



Received November 18, 2020, accepted December 12, 2020, date of publication December 16, 2020, date of current version December 30, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3045189

# Analysis of the Applicability of Dilution of Precision in the Base Station Configuration Optimization of Ultrawideband Indoor TDOA Positioning System

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This work was supported in part by the National Natural Science Foundation of China under Grant 61771151, in part by the Guangxi Innovation-Driven Development Project under Grant AA18118039, in part by the Guangxi Science and Technology Plan Project under Grant AD18281044, and in part by the Director Fund Project of Key Laboratory of Cognitive Radio and Information Processing of Ministry of Education under Grant CRKL190104.

**ABSTRACT** With the increasing demand for location awareness, indoor positioning has gradually become one of the research hotspots. In recent years the indoor positioning research field generally introduced dilution of precision (DOP) in the field of satellite navigation to the optimization of base station (BS) configuration, but in practice, the distribution of DOP and the distribution of errors is far from the same. This paper analyzes the applicability of DOP in the indoor time difference of arrival (TDOA) positioning systems from various aspects. Then, according to the ultrawideband (UWB) ranging error model, the TDOA time-difference measurement error model is derived and used as the BS configuration optimization metric. Finally, the experiments are conducted in 8 m \* 8 m \* 3 m small-scale scene and 100 m \* 30 m \* 10 m large-scale scene respectively to compare the positioning accuracy of the three BS configurations under different receiving signal-to-interference ratio (SIR). At the same time, the experiment is conducted in outdoor standard football field to compare the influence of multipath on the positioning accuracy of the three BS configurations under the conditions of two SIR. The experimental results show that the optimized BS configuration with DOP as the optimized target is not the best BS configuration, and the positioning accuracy is not as good as the commonly used cuboid 8-BS configuration in low SIR environment. It proves that DOP cannot be used as a decisive metric for the BS configuration optimization of UWB indoor positioning, but can be used as a reference index, and the optimized BS configuration with TDOA time-difference measurement error as the optimization target has higher positioning accuracy.


**INDEX TERMS** Dilution of precision, indoor positioning, ultrawideband, base station configuration.

## I. INTRODUCTION

With the development of wireless communication technology, location-based services have become a basic requirement for many Internet of Things (IoT) applications. Today, radio-based positioning has been widely used in navigation and tracking, and satellite-based positioning systems, such as the Global Positioning System (GPS), can be employed for

in-vehicle and personal navigation. However, satellite signals cannot provide reliable location service in an indoor environment because they are blocked by buildings [1]. As a result, a number of wireless positioning technologies are available for indoor scenes to position and track people and objects: Bluetooth, Wi-Fi, geomagnetic, pedestrian dead reckoning (PDR), sound, and ultrawideband (UWB) [1].

UWB and other indoor positioning technologies are essentially examples of the indoor pseudo-satellite positioning. The difference is that satellites are orbit-limited and highly

The associate editor coordinating the review of this manuscript and approving it for publication was Mohamed Kheir .

dynamic, whereas indoor positioning base stations are static, and the location of the base stations has an important impact on positioning accuracy. Given the similarity between the indoor positioning and satellite positioning, in recent years, research in the field of indoor positioning has introduced dilution of precision (DOP), which evaluates the effect of satellite conjugation on GPS accuracy, into the optimization of indoor positioning base station configuration [2]. In practice, the distribution of DOP is different greatly from the distribution of positioning errors, so the applicability of DOP for indoor positioning base station (BS) configuration optimization needs to be analyzed.

The BS configuration in positioning systems usually adopts the method of design and verification. It roughly selects the regular configurations based on the scene structure, and the positioning accuracy is analyzed using correlation criteria. Commonly used precision analysis guidelines include the Cramer–Rao bound (CRB) and DOP. Some scholars use multiparameter fusion methods for analysis by combining accuracy and coverage. CRB is a general method for assessing the benchmark toughness of any unbiased estimated quantity [3] and has been widely used to optimize BS configuration. Yang *et al.* used CRB for individual target points to derive the optimal layout of BSs at polyhedral vertices, but did not conduct an overall study on the BS layout of multiple target points in the positioning region [4]. Chang *et al.* studied the CRB for fixed anchor point positioning and determined the CRB upper and lower bounds for local geometries consisting of anchor points only, showing that the local geometry can be applied to predict the accuracy of the estimated position [5], and the derived CRB upper and lower bounds can be applied to base station deployment as an optimization target, thus allowing the accuracy of the prediction of the global estimated position to be improved. However, in most cases, the methods of using CRB for BS configuration optimization are based on an exhaustive search for the smallest average CRB to obtain an optimal anchor point layout. In [6], the whole positioning area is divided into several grids, and BS location is obtained by permutation and combination, and the whole plane is evaluated. This method has high computational complexity and large amount of calculation.

