

AN OPTIMAL DEPLOYMENT METHOD OF UWB POSITIONING BASE-STATION

Jinkun Li^{1*}, Chundi Xiu¹, Dongkai Yang¹

¹ Department of Electronic Information Engineering, Beihang University, Beijing, China - jkl.Reuben@163.com, imolive@163.com, edkyang@buaa.edu.cn

KEY WORDS: UWB Positioning; Optimized Base-Station Deployment; Genetic Algorithm; Position Dilution of Precision; Sharing-Value.

ABSTRACT:

Aiming at the prominent problem of high deployment cost of UWB (Ultra Wideband) positioning system and the waste of resources caused by repeated coverage of UWB base-station signals, the optimal deployment of the location and number of UWB positioning base stations is studied. Using Genetic Optimization Algorithm to optimize the objective function with Position Dilution of Precision (PDOP) and base-station Sharing-Value. The simulation and experimental results show that for the optimization of the location of UWB base stations, the three-dimensional average positioning error of the optimized layout method can be reduced by at least 0.3m compared with other typical layout methods; for the optimization of the number of base stations, the number by the optimized layout method is significantly lower than the typical layout method and decreases more as the actual base station deployment area increases. Therefore, the performance of the proposed method for optimal deployment of UWB positioning base stations is fully verified, which provides a reference for the optimal deployment of UWB positioning base stations in practical applications.

1. INTRODUCTION

With the growing demand for location-based services, indoor positioning (ZEKAVAT S R and D., 2021, Yassin et al., 2017) has gradually become a research hotspot. Ultra Wideband (UWB) (Oppermann and Iinatti, 2004, Ruming, 2009) positioning technology has attracted more and more attention due to the advantages of high positioning accuracy. For UWB positioning technology, the cost of base-station deployment network limits its wide application. A reasonable base-station deployment method can effectively reduce the cost of UWB system deployment and improve the positioning accuracy. Therefore, it is of great significance to study the optimal deployment method of UWB base stations. At present, there have been some studies on the deployment of UWB base stations at home and abroad. Peng (Yifan et al., 2017) used the Dilution of Precision (DOP) as the evaluation index of the layout of UWB base stations and verified that there was a correlation between DOP and positioning accuracy. Yang (Deng et al., 2020) used multiple base stations for simulation, and considered the influence of the direction of the base-station antenna on the positioning accuracy. The simulation results show that the layout of UWB base stations has a greater impact on the positioning accuracy, and the more averaged the distribution of distances from the area to be located to each base station, the higher the positioning accuracy. Another literature (jindong, 2021) summarized the three-stage design method of UWB base station layout scheme suitable for underground parking garages, and provided a scientific base-station layout process for practical scenarios. Richa Bharadwaj et al. (Bharadwaj et al., 2014, Bharadwaj et al., 2012) used the Geometric Dilution of Precision (GDOP) to evaluate the layout of base stations, and used a small UWB antenna to simulate and verify several typical layouts, including three base-station layouts. The proposed structure has the advantage of compactness and high precision. Zhong (jiawei, 2018) used the Position Dilution of Precision (PDOP) as an evaluation criterion, and proposed an optimal algorithm to optimize the UWB base-station

deployment, which broke the limitation of only studying typical layout methods. An optimization algorithm is essentially a traversal in a given direction. For the choice of optimization search algorithm, most existing mechanisms use heuristics to search for a good solution. Common ones include Simulated Annealing Algorithm (R. Battiti and Delai, 2003), Genetic Algorithm (Zirazi et al., 2012, He et al., 2011) and Differential Evolution Algorithm (Zhao et al., 2008). Compared with other optimization algorithms, the Genetic Algorithm is widely used and has strong robustness, global search ability and fast search speed. It can be widely used to solve optimization problems such as combinatorial optimization, adaptive control, planning and design. This paper provides a new method for the deployment of UWB positioning base-station network by establishing a mathematical model to solve the optimal deployment location and number of base stations. This paper is organized as follows. In section 2, it introduces how to obtain the farthest transmission distance of the base station, the signal coverage model of the base station and the optimization algorithm used; the third section and the fourth section provide the optimal deployment principle of the location and number of UWB base stations respectively; some simulation experiments are conducted in section 5 to verify the positioning performance of the proposed algorithm. And conclusions are given at last.

