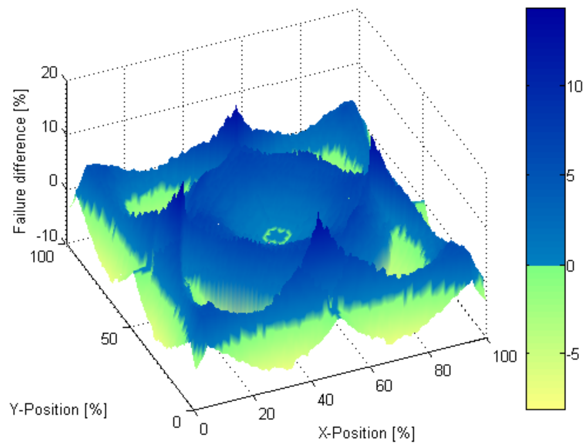

Fig. 10. Gain of precision as failure difference between WCL with a communication range of 96% and AWCL with a communication range of 105% and a reduction part of 55%

due to AWCL. On the first look one can see that failure vectors are more even distributed than in WCL. To our own surprise, it looks like the spot in the middle has been turned into five smaller ones. The central area with small failure vectors has become larger in comparison to WCL. The other four concentration points have been drawn towards the corners.

To have a more visual idea in which parts of the described simulation environment most improvements of localization could be achieved, the localization failure of WCL and AWCL has been compared and illustrated. Therefore for each point in the field, the localization failure produced by AWCL has been subtracted from the localization failure produced by WCL. The result is illustrated in Fig. 10. Any positive value in this illustration indicates an improvement, which has been achieved by using AWCL. It can be seen in the figure, that AWCL brings a high advantage in a wide range of the simulated field and some disadvantages in only a few parts. However, the advantages outweigh the disadvantages.

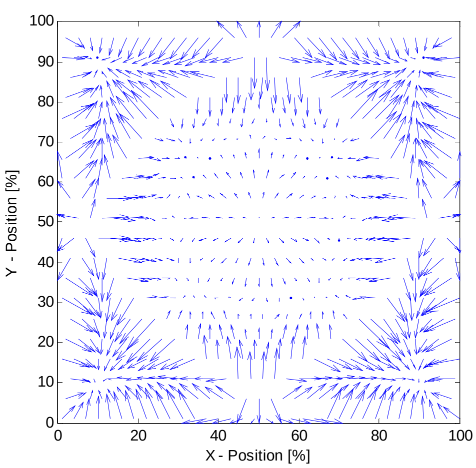

Fig. 9. Failure vectors, pointing from the real position to the estimated one, calculated with AWCL using a communication range of 105% and a reduction part of 55%

The given examples of WCL and AWCL are showing the performance of both approaches for, in each case, a special configuration of the used parameters, i.e. communication range and reduction part. A further claim of AWCL is to perform also well, if the communication range is not as good as expected. It has already been shown in Fig. 7 that for higher communication ranges, AWCL provides localization failures which are significantly lower than these of WCL.

The next step in our research was to find a reduction part which performs generally well for communication ranges above 100%. We found such a configuration with a reduction part of 66% of the minimum LQI. Fig. 11 shows some configurations with various reduction parts. From our point of view 66% is a configuration which leads to a balanced state over the given communication range. To compare this with WCL, we calculated the localization failure for WCL and AWCL for a communication range of 125%. This seams to be a realistic value where communication between beacon nodes is possible. As mentioned before the difference between both localization failures has been calculated and illustrated in Fig. 12. The benefit of AWCL in this illustration can be seen especially in the outer parts of the simulation area. In these regions, AWCL provides an average localization failure much lower than WCL. Also in the centre, AWCL beats WCL and the localization failure is at most equal to WCL. A comparison of the presented configurations will be given in Section V.D after a short analysis of quadratic quantification.