Since geometric dilution of precision (GDOP) decouples the geometric aspects from the propagation aspects of positional error estimation [8], in recent years GDOP in the field of satellite navigation has begun to be introduced into indoor positioning. In studies on the BS configuration optimization of indoor positioning, Sharp *et al.* analyzed GDOP for several specific cases and compared it with simulations of several typical geometries of indoor positioning system, and the results showed that GDOP exhibited good agreement with experimental results except when the mobile station (MS) was close to the BS [2], [7], but due to NLOS and multipath issues in the indoor environment far more complex than Global Navigation Satellite System (GNSS), GDOP usually overestimating the accuracy of the positioning results when

the MS is close to BS. Lv *et al.* presented new mathematical expressions for GDOP in the time of arrival (TOA) and angle of arrival (AOA) positioning systems and analyzed the influence of adding a new anchor node at different locations [8]. This part of the study provides useful information for the design and testing of positioning systems, improving GDOP for indoor environments and making it somewhat adaptable to complex indoor environments.

Bharadwaj *et al.* conducted a comparative study of four BS configurations (cuboid-shape, Y-4, L-3, and mirror-based) and for the first time introduced GDOP as a tool for evaluating UWB BS configurations [9]–[11], the authors' focus on BS configurations is to ensure accuracy while making the BS configuration more compact and reduce the cost as much as possible. An accuracy comparison, which was evaluated by the GDOP mean values, was performed by Ren *et al.* between an 8-base-station configuration and the three configurations proposed by Ren *et al.* [12], Wang [13]. The use of a small number of BS has the advantage of saving space resources and costs when the requirement for positioning accuracy is not high, but this type of study only focuses on several typical BS configurations and does not propose a method for optimizing BS configurations. Wang *et al.* used four BS configurations to study the distribution of DOP and the relationship between DOP and BS configurations [14], differing from previous studies that only focused on static MS for localization, Wang also performed localization experiments on dynamic MS. Zhang *et al.* weighted summation of multiple DOP as an optimization target and then used the method based on maximum convex-hull (OSMC) to obtain the optimal BS configuration [15], which differs from previous studies in that Zhang weighted summation of multiple DOP and gave a method to solve the BS configuration optimization instead of directly evaluating the BS configurations with the mean value of GDOP and comparing only a few kind of typical BS configurations.

Zhong quantitatively analyzed the BS configuration performance based on the three evaluation metrics: position dilution of precision (PDOP), coverage redundancy and BS node density. Then the location areas were divided into a single set of BS service space and multiple sets of BS service space according to the UWB sensing radius and location principle. A mathematical model of the optimal geometric BS configuration using PDOP was established in the single set BS service space, and finally the model was iteratively solved by a genetic algorithm [16]. The authors directly take PDOP as the objective function of BS configuration optimization and establish a mathematical model, and considering the need for multicellular systems in large scenes at the same time, which is of great help to the current BS configuration research.

At present, most of the indoor positioning BS configuration studies, except for [15], [16], use design and verification methods to compare several classical BS configurations without proposing a solution method for the optimal BS configuration, whereas [16] only uses PDOP as the optimization

target in the single set of BS service space. After the introduction of DOP in recent years, it has become common to use various DOP mean values to evaluate the performance of a BS configuration, but there are few analyses on the applicability of DOP in indoor positioning. In practice, DOP was originally designed to be used in large scale positioning scenes in the field of satellite navigation, whereas indoor positioning, a small-scale positioning scene, faces far more complex NLOS and multipath problems than the GNSS, and is also somewhat different from GNSS in terms of application. Therefore, it is necessary to analyze the applicability of DOP in the field of UWB indoor positioning base station configuration optimization and then design a reasonable optimization target and optimization strategy.