2. BASE STATION SIGNAL COVERAGE MODEL AND ALGORITHM

2.1 Free Space Propagation Model

In order to determine the maximum coverage of the base-station, the free space propagation model is used, and the relationship between Received Signal Strength Indicator (RSSI) and wireless signal transmission distance is used for calculating base-station coverage area radius. Under ideal conditions, when the wireless signal propagates in free space, the energy will not be absorbed by obstacles, and will not be refracted and scattered. However, in the indoor environment, the propagation

* Corresponding author

of the signal is affected by factors such as refraction, reflection, and diffraction. Due to the influence of multipath propagation, the propagation of the signal is no longer a simple direct model. The signal received at a certain time point is formed by the superposition of the direct signal and various reflected signals. Due to the different envelopes of the received signals, the distribution of statistical characteristics of multipath fading in indoor environments is divided into two types: Rayleigh distribution and Rice distribution. When there is a direct wave in the path of the multipath channel, the envelope of the received signal obeys the Rice distribution. The decay model equation is shown in formula (1).

$$p_r(d) = p_r(d_0) + 10n \log(d/d_0) + \xi \quad (1)$$

where $p_r(d)$ = RSSI at distance d_0 from base-station
 $p_r(d_0)$ = Environmentally dependent path loss factor
 n = RSSI at distance d from base-station
 ξ = A random variable with a Rice distribution

In the equation, the path loss factor n is usually 1.6-1.8 in the indoor propagation environment. Different UWB chips and modules have different maximum received signal strengths. At present, the more commonly used UWB chip is DW1000, and the more commonly used UWB module is DWM1000, which integrates the DW1000 chip and various antennas with different parameters. According to the official manual, the DWM1000 module (including DW1000 chip and antenna, etc.) has a maximum received signal power of 0dBm. Generally, d_0 is generally selected as 1m and $p_r(d_0)$ is obtained through actual measurement.

2.2 UWB Base Station Signal Coverage Model

2.2.1 Single base station signal coverage model The coverage area of an UWB base station is a sphere whose origin is the position coordinates of the base-station and the radius is the farthest propagation distance of the base station signal. As is shown in Figure 1.

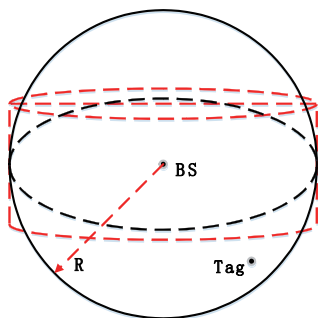


Figure 1. Single base-station signal coverage model.

Compared with the farthest transmission distance of UWB (that is, the radius of the sphere), the indoor height is much shorter. Therefore, to simplify this model, the indoor base-station coverage model of UWB can be regarded as a cylinder centered on the base-station coordinate. The coordinate of the UWB base-station is (x, y, z) , and the coordinate of the tag is (x_T, y_T, z_T) , then the distance between the base station and the tag is shown in formula (2).

$$d = \sqrt{(x - x_T)^2 + (y - y_T)^2 + (z - z_T)^2} \quad (2)$$

The base station's perception probability of tags is a Boolean perception model, either 1 or 0, as is shown in formula (3).

$$P = \begin{cases} 1 & d \leq R \\ 0 & d > R \end{cases} \quad (3)$$

where R = Base station signal maximum coverage radius

It can be seen from the equation (3) that if the tag is placed outside the farthest coverage distance of the base-station, the distance information between the two cannot be obtained.

2.2.2 Four base station signal coverage model This paper adopts the Time Differences of Arrival (TDOA) positioning method, so any point in the positioning area can ensure that at least four base stations distance information can be obtained. The top view of four base station signal coverage model is shown in Figure 2.