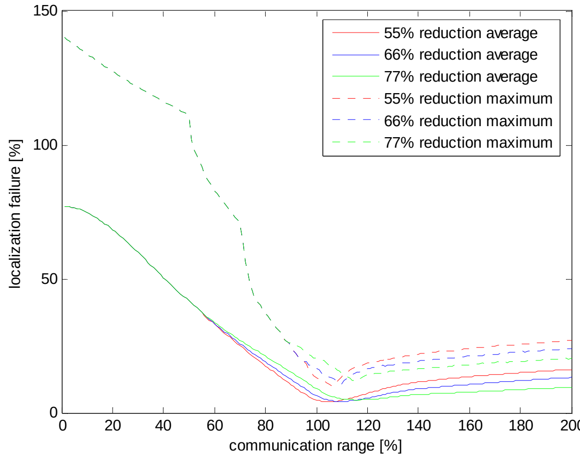

Fig. 11. Localization failure over the communication range for linear AWCL with a reduction part of 55%, 66% and 77%.

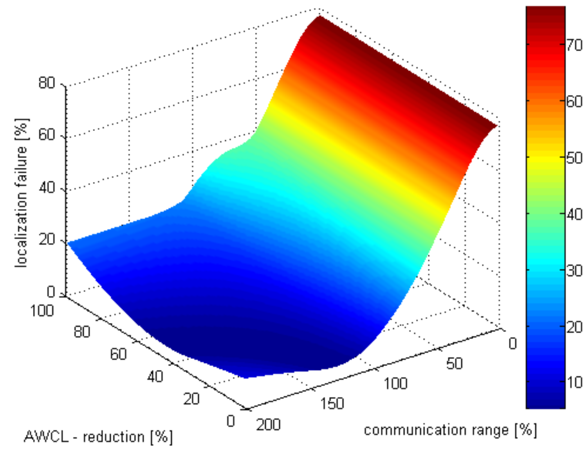

Fig. 13. Averaged localization failure over the reduction part and the communication range, using quadratic quantisation. Reduction leads to a smaller failure in a limited part.

C. Improvements for quadratic WCL

As already mentioned, we also studied the influence of AWCL in combination with quadratic quantification. As we did for linear weight, we varied once more the communication range from 0% to 200% and the reduction part from 0% to 100%. An overview of the achieved average localization failure is given in Fig. 13. In contradiction to the linear quantification a smaller reduction part leads to a small improvement for communication ranges higher than 100%. A higher reduction part would lead to impairment.

In our simulations we found out that the best average localization failure achievable with quadratic WCL can be found at a communication range of 129% of the beacon distance. The localization failure at this point is 4.76%. Using AWCL in combination with quadratic quantification the least localization failure is 4.72% at a communication range of 136%. So the achievable gain by using quadratic AWCL instead of quadratic WCL is quite small. Nevertheless, it outperforms WCL. Comparing linear AWCL to the quadratic approaches it outperforms both with an average localization failure of 4% as shown before. Fig. 14 also illustrates that even AWCL with the general reduction part of 66% achieves results comparable with quadratic WCL.

Nevertheless as identifiable in Fig. 13 similar to linear quantification AWCL leads to improved localization for higher communication ranges.

D. Comparison

As mentioned in the previous Sections, linear WCL provides localization with a weak precision, although it is much better than simple CL. Within the quantifying localization approaches, WCL achieves the highest localization failure in comparison to AWCL as well as quadratic WCL and quadratic AWCL. As expected each

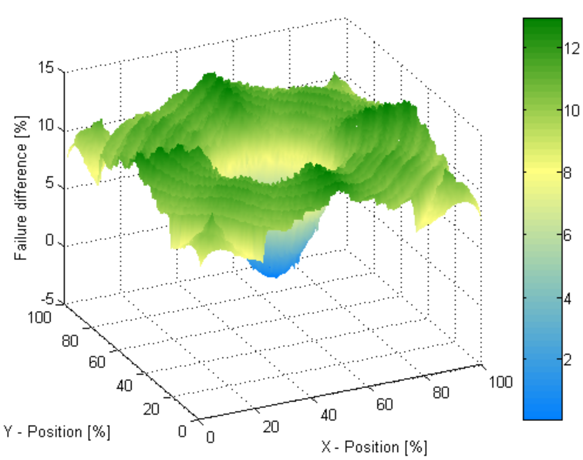

Fig. 12. Gain of precision as failure difference between WCL and AWCL with a communication range of 125% and an AWCL reduction part of 66%