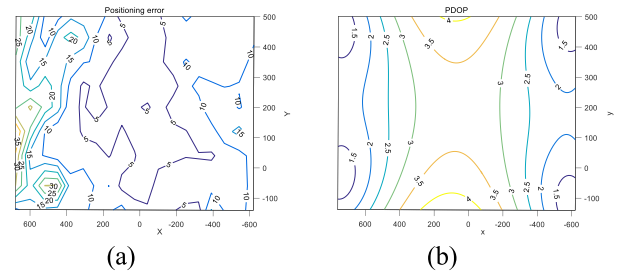
Based on the issues identified by the research on the use of DOP in the indoor positioning base station configuration, this paper analyzes the applicability of DOP in the optimization of indoor time difference of arrival (TDOA) positioning system base station configuration, and makes the following contributions:

- 1) It deduces that the DOP only considers the angles between MS and BSs but ignores NLOS and multipath, and the difference in relative distance between MS and each BS.
- 2) The TDOA time-difference measurement error model is deduced from the UWB ranging error, which is used as a BS configuration optimization metric.
- 3) Several BS configurations are assessed in small-scale scene and large-scale scene respectively, and the experimental results further demonstrate that DOP cannot be used as a decisive metric for the BS configuration optimization of UWB indoor positioning.
- 4) The experimental results in the outdoor standard football field show that the multipath has little effect on the positioning accuracy under the condition of high receiving signal-to-interference ratio (SIR), whereas the influence of multipath on the positioning accuracy is more serious when the received SIR is low.

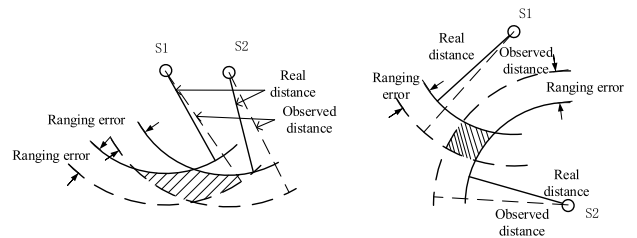
**II. ANALYSIS OF THE APPLICABILITY OF DOP**

GDOP is currently the most popular metric in determining a good BS configuration in positioning systems. In positioning applications that do not include estimates of time-offset errors, GDOP should be replaced with a Position Dilution of Precision (PDOP) [17]. PDOP represents the ratio of the positioning error to the ranging error [18]. The size of the DOP value is proportional to the error of GPS positioning, and the larger the DOP value, the lower the positioning accuracy.

GPS satellites constantly broadcast their own position information, attaching a time stamp to the data packet [19]. After receiving the packet, the GPS receiver subtracts the time on the timestamp from the current time to get the transmission time of the data packet, thus obtaining the distance between the satellite and the receiver. Finally, the position of the receiver is identified using the TOA position estimation method.



**FIGURE 1. Comparison of the positioning error distribution and the PDOP distribution. (a) Positioning error distribution; (b) PDOP distribution.**



**FIGURE 2. Two-star ranging.**

In practice, the distribution of DOP values is quite different from the distribution of the positioning error, as shown in Fig. 1, where Fig. 1 (a) shows the distribution of positioning error and Fig. 1 (b) shows the distribution of PDOP. From the contour plot of Fig. 1 (a), it can be seen that in the actual localization, the central region is better and the border region is worse, whereas in contrast, the contour plot of Fig. 1 (b) shows that the PDOP is smallest at the four corners, and since the PDOP is proportional to the localization error [18], it can be considered that the localization is best at the four corners, while the central region is worse, which is completely opposite to the trend of the actual error distribution. In an indoor positioning system where the average error is expected to be as low as possible, the DOP value is not a good way to evaluate the performance of the BS configuration.

