DE GRUYTER OPEN

Reports on Geodesy and Geoinformatics vol. 103/2017; pp. 1-9 DOI: 10.1515/rgg-2017-0001

Original article

Received: 15 July 2016 / Accepted: 4 January 2017

AN EXAMPLE AND ANALYSIS FOR AMBIGUITY RESOLUTION IN THE INDOOR ZIGBEE POSITIONING SYSTEM

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Abstract

This paper presents ambiguity resolution in the range-based ZigBee positioning system. The system is using the phase shift measurements to determine the distances between user and anchors. In this paper, the ambiguity is defined as the number of full reps of a certain distance added to the measurement result. The way of resolving ambiguities in the positioning system is described and an experiment results are presented. Featured algorithm is successful in finding ambiguities and correct location of the user.

Keywords: *ZigBee, ranging, indoor navigation, ambiguity resolution*

1. Introduction

Indoor navigation is gaining more and more attention in the modern society, industry and business. The overall goal of indoor navigation is to provide the GNSS-like functionality in places where GNSS signals are not available. There are many approaches and concepts of indoor positioning systems – from inertial systems, pseudolite systems, to computer vision systems (Farid et al, 2013). One possible approach is to incorporate a physical layer of wireless communication systems into navigation system. The application of communication networks for this task provides a lot of benefits over other systems. It can use existing infrastructure, the devices are generally cheap and easily accessible and they can be used for more purposes then just for navigation. The large drawback is the low accuracy of results obtained by these systems. The most popular radio signal strength indicator (RSSI) based systems are achieving the accuracy of few meters which is not always satisfactory (it reaches the level of 1-2 meters at its best). Moreover it strongly depends on the environment, so the functionality is strongly limited in changing environment (eg. in presence of many people or vehicles) is limited (Zhu & Feng, 2013) Another approach to positioning with use of wireless networks is range-based positioning. In the range–based indoor positioning systems the distances from the fixed anchors to the user (rover) are measured. Then the position of the user is calculated using trilateration. This method is based on finding the intersection of three or more circles (in 2D) or spheres (in 3D). The idea of trilateration in two dimensions is depicted in Figure 1. In Figure 1 point P depicts the estimated user location, T1; T2; T3; T4 are anchors and r1; r2; r3; r4 are measured distances. Due to the errors in the measured distances, the circles does not intersect at a single point. A rule of a thumb is that the center of the gravity of the greyed out area is considered as the most plausible user location.

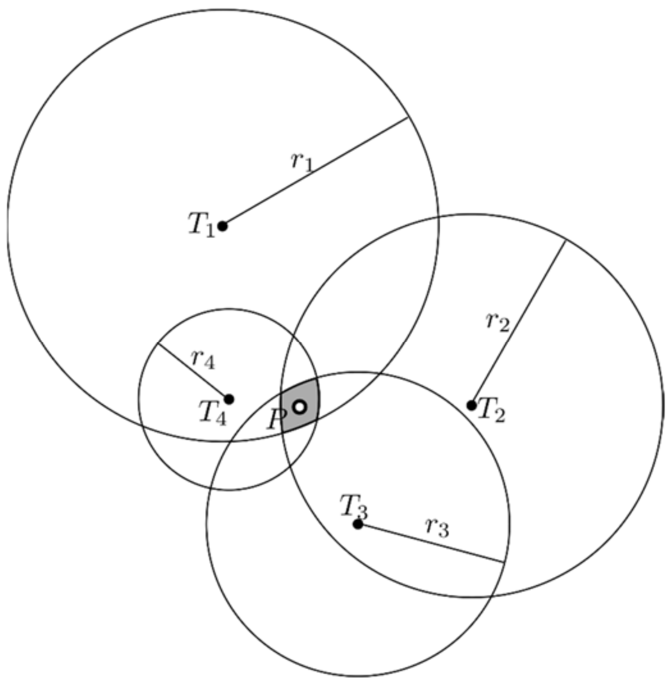

Fig. 1. Trilateration in 2D

To obtain anchor–user distances few techniques can be utilized. The most common one is based on the dependency between RSSI and distance. Assuming a known propagation equations, the RSSI to each anchor can be translated to distances. The major drawback of this technique is a strong variability in devices and propagation parameters (eg multipath) which makes it difficult to obtain a correct distance with different communication devices. Another approach is based on measuring the time of flight of the signal between devices. This technique comes in many variants: time of flight (TOF), differential time of flight (TDOF), time of arrival (TOA). The accuracy of these approaches is limited, because of the parameters of oscillators used in the communication devices. The novelty in ranging in communication networks is the utilization of phase shift measurement.