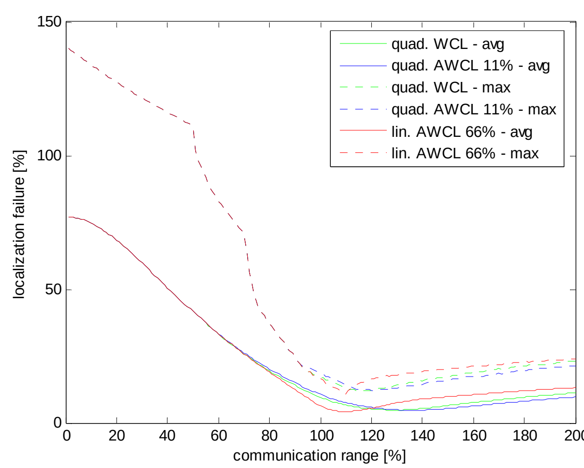

Fig. 14. Localization failure over the communication range for quadratic WCL, quadratic AWCL with a reduction part of 11% and linear AWCL with a reduction part of 66%.

TABLE I
COMPARISON OF CENTROID BASED LOCALIZATION APPROACHES

	CL	WCL linear	AWCL linear	WCL quadratic	AWCL quadratic
Communication range [%]	87	96	105	129	136
Reduction part [%]	-	-	55	-	11
Average localization failure [%]	18	5.5	4	4.76	4.72
Maximum localization failure [%]	45	18	10.7	13.72	13.87

studied approach owns a special configuration which leads to the best performance in terms of localization failure. These best case configurations, as identified in the previous Sections, are brought together in TABLE I. It is shown, that for quadratic quantification AWCL is very close to WCL. Furthermore the linear AWCL is shown as the approach which achieves the smallest localization failure within the studied approaches. It performs even better than quadratic WCL and quadratic AWCL.

As mentioned before, the chosen communication range has an important influence on the achievable localization failure. In real sensor networks, it is nearly impossible to adjust the best communication range as shown in this work as well as in previous work. Therefore, we had a focus on how the localization approaches perform for different communication ranges. As shown in Fig. 7, linear WCL performs better than linear AWCL if the communication range is smaller than approximately 98% of the beacon distance. But more important, AWCL outperforms WCL for higher distances. A similar situation could be found, for quadratic quantification. Here, quadratic WCL performs better if the communication range is up to 130%, for higher communication ranges quadratic AWCL performs better. But as it was also shown in Fig. 14, for a communication range up to 120% linear AWCL provides better localization results than quadratic approaches. This implies that linear AWCL offers more precise and more robust localization than quadratic WCL, but uses lower computational complexity.

VI. CONCLUSION AND FUTURE WORK

This paper presented AWCL as an improvement of WCL. The idea of AWCL, to reduce measured LQI values of each beacon in range by a part of the lowest LQI, has been illustrated in Section III. It was shown in several simulations, that this approach provides advancement compared to WCL. On the one hand the localization failure for the best chosen communication range could be outperformed. The average localization failure could be reduced from 5.5% to 4%, while the maximum localization failure decreased from 18% to 10.7%. On the other hand AWCL performs better for communication ranges larger than the beacon distance. The optimal communication range for AWCL is 105% and the localization failure is about 7 percent points lower, compared to WCL, using a communication range larger than 115%. This makes AWCL more useful for real WSN than WCL, because beacons can communicate with each other and the ratio between communication range and beacon distance can vary. It was even shown that linear AWCL outperforms quadratic WCL while using nearly the same computational cost. For a communication range up to 120% linear AWCL comes with a localization failure, lower any WCL approach.

The next step is to implement our approach on a real sensor network. But there are also some more points to investigate. In the presented approach we used a several percentage for reducing the LQI. Another possibility is to define an LQI threshold and to reduce all LQI values about the same value so that the smallest LQI do not undergoes the threshold. Keeping in mind that the presented studies have been done for a small arrangement of four beacons, it is also important to find out how AWCL performs in an arrangement of more beacons. Especially close to the beacons the results will differ to those given in this paper.

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