**A. RELATIONSHIP BETWEEN BS CONFIGURATION AND DOP**

As an example of two-star ranging (as shown in Fig. 2), S1 and S2 are satellites, with solid lines representing the real distance and dashed lines representing the observed distance. Under the condition that the ranging error is fixed, the GDOP value is very high when the satellites’ angular position in the sky is relatively close. At that time, the satellite signal will produce an overlapping region (the shaded region in Fig. 2) at the smaller angle position, so that the closer the distance, the larger the overlapping region. Since the final positioning results fall within the overlapping region, the larger it is, the greater the effect on the positioning accuracy. Therefore, when the satellites are at certain distance from each other and the position of the MS is surrounded by the satellites [2], the signal is clearer at the point of intersection, and the error is reduced. In the TOA positioning systems, the GDOP at

the center of an N-sided regular polygon is mathematically given, and the simulations have proven that the GDOP is the smallest at the center [20]. Most studies show that the DOP increases rapidly as the distance between the MS and the center of the polygon increases, especially outside the polygon [2], [20].

PDOP is obtained using the horizontal dilution of precision (HDOP) and the vertical dilution of precision (VDOP),

$$PDOP = \sqrt{HDOP^2 + VDOP^2}, \quad (1)$$

whereas HDOP and VDOP are obtained using the observation matrix  $H$  and the weight coefficient matrix  $Q$ . The observation matrix  $H$  is

$$H = \begin{pmatrix} \frac{x_1-x}{r_1} & \frac{y_1-y}{r_1} & \frac{z_1-z}{r_1} \\ \vdots & \vdots & \vdots \\ \frac{x_n-x}{r_n} & \frac{y_n-y}{r_n} & \frac{z_n-z}{r_n} \end{pmatrix}, \quad (2)$$

where  $(x, y, z)$  are the coordinates of the MS,  $(x_n, y_n, z_n)$  are the coordinates of the  $n^{\text{th}}$  BS, and  $r_n$  is the distance from the MS to the  $n^{\text{th}}$  BS. The weight coefficient matrix  $Q$  is calculated as follows:

$$Q = (H^T H)^{-1}. \quad (3)$$

$Q$  is a  $3 \times 3$  matrix, where  $q_{ii}$  is the diagonal element of  $Q$ , then PDOP can be found as follows:

$$PDOP = \sqrt{q_{11} + q_{22} + q_{33}} \\ = \sqrt{\frac{\sum_{i=1}^n \left(\frac{x_i-x}{r_i}\right)^2 + \sum_{i=1}^n \left(\frac{y_i-y}{r_i}\right)^2 + \sum_{i=1}^n \left(\frac{z_i-z}{r_i}\right)^2}{|H^T H|}}. \quad (4)$$

From (4), we know that molecule

$$\sum_{i=1}^n \left(\frac{x_i-x}{r_i}\right)^2 + \sum_{i=1}^n \left(\frac{y_i-y}{r_i}\right)^2 + \sum_{i=1}^n \left(\frac{z_i-z}{r_i}\right)^2 \quad (5)$$

is always equal to  $n$ , so the size of PDOP is inversely proportional to  $|H^T H|$ . From the observation matrix  $H$ , the distance from each BS to the MS has been normalized and the positions of all BSs are represented by vectors of length 1. That is, the distances from all BSs to the MS are assumed to be equal, ignoring the difference in distance between each BS and the MS (i.e.,  $r_i \gg |r_i - r_j|$ , which is reasonable in satellite positioning) and considering only the angles from BSs to the MS. Thus the size of PDOP is only related to the angles between BSs and the MS, and not to the difference in relative distance from each BS to the MS. H.B. Lee [19] has explained the principle and application of DOP in detail, so it will not be discussed here.

The effect of the angles between the BSs and the MS on the DOP will be discussed below using an example of an indoor 3-BSs positioning. Since the distances between the BSs and the MS are normalized, the BSs can be considered to be on a unit circle, with the MS constituting the center

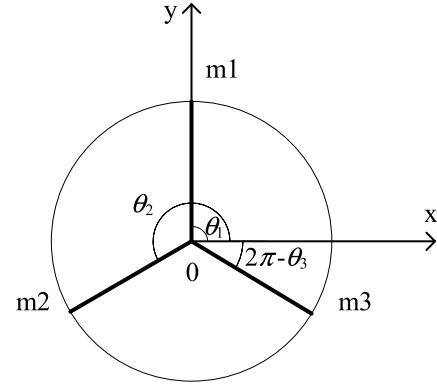


FIGURE 3. DOP varies with the angles between BSs.