2. ZigBee ranging using phase shift measurements

In this article the AT86RF233 ZigBee module is used for ranging. This module allows to measure the distance in several ways: RSSI, time of flight and phase shift measurement. From these three methods the phase shift measurement is the most accurate. The performance of this unit is described in (Rapinski, 2015). As described in the data sheet the ranging procedure consists of a few steps:

1) coordinator is sending a ranging request to the reflector;
2) ranging initialization;
3) time synchronization;
4) ranging start;
5) ranging measurement;
6) request measurement data;
7) transfer data and calculate distance;
8) range result indication.

All of the points listed above, except point 5 are IEEE 802 compliant. Ranging itself stops the IEEE 802 communication and the Atmel proprietary procedure is used to measure the phase shift.

3. Problem description

Tests of the ranging capabilities of the AT86RF233 were performed using the REB233SMAD evaluation kit. During the tests, the communication in the line-of-sight condition was possible even at 250 m. To minimize the effect of multipath propagation, antenna diversity was used. The evaluation board used for the measurements is equipped with two antennas and all of the combinations of two antenna pairs are used. Therefore four distances are obtained as a result of a single ranging procedure. Results were processed according to the procedure described in (Rapinski & Smieja, 2015). As a result of ZigBee ranging a single distance was obtained which was used in trilateration. The problem was the phase shift measurement results "reset" to zero at 75, 150 and 225 meters. In the AT86RF233 Low Power, 2.4GHz Transceiver for ZigBee, RF4CE, IEEE 802.15.4, 6LoWPAN, and ISM Applications preliminary datasheet available on the Atmel web site, there is no information about this issue. The only useful information about this is the part of the description of the phase difference measurement concerning register summary, which states that the PMU result is an 8 bit register (which affects readings resolution), and that ranging is performed on an intermediate frequency. Nevertheless, the issue exists and must be addressed in order to obtain correct positioning results. The nature of phase shift measurements is causing the results to be in the range of a single wave length. Figure 2 depicts the behavior of measurement results. The dashed line shows theoretical dependency between true and measured distance, while solid line depicts the measurement itself. There are many approaches to compute a user position using trilateration.

In this article the objective function to be minimized is defined as:

$$\sum_{i=1}^{n} v_i v_i = min. \quad (1)$$

$$v_i = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - d_i \quad (2)$$

where:

v – residuum [m],
x_i, y_i, z_i – coordinates of the i-th node,
x, y, z – user coordinates,
d_i – distance to the i-th node.

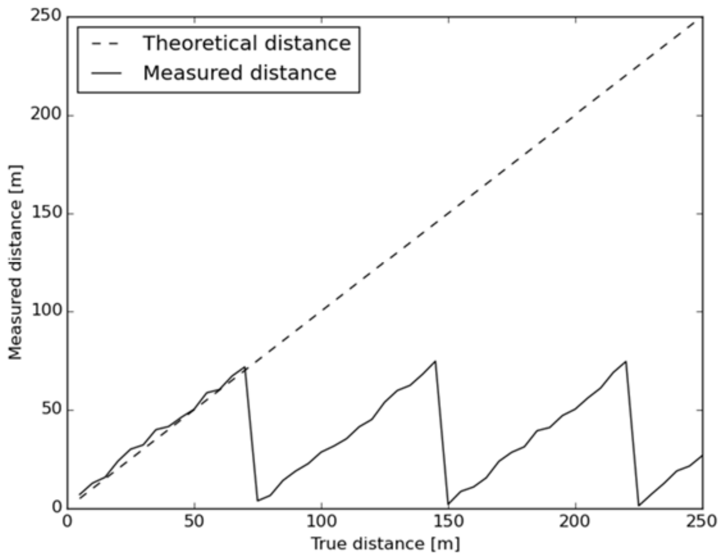

Fig. 2. Distance measurement results

This approach is correct if none of the measured distances exceeds 75 m but if a certain distance exceeds 75 m the equation of residuum takes the form:

$$v = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - (d_i + 75) \quad (3)$$

So in the overall case the residuum should be denoted as:

$$v = \sqrt{(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2} - d_i - 75N_i \quad (4)$$

where N_i is the number of full 75 m reps.