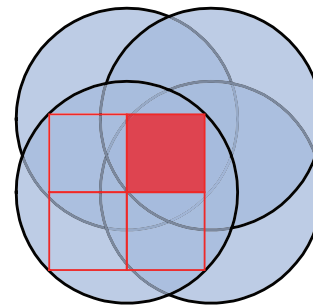


Figure 2. Top view of four base-station signal coverage model.

As can be seen from the Figure 2, in order to simplify the model, every two base stations coverage areas are approximately regarded as two tetrahedral areas. Therefore, the coverage area of the four base stations which is the common coverage space of the four cylinders can be approximately regarded as a tetrahedron area.

2.3 Base Station Optimal Deployment Using Genetic Algorithm

When using Genetic Algorithm to solve the problem of optimal deployment of UWB base stations, the main process is shown in figure 3. The main steps are as follows:

- 1) Set the optimization objective function, the size of the target area, the number of reference points (RP) and the number of base stations, and set the parameters of the Genetic Algorithm, including the initial population size and the number of iterations;
- 2) Randomly generate the initial population, encode it to obtain a set of code strings, each code string represents a distribution mode of base stations, that is, the three-dimensional coordinates of the base stations, and calculate the fitness objective function value according to the phenotype of the individual population;
- 3) Carry out the three most basic operations of the Genetic Algorithm: selection, crossover and mutation. The principle of selection is to select individuals with higher fitness as the parent, so that the next generation has the opportunity to produce better offspring individuals. The selection method adopts sorting selection, that is, sorting all individuals in the group according to their fitness, and assigning the probability of each individual being selected based on this sorting.

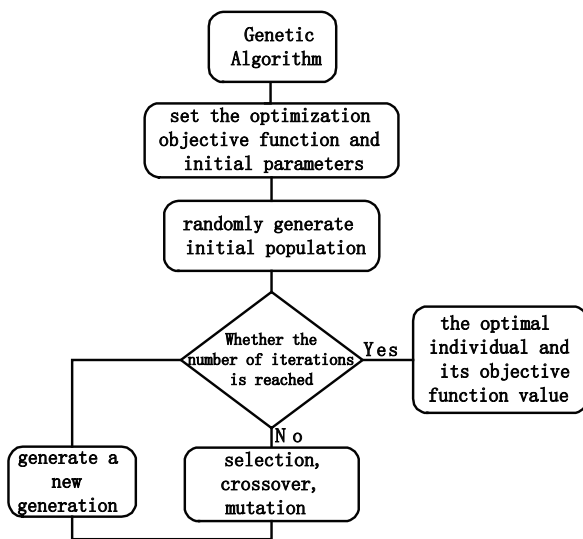


Figure 3. Genetic Algorithm Flowchart.

The principle of crossover is that the selected parent individuals will undergo partial genetic recombination to complete the reproduction process. The design of the crossover operator includes two aspects: one is how to determine the position of the crossover point, and the other is how to exchange some genes. The crossover operator adopts single-point crossover, that is, a crossover point is randomly set in the individual coding string, and then part of the genes of the two paired individuals are exchanged with each other at this point. The principle of mutation is to select individuals to be mutated in the offspring population, and then randomly change one gene or some genes with a certain probability. The design of mutation operation includes two aspects: one is how to determine the position of the mutation point, and the other is how to replace the gene value. The mutation method adopts uniform mutation, that is, each gene in an individual is replaced by a random number that conforms to a uniform distribution within a certain range with a small probability; 4) Find the individual with the largest fitness value in the new population, record its individual phenotype and its objective function value. This individual phenotype is the optimized base-station layout.

3. OPTIMIZED DEPLOYMENT OF THE LOCATION OF UWB BASE STATIONS

The optimal deployment of base-station location is to optimize the deployment location of four base stations in the tetrahedral coverage area determined by the maximum coverage area of the UWB base-station.

3.1 Position Dilution of Precision

In the navigation system, the DOP value is usually used to measure the influence of the spatial geometric layout of the positioning base-station on the precision. The PDOP value can more accurately reflect the layout of the positioning base-station in the three-dimensional direction. Because PDOP involves base stations' coordinates and target labels, and there is no other redundancy. Therefore, this paper selects N reference points in the target positioning area evenly at equal intervals,

and replaces the PDOP of all points in the target area with N reference points, thereby realizing uniform sample sampling.