of the circle. In Fig. 3,  $m_1$ ,  $m_2$ , and  $m_3$  are the positions of the three BSs; angle  $\theta_1$  (between  $m_1$  and the x-axis) and angle  $\theta_2$  (between  $m_2$  and the x-axis) are known variables, and angle  $\theta_3$  (between  $m_3$  and the x-axis) is an unknown variable. Substituting  $\theta_1$ ,  $\theta_2$  and  $\theta_3$  into (2), (3), and (4) yields the following:

$$H^T H = \begin{pmatrix} \sum_{i=1}^3 x_i^2 & \sum_{i=1}^3 x_i y_i \\ \sum_{i=1}^3 x_i y_i & \sum_{i=1}^3 y_i^2 \end{pmatrix} \\ = \begin{pmatrix} \sum_{i=1}^3 \cos^2 \theta_i & \sum_{i=1}^3 \sin \theta_i \cos \theta_i \\ \sum_{i=1}^3 \sin \theta_i \cos \theta_i & \sum_{i=1}^3 \sin^2 \theta_i \end{pmatrix}, \quad (6)$$

$$|H^T H| = \sin^2(\theta_1 - \theta_2) + \sin^2(\theta_3 - \theta_1) + \sin^2(\theta_3 - \theta_2), \quad (7)$$

$$Q = (H^T H)^{-1} \\ = \begin{pmatrix} \frac{\sum_{i=1}^3 \sin^2 \theta_i}{|H^T H|} & -\frac{\sum_{i=1}^3 \sin \theta_i \cos \theta_i}{|H^T H|} \\ -\frac{\sum_{i=1}^3 \sin \theta_i \cos \theta_i}{|H^T H|} & \frac{\sum_{i=1}^3 \cos^2 \theta_i}{|H^T H|} \end{pmatrix}, \quad (8)$$

$$PDOP = \sqrt{\frac{\sum_{i=1}^3 \sin^2 \theta_i}{|H^T H|} + \frac{\sum_{i=1}^3 \cos^2 \theta_i}{|H^T H|}} \\ = \sqrt{\frac{3}{\sin^2(\theta_1 - \theta_2) + \sin^2(\theta_3 - \theta_1) + \sin^2(\theta_3 - \theta_2)}}, \quad (9)$$

where  $x_i = \cos \theta_i$  and  $y_i = \sin \theta_i$ . From (9), it can be seen that the angles  $(\theta_3 - \theta_1)$  and  $(\theta_3 - \theta_2)$  directly determine the size of PDOP, so PDOP is a function of  $\theta_3$ , decreasing with an increasing in  $\sin^2(\theta_3 - \theta_1) + \sin^2(\theta_3 - \theta_2)$ . At the same time, since  $\sin^2(\theta_3 - \theta_1)$  and  $\sin^2(\theta_3 - \theta_2)$  change periodically, it is not the size of the angles between the BSs that is more important, but their relative distance from each other (the further, the better).

**B. RELATIONSHIP BETWEEN BS CONFIGURATION AND TDOA TIME-DIFFERENCE MEASUREMENT ERROR**

In indoor positioning, the main source of positioning error is temporal measurement error (i.e., ranging error), which is caused by physical measurements, NLOS, and multipath effects, and UWB ranging error is mainly caused by NLOS. The interference of NLOS can be eliminated in a see-through environment, but the multipath effect is unavoidable, and only in a microwave anechoic chamber can the effects of multipath effect be eliminated by absorbing electromagnetic waves through the special material on the walls, however, it is impossible to have the conditions of a microwave anechoic chamber in actual engineering applications. Even if the UWB signal is separated by at least one pulse width duration so that the signals do not overlap, it is simply better resistant to multipath effects relative to narrowband signals, but it is still not completely avoided the interference of multipath effects [21]. The S-V channel model is the commonly used UWB channel model [22], and the IEEE Working Group has also proposed two standard channel models for UWB systems based on the S-V model, the IEEE802.15.3a UWB channel model and the IEEE802.15.4a UWB channel model, in which the channel model has explicitly revealed that UWB signal decay obeys an exponential distribution. In the case of excluding NLOS interference, a positive correlation between UWB ranging error and range has been proposed [23,24] and experimentally verified. When the MS is closer to BS, the direct path signal always arrives before other multipath signals, and its energy is much larger than the energy of other multipath signals, and the receiving SIR is high, so that the direct path signal is easy to distinguish. When the MS is farther away from BSs, due to signal decay obeys the exponential distribution, the gradient of signal decay tends to 0, even if the direct path signal than the multipath signal first reached the receiving antenna, but the energy of the direct path signal and other multipath signal energy difference is very small, not easy to distinguish. At this time, the main component of the received signal is no longer a direct path signal, the Ricean K-factor approaches 0, and the signal changes from a Ricean distribution to a Rayleigh distribution. The receiving SIR decreases, which increases the probability of missed detection and false alarms, and thus is subject to more severe multipath effect interference. In the NLOS environment, there is no direct path signal in the received signal, but only multipath signal, which is not easy to distinguish, so the NLOS identification and compensation of UWB is also one of the current research focus.