The choice of the minimization of the objective function method is also an important topic. In the case presented in this article the Nelder-Mead simplex method (also called downhill simplex method or amoeba method) was used (Nelder & Mead, 1965). It is a numerical algorithm which allows to find a minimum of a unimodal function based only on the computation of the values of the objective function. No linearization of the objective function is required which is also important. This issue is described in details in (Rapinski & Cellmer, 2015).

4. Ambiguity resolution

There is a similarity between the ZigBee phase shift ranging ambiguity and GNSS phase measurements ambiguity. In satellite surveys this issue is well known and described (Teunissen & Verhagen, 2009). In range-based ZigBee positioning the number of unknown parameter in trilateration with ambiguities is equal to the number of coordinates plus the number of ambiguities (there is one ambiguity for each anchor). In the static GNSS surveys the change in the satellite constellation in two consecutive GNSS epochs provides the supernumerary observables and the change in geometry required for the ambiguity resolution. In real time GNSS surveys with the on the fly ambiguity resolution, the search procedures are usually used. There are also other, more sophisticated techniques like MAFA method (Cellmer, 2011; Cellmer et al, 2013). In the indoor navigation the anchors are fixed so there is no change in geometry of the trilateration. If we want to use single epoch, there is more unknowns then observables in the set of equations. This is the reason, why the search procedure must be introduced. The GNSS are using the measurements of a carrier wave phase shift. The carrier frequency for these systems are in the range from 1.164 GHz to 1.610 GHz which corresponds to 0.18–0.25 m wavelength. With this wavelengths the number of candidates for a correct solution can be significant. In case of the ZigBee phase shift ranging, there will be only one or two possible ambiguity values for each anchor. The search procedure presented in this paper assumes the calculation of the solution for all the combinations of ambiguities. Subsequently, the solution is computed for each combination of ambiguities, resulting in the x, y and z coordinates of the user which is the candidate for a correct solution. The number of candidates is equal to the number of all combinations. To test which solution is correct, the RMS of the result is calculated as:

$$RMS = \sqrt{\frac{\sum vv}{n}} \quad (5)$$

The solution with the smallest RMS is considered as the correct one. This approach has relatively high numerical cost since the minimization of the objective function must be performed many times. However assuming relatively small area of the building interior (it will rarely exceed 150 m) and limited number of anchors, it seems to be reasonable. The example is presented in the next section. After the first measurement, when the ambiguity to each anchor is known, the search procedure should be performed only if a new anchor is found with an unknown ambiguity. System should track the changes in range and if the measured distance is crossing 0 (or 75) then the ambiguity should be updated (either by adding or subtracting 1 from the ambiguity assigned to the observation). In both of this cases the number of combinations to be checked is equal to the maximum range of the device divided by 75 and rounded up. The overall diagram of positioning algorithm is depicted in Figure 3.

The performance and quality of the measurements decrease with increasing distance (Rapinski, 2015). Therefore it is a good idea to limit the range of the transmission, especially in multipath environment. This can be done by limiting the transmit power.

5. Experiment description and results

To depict the issue described in previous sections, the experimental measurements were taken. The experiment was performed in the favorable environment (outdoors, small human traffic, line of sight propagation). Five anchors and one stationary rover were used. The layout of the experiment is depicted in Figure 4.

In ranging with the use of At86RF233 a single device can pay one of three roles. "Coordinator" is the device managing all other devices (eg. request of ranging from one node to another in the network, connection to user interface). Initiator is the device that requests the ranging between two devices and the reflector is the device that responds to the initiator’s request. In the presented experiment, rover was playing the role of coordinator and initiator and anchors were reflectors. It means that the ranging process was started by the rover transceiver five times – once for each anchor.