3.2 Constraints and Objective Functions

In order to optimize the positioning base-station layout, the objective function is set as the product of the PDOP mean and the standard deviation of each reference point, which can ensure that the PDOP value of each point is as small as possible while avoiding the occurrence of many abnormal PDOP deviation values. PDOP mean formula is shown in equation (4):

$$E(PDOP_1, PDOP_2, \dots, PDOP_N) = \frac{1}{N} \sum_{i=1}^N PDOP_i \quad (4)$$

where N = the number of sample points

PDOP standard deviation equation for each sampling point is shown in equation (5):

$$STD = \left(\frac{1}{N} \sum_{i=1}^N (PDOP_i - E(PDOP))^2 \right)^{1/2} \quad (5)$$

The adaptive value of the objective function is shown in equation (6):

$$fitness = E_i * STD_i \quad (6)$$

4. OPTIMIZED DEPLOYMENT OF THE NUMBER OF UWB BASE STATIONS

The optimal deployment of the number of base stations means that in the area covered by more than four base stations, the tetrahedral area determined by the four base stations is used as the unit to fill the large area with grids. The specific schematic diagram is shown in Figure 4.

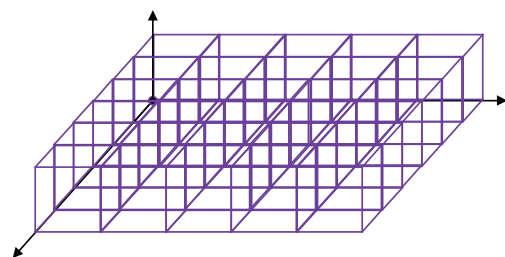


Figure 4. Location area rasterized fill figure.

4.1 Base Station Sharing-Value

In the principle of optimal deployment of base stations, the concept of Sharing-Value is proposed, that is, the number of regular tetrahedrons used by a base station in common. As shown in Figure 5, when the base-station is placed on the green edge of the left regular tetrahedron, the sharing degree of the base-station is 4, that is, the base-station can be shared by four single tetrahedrons. Corresponding to the top view, as shown in

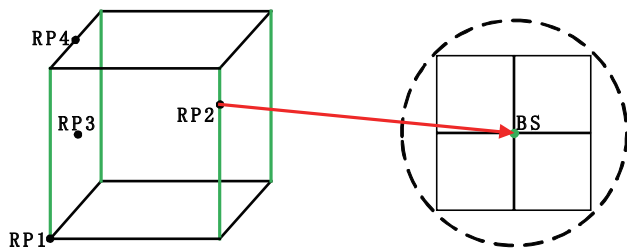


Figure 5. Schematic diagram of base-station Sharing-Value.

the dotted circle on the right, there are also base stations with a sharing degree of 2.

The optimal deployment principle of this part should mainly consider the size of the base-station Sharing-Value, and also take into account the factors of positioning accuracy. The greater the Sharing-Value, the less the number of base stations used in the deployment, but it will also lead to a decrease in the positioning accuracy.

4.2 Constraints and Objective Functions

When using the Genetic Algorithm to solve the problem of optimal deployment of the number of UWB base stations, it is similar to the steps of optimal deployment of the base station location. The difference is that in the Genetic Algorithm used in this part, the constraint condition of the sum of the Sharing-Value of the four base stations is added, and that is shown in equation (7).

$$fitness = \sum_{i=1}^4 Shared_Value_i \quad (7)$$

where i = the base station label, and the values are 1-4

The UWB base-station deployment mode considering both the number of base stations and the positioning accuracy is solved.