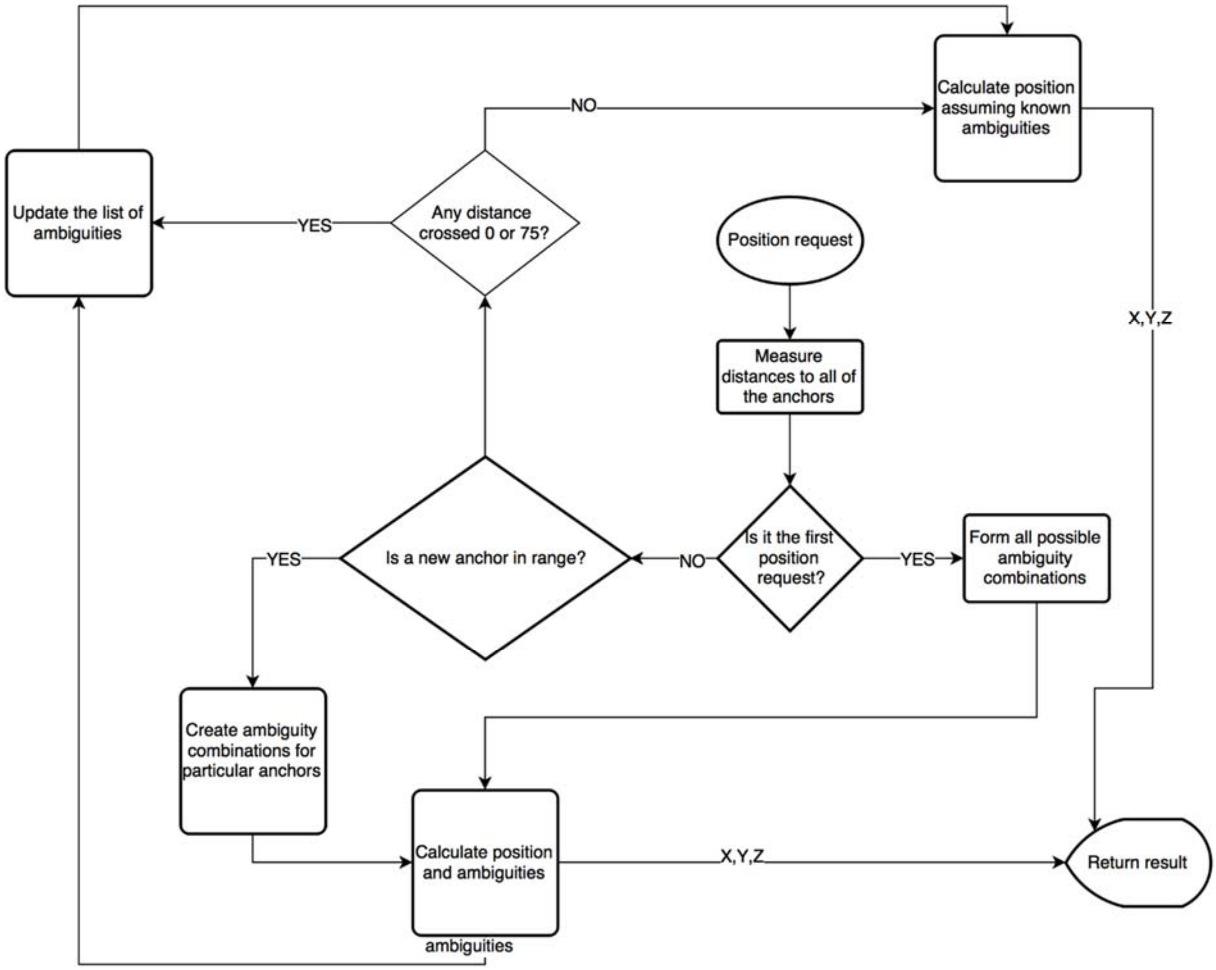

Fig. 3. Algorithm used in each positioning epoch

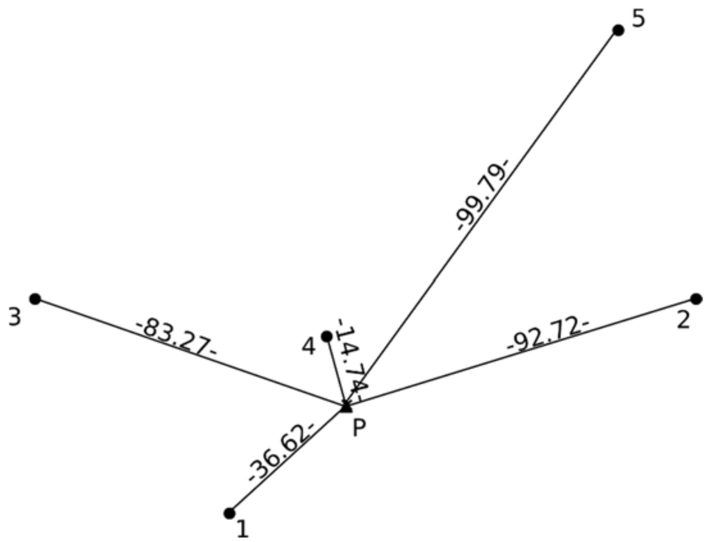

Fig. 4. Experiment layout

Distances to anchors 1 and 4 were smaller than 75 m, and the rest of distances were between 75 m and 150 m. In other words the ambiguities exist for anchors 2, 3 and 5. In this example the maximum value of Ni is assumed to be 1 (the largest measured distance can be 150 m). Since there are 5 anchors, there are $2^5 = 32$ possible combinations of the ambiguity parameters. This combinations are generated using a 5-digit binary number representation. Obtaining all of the combinations is equal to counting from 0 to $n - 1$ using binary numbers, where n is the number of anchors. Each digit in this number represents the ambiguity of a single distance. For example the number 7 in five digit binary is 00111. It means that the ambiguity equal to 1 is considered to exist for the third, fourth and fifth anchor. In the case described in this article, there are 32 candidates for the correct solution.

Testing all of the candidates using a Python 2.7 script took about 0.3 s on a modern desktop computer. The most time consuming task in the algorithm is the iterative process of Nelder-Mead optimization. There is no simple method to estimate the computational complexity of Nelder–Mead method (Singer & Singer, 1999), therefore only the number of iterations and the number of function evaluations are presented. Figure 5 depicts the number of function evaluations and the number of iterations required to find the minimum of the objective function for each combination of ambiguities.

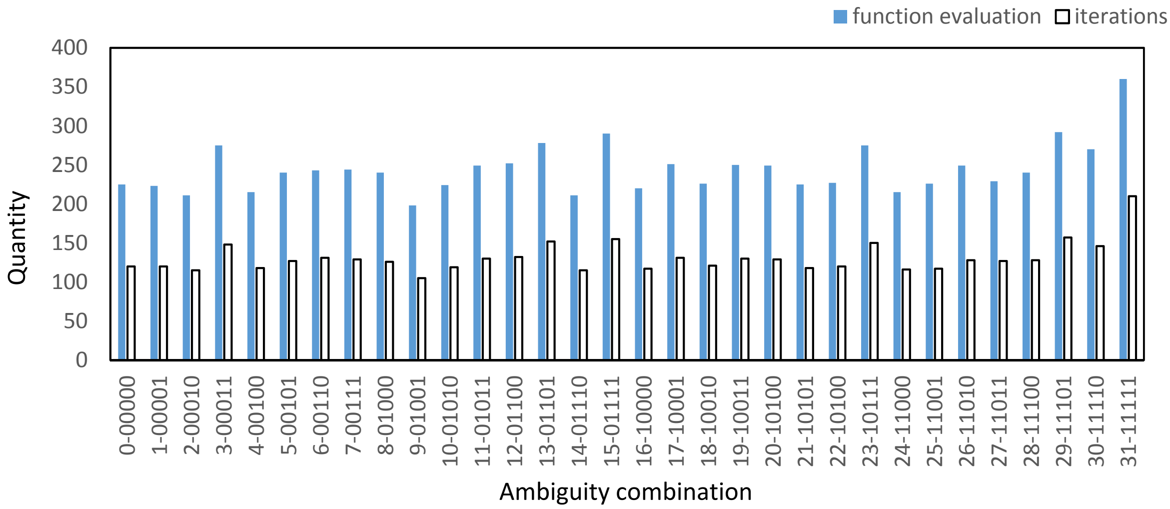

Fig.5. Number of iteration and function evaluations

Assuming, that this procedure is repeated only in cases when the user's device is taking the measurements for the first time, it seems reasonable and no search procedure optimization is required. However if larger area would be considered, the maximum value of ambiguity N_i would increase to 2 and the number of combination would be $3^5 = 243$.

Figure 6 depicts all of the candidates for the correct solution (marked with crosses). It is clear that only one candidate is close to the true rover position P.The values of RMS for particular combinations are presented in Figure 7. The combination number 13 has the smallest RMS. It corresponds to the 01101 combination of ambiguities, which is the correct one.