5. SIMULATION EXPERIMENT AND RESULT ANALYSIS

5.1 Base Station Ranging Experiment

The free space propagation model can theoretically determine the farthest transmission distance of the UWB module used. However, since the hardware itself also includes modules such as antennas that affect the transmission distance of the UWB base-station, and there is an error limit between practical application and theory. The actual ranging accuracy and stability is also different due to the quality of the hardware. Therefore, the ranging experiment of the base-station is carried out first. Considering the underground garage on the second lower floor of Building F, Beihang's new-main-building. The distance between the four base stations and the tags were tested multiple times and the average value was taken as the longest transmission distance of the UWB base-station. The transmission distance of the UWB base-station used in the actual measurement is 20m, and the inherent error is 0.5-0.7m. Based on this, the largest regular tetrahedron area that can be covered by four base stations of 15m*15m*3m is selected for simulation and positioning experiments of a single group of base stations.

5.2 UWB Base Station Location Optimization

5.2.1 Simulation and Result Analysis In the positioning area, a reference point is selected every 1m along the three axes of space, and a total of 392 reference points are selected in the space area of 15m*15m*3m. As is shown in Figure 6.

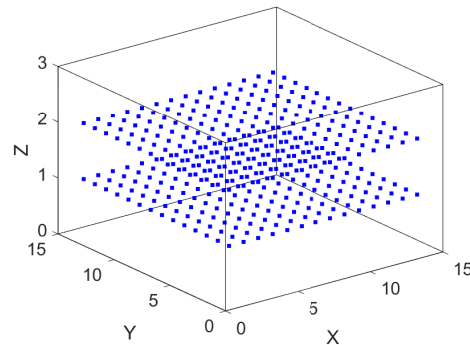


Figure 6. Reference point distribution figure.

In the Genetic Algorithm, the initial population size is set to 100, the number of iterations is set to 50, and the length, width, and height of the target area are set to 15m, 15m, and 3m, respectively. The optimized layout obtained from the solution and the four base stations coordinates of two other typical layout methods are shown in Table 1.

	BS1	BS2	BS3	BS4
Optimized layout	(0,7,0)	(5,0,3)	(15,7,0)	(8,15,3)
"Cube" layout	(15,0,0)	(0,0,3)	(0,15,0)	(15,15,3)
"Y" layout	(15,0,0)	(15,0,3)	(0,0,0)	(15,15,0)

Table 1. Four base stations with different layout methods base-station coordinate table.

The three-dimensional view of the base-station location is shown in Figure 7.

	mean	STD	fitness
Optimized layout	2.9598	0.5957	1.7780
"Cube" layout	3.5809	0.5686	2.0362
"Y" layout	3.6940	1.0558	3.9000

Table 2. Four base stations different layout methods PDOP parameter value.

The corresponding PDOP parameter values are shown in Table 2.

For the optimized layout and two typical layout methods, the mean PDOP values are 2.9598, 3.5809, and 3.6940, and the fitness values are 1.7780, 2.0362, and 3.9000, respectively. Among them, the optimized layout is the smallest, and the layout method is better than the two typical layout methods.

5.2.2 Static Single Point Positioning Experiment The positioning experiment was carried out in the underground garage on the second lower floor of Building F, Beihang's new-main-building, and a 15m*15m*3m regular tetrahedron area was selected for this part of experiment. The positioning experiments were carried out respectively for static single-point experiments and dynamic walking experiments. The acquisition equipment is four base stations and one tag including DWM1000 UWB chip and the experimental scene is shown in Figure 8.

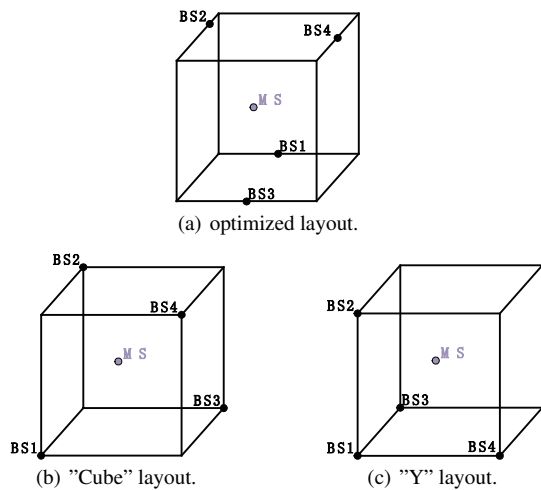


Figure 7. Different layouts of four base stations.



Figure 8. Experimental scene graph.