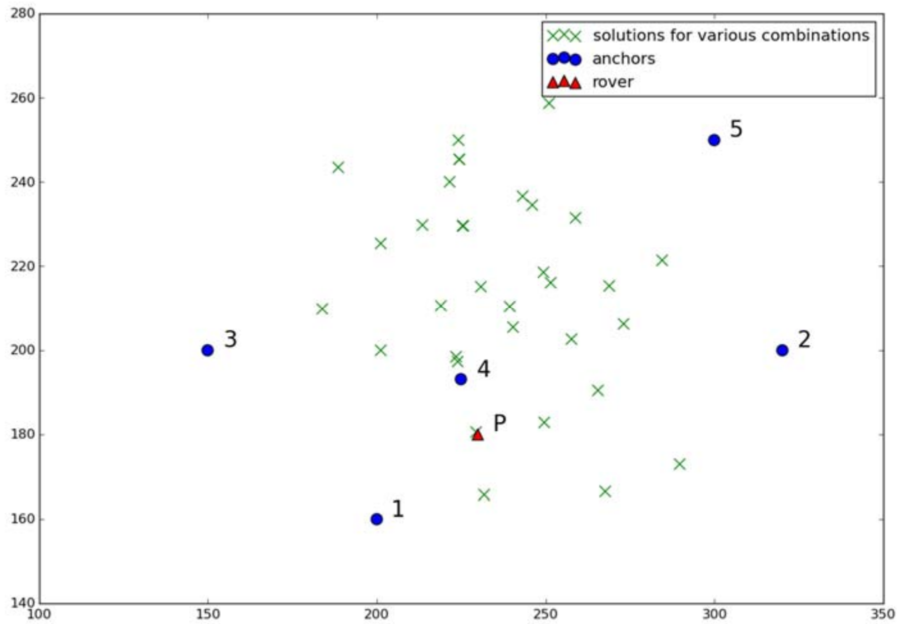

Fig. 6. Results of each search step

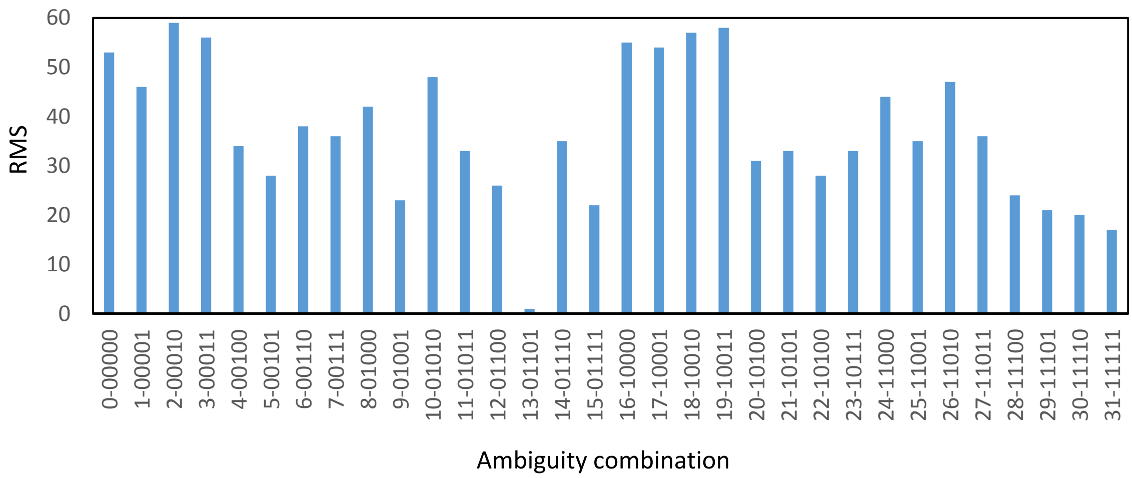

Fig. 7. RMS values used for ambiguity resolution

6. Conclusions

The issue of ambiguity in positioning with ZigBee phase shift measurements described in this paper can be easily resolved. The similarity to the GNSS phase observation ambiguities is clear however the difference in wavelength makes the ambiguity resolution much easier for the ZigBee system. Application of the search procedure gives good results with relatively small computational cost. The computational cost is higher when the ambiguities are not known for all of the anchors. After resolving the ambiguities for the first time, they can be used for further positioning excepting the situation when new appears in view. In such a case two subsequent must be checked. An example of the proposed approach is presented using five anchors and known user position.

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