In the static single-point experiment, several typical specific points are selected, and the positioning accuracy of the selected points is tested under different layout methods. The experiment results are shown in the Figure 9. From the figure, we can see that the accuracy of each point of the optimized layout is better than that of the "cube" layout and the "Y" layout. However, the two typical layouts are similar in the positioning accuracy of the selected points due to the difference in the mean PDOP value of only 0.1.

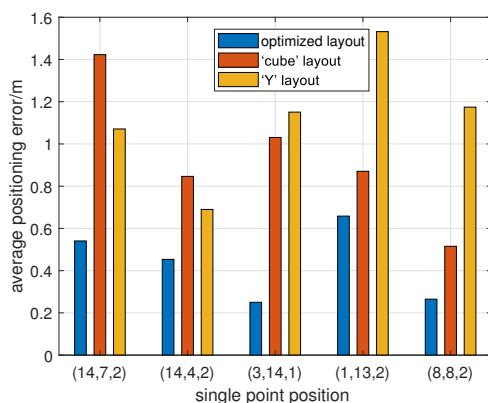


Figure 9. Static single-point average positioning error of different layout methods.

For the three-axis positioning accuracy under the optimized layout, as shown in Figure 10, from the positioning accuracy of the xyz-axis, the x-axis and y-axis positioning errors are similar, and significantly smaller than the z-axis positioning error, indicating that the z-axis static positioning results are highly volatile.

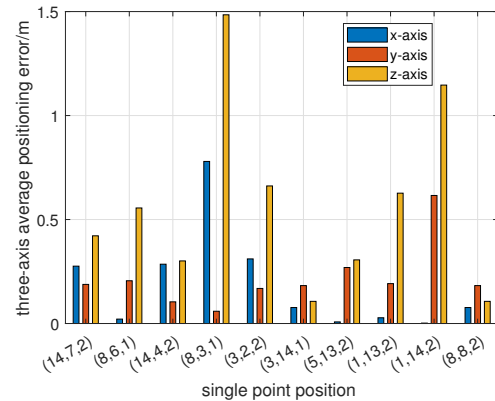


Figure 10. Static single-point three-axis average positioning error.

5.2.3 Dynamic Continuous Positioning Experiment In the dynamic walking experiment, according to the established "rectangular" route, the positioning accuracy of the selected route was tested under different layouts. The experiment results are shown in Table 3.

	Optimized layout	"Cube" layout	"Y" layout
3D error	1.48	1.79	1.88
2D error	0.42	0.54	0.66

Table 3. Four base stations with different layouts average positioning error table.

It can be seen from the table that, compared with the two typical layouts, the optimized layout improves the 3D positioning accuracy by 0.3-0.4m, 21.65 percent and 25.47 percent respectively; Whether it is 3D positioning or 2D positioning, the optimized layout is better than the two typical layout methods. The 3D positioning error CDF curve is shown in the following figure:

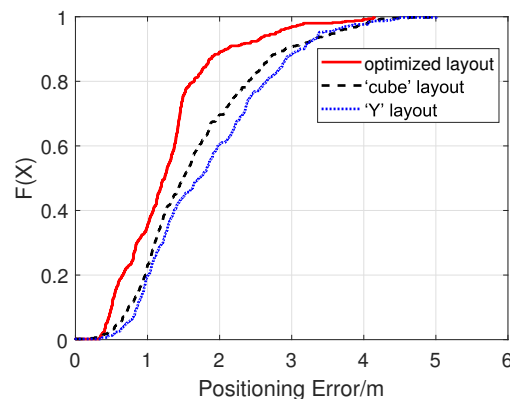


Figure 11. Average position error CDF curve.

As can be seen from Figure 11, the CDF curve of the optimized layout converges faster and the positioning accuracy is higher.

5.3 Optimization of The Number of UWB Base Stations

For the optimal deployment of the number of base stations, the simulation solves the optimal layout when the Sharing-Value of a single group of four base stations are 8, 10, 12, 14, and 16, respectively. The coordinates of the resultant base stations are shown in the Table 4.

	BS1	BS2	BS3	BS4	mean
“8” layout	(0,7,0)	(5,0,3)	(15,7,0)	(8,15,3)	2.9598
“10” layout	(0,8,0)	(9,0,0)	(15,15,0)	(10,15,3)	3.1948
“12” layout	(15,0,0)	(5,0,3)	(0,15,0)	(15,12,3)	3.3046
“14” layout	(15,0,0)	(0,0,3)	(0,15,0)	(10,15,3)	3.4014
“16” layout	(15,0,0)	(0,0,3)	(0,15,0)	(15,15,3)	3.5809

Table 4. Optimal layout base-station coordinate and its PDOP mean under different Sharing-Value table .

The three-dimensional view of the base-station location is shown in Figure 12.

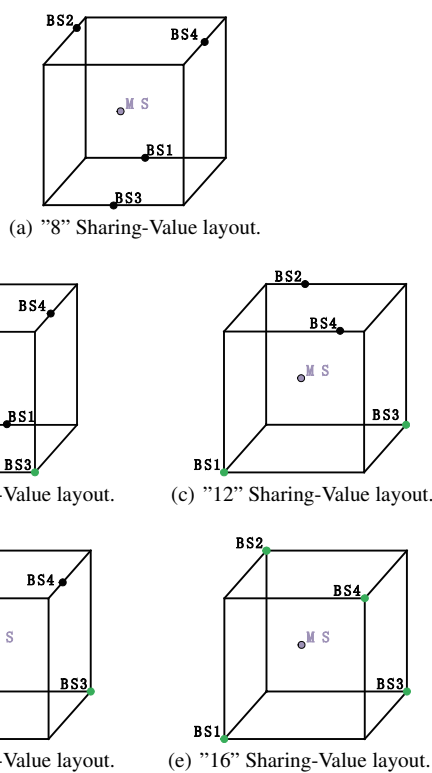


Figure 12. Optimized layout of four base stations with different Sharing-Value.

Among them, the dots which locate at the vertex of a tetrahedron are the deployment positions of base stations with a Sharing-Value of 4, and the other dots are the deployment positions of base stations with a Sharing-Value of 2. The simulation area is to select a “square” area of 90m*80m*3m and a “narrow and long” area of 100m*15m*3m+15m*70m*3m, as shown in Figure 13.

The two types of simulation areas are deployed by using the four base stations layout with different degrees of sharing required above. The number of base stations used is shown in Table 5.

It can be seen from the table that for the two simulation areas, the number of base stations required for the four base-station

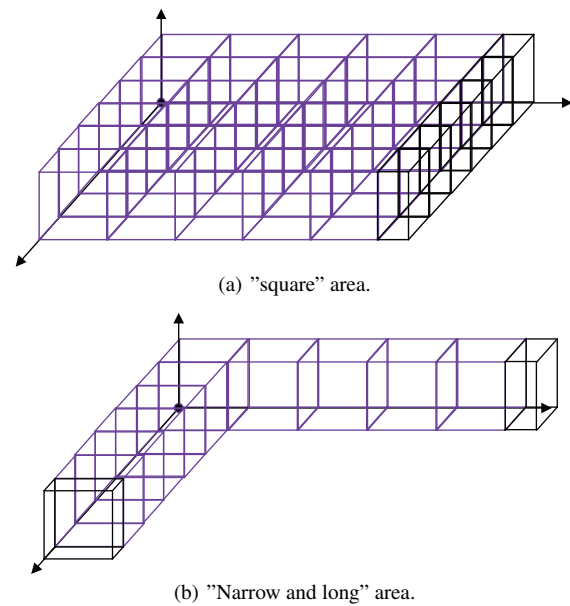


Figure 13. Two types of location area rasterized fill figure.

	“8”	“10”	“12”	“14”	“16”
“square” area	80	67	55	51	45
“Narrow and long” area	37	36	29	28	26

Table 5. Deployment numbers of two types of regional base stations under different Sharing-Value table.

“8” sharing degree layout is the largest, and the two areas are 80 and 37 respectively; the number of base stations that is deployed by the four base-station “16” sharing degree layout is the least, the two areas are 45 and 26 respectively. The number of base stations decreases with the increase of the Sharing-Value. And it is not difficult to infer that, compared with other layout methods, the number of base-station deployments required by the four base-station “8” Sharing-Value layout method decreases more with the increase of the actual deployment area, and the optimized effect is more obvious. According to the PDOP value and aforementioned experimental results, the positioning accuracy decreases with the increase of the Sharing-Value. Therefore, in practical applications, according to the minimum requirement of positioning accuracy, the optimal layout mode with the least number of base stations would be selected.

CONCLUSION

A new method for optimal deployment of UWB positioning base stations is proposed. The simulation and experimental results show that the Genetic Optimization Algorithm can effectively solve the optimal layout of UWB base stations. Compared with other typical layouts, the UWB positioning accuracy is significantly improved. Using Sharing-Value as the evaluation criteria, the proposed method can effectively reduce the deployment number of UWB base stations while ensuring the positioning accuracy, thereby reducing the deployment cost of the UWB positioning system. Both the location and number of UWB positioning base stations are optimized from a theoretical point of view, and good results are obtained through simulation and experimental verification. Therefore, the paper provides a new reference for the practical deployment application of UWB positioning system.

ACKNOWLEDGEMENTS

This work is supported by the Elastic Architecture Design and Key Technology Verification of PNT System Project(2020YFB0505800).

REFERENCES

- Bharadwaj, R., Alomainy, A., Parini, C., 2012. Study of ultra wideband localisation techniques using various monitoring configurations. *2012 6th European Conference on Antennas and Propagation (EUCAP)*, 2035–2038.
- Bharadwaj, R., Parini, C., Alomainy, A., 2014. Ultrawideband-Based 3-D Localization Using Compact Base-Station Configurations. *IEEE Antennas and Wireless Propagation Letters*, 13, 221-224.
- Deng, Y., Jian, W., minmin, W., yalei, Z., 2020. Analysis of the impact of base station deployment on positioning accuracy in emergency environments. *Surveying and Mapping Bulletin*, 90-94.
- He, Y., Meng, W., Ma, L., Deng, Z., 2011. Rapid deployment of aps in wlan indoor positioning system. *2011 6th International ICST Conference on Communications and Networking in China (CHINACOM)*, 268–273.
- Jiawei, Z., 2018. Research on base station layout method for uwb indoor positioning. master's thesis, Shenzhen University.
- Jindong, W., 2021. UWB base station layout optimization method for underground parking garage. *Intelligent Transportation*, 78-84.
- Oppermann, I, M. H., Iinatti, J., 2004. UWB Theory and Applications (Oppermann/UWB: Theory and Applications) — Front Matter. i-xxiv.
- R. Battiti, M. B., Delai, A., 2003. Optimal wireless access point placement for location-dependent services. *Technical report DIT*, 3–52.
- Ruming, C., 2009. UWB technology development prospect and its frequency plan. *Mobile Communications*, 33, 71-74.
- Yassin, A., Nasser, Y., Awad, M., Al-Dubai, A., Liu, R., Yuen, C., Raulefs, R., Aboutanios, E., 2017. Recent Advances in Indoor Localization: A Survey on Theoretical Approaches and Applications. *IEEE Communications Surveys and Tutorials*, 19(2), 1327-1346.
- Yifan, P., Guangyun, L., Li, W., minglei, L., 2017. UWB indoor positioning station layout PDOP value analysis. *Journal of Navigation and Positioning*, 5(2), 103-106.
- ZEKAVAT S R, B. R. M., D., D. G., 2021. An overview on position location: past, present, future. *International Journal of Wireless Information Networks*, 28(1), 47–76.
- Zhao, Y., Zhou, H., Li, M., 2008. Indoor access points location optimization using differential evolution. *2008 International Conference on Computer Science and Software Engineering*, 1, 382–385.
- Zirazi, S., Canalda, P., Mabed, H., Spies, F., 2012. Wi-fi access point placement within stand-alone, hybrid and combined wireless positioning systems. *2012 Fourth International Conference on Communications and Electronics (ICCE)*, 279–284.