In the process of ranging, there will be errors caused by physical measurement, even in the LOS environment and without multipath interference. The error equation can be expressed as  $\gamma_{P,i} = a + br_i + \varepsilon_i$  after a linear fit, where  $\gamma_{P,i}$  is the physical measurement error,  $a$  is the system's own error,  $b$  is the distance influencing factor,  $a + br_i$  constitutes the systematic error,  $\varepsilon_i$  is the random error, and  $r_i$  is the distance. It is proposed in [22] to model the multipath error and obtain  $\gamma_{M,i} = G \log(1 + r_i)$ , where  $\gamma_{M,i}$  is the error caused by the

multipath effect, and  $G$  is the parameter to normalize the error, so that the normalized error obeys Gaussian distribution, so the error equation should be

$$\gamma_i = \gamma_{P,i} + \gamma_{M,i} = a + br_i + \varepsilon_i + G \log(1 + r_i). \quad (10)$$

Since TDOA uses the arrival time difference (i.e., the distance difference between the MS and each BS) to solve for the MS's coordinates, the observed distance difference  $\hat{r}_{ij}$  between each BS is as follows:

$$\begin{aligned} \hat{r}_{ij} &= \hat{r}_i - \hat{r}_j = (r_i + \gamma_i) - (r_j + \gamma_j) \\ &= (r_i - r_j) + b(r_i - r_j) + (\varepsilon_i - \varepsilon_j) + G \log \frac{1 + r_i}{1 + r_j} \\ &\approx (r_i - r_j) + b(r_i - r_j) + G \log \frac{1 + r_i}{1 + r_j}, \end{aligned} \quad (11)$$

where  $(r_i - r_j)$  is the real distance difference, and  $b(r_i - r_j) + G \log[(1 + r_i)/(1 + r_j)]$  is the error. Random errors  $(\varepsilon_i - \varepsilon_j)$  are negligible because they are small enough. According to the TDOA formula:

$$\begin{pmatrix} x_2 - x_1 & y_2 - y_1 & z_2 - z_1 & r_{21} \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 & r_{31} \\ \vdots & \vdots & \vdots & \vdots \\ x_n - x_1 & y_n - y_1 & z_n - z_1 & r_{n1} \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ r_1 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} K_{21} - r_{21}^2 \\ K_{31} - r_{31}^2 \\ \vdots \\ K_{n1} - r_{n1}^2 \end{pmatrix}, \quad (12)$$

where

$$A = \begin{pmatrix} x_2 - x_1 & y_2 - y_1 & z_2 - z_1 & r_{21} \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 & r_{31} \\ \vdots & \vdots & \vdots & \vdots \\ x_n - x_1 & y_n - y_1 & z_n - z_1 & r_{n1} \end{pmatrix}, \quad (13)$$

$$\theta = \begin{pmatrix} x \\ y \\ z \\ r_1 \end{pmatrix}, \quad (14)$$

$$b = \frac{1}{2} \begin{pmatrix} K_{21} - r_{21}^2 \\ K_{31} - r_{31}^2 \\ \vdots \\ K_{n1} - r_{n1}^2 \end{pmatrix}, \quad (15)$$

$$\theta = A^+ b = (A^T A)^{-1} A^T b, \quad (16)$$

then the TDOA formula that uses observations  $\hat{r}_{ij}$  to calculate should be changed to the following:

$$\begin{pmatrix} x_2 - x_1 & y_2 - y_1 & z_2 - z_1 & \hat{r}_{21} \\ x_3 - x_1 & y_3 - y_1 & z_3 - z_1 & \hat{r}_{31} \\ \vdots & \vdots & \vdots & \vdots \\ x_n - x_1 & y_n - y_1 & z_n - z_1 & \hat{r}_{n1} \end{pmatrix} \begin{pmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \\ \hat{r}_1 \end{pmatrix} = \frac{1}{2} \begin{pmatrix} K_{21} - \hat{r}_{21}^2 \\ K_{31} - \hat{r}_{31}^2 \\ \vdots \\ K_{n1} - \hat{r}_{n1}^2 \end{pmatrix}. \quad (17)$$

In solving (17), the following is obtained  $\hat{\theta} = \hat{A}^+ \hat{b}$ , and the positioning error

$$\Delta = \hat{\theta} - \theta = \begin{pmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta r_1 \end{pmatrix}, \quad (18)$$

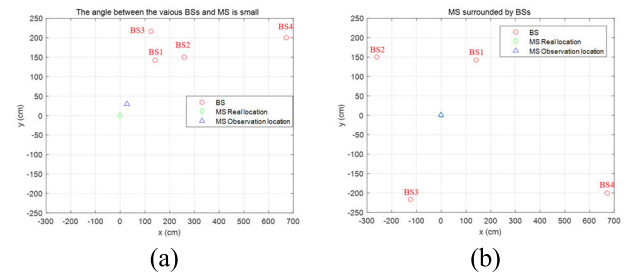
then the TDOA time-difference measurement error is obtained

$$\varphi = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}. \quad (19)$$

It can be found that the error of the MS is positively related to the squared sum of the distance difference  $r_{ij}$ . However, the MS positioning accuracy is not only affected by the distance difference, but also the angle between MS and BS, if the angle between the various BSs and MS is smaller, the positioning error is larger; on the contrary, if the MS is in the area surrounded by BSs, the positioning error is smaller, which is also proved by the PDOP. Taking 2D positioning as an example (as shown in Fig. 4), the TDOA formula has three unknowns  $x$ ,  $y$ , and  $r_1$ . Three equations are required to obtain the unique solution, thus requiring four BSs. In Fig. 4 (a), BSs are all located in the first quadrant, and in Fig. 4 (b), there are BSs in all four quadrants, where BS1, BS2, BS3, and BS4 are BSs (BSs are indicated by red circles), the true position of MS is located at the origin of the coordinate axis (the true position of MS is indicated by a green diamond), the MS observation position is indicated by a blue square, and the distance from each BS to the true position of MS is equal in both graphs, with only the angle changed. As shown in the Fig. 4, when the distance measurement error is the same, the angle between BSs and MS also has a large influence on the TDOA solving results. Therefore, using the TDOA time-difference measurement error as the optimization target can fully take into account the influence of physical measurement and multipath effect on the distance measurement accuracy, and at the same time, the influence of the angle between BSs and MS on the TDOA solving results, which makes it reliable in the BS configuration optimization of UWB indoor positioning.

### C. SCOPE OF APPLICATION OF DOP IN BS CONFIGURATION

In indoor positioning, the influence on positioning accuracy of the ranging error (i.e., time measurement error) is equally important to that of the angles between BSs and MS. Since the ranging error of the electromagnetic wave is positively correlated with the range [23], [24], the distances between BSs and MS in indoor positioning need to be shortened as much as possible to reduce the ranging error. DOP, however, ignores the difference in relative distance between each BS and MS. This is due to the fact that in satellite positioning, the distance between a satellite and a receiver is much greater than the difference in distance from each satellite to the receiver, where the distance from each satellite to the receiver can be considered equal so the ranging statistical errors of



**FIGURE 4.** The effect of the angle between MS and BSs on the solving result of TDOA. (a) The angle between the various BSs and MS is small; (b) MS surrounded by BSs.

all satellites can be considered equal. On the other hand, GNSS is interfered by NLOS mainly because of the shielding of tall buildings in the city, which is the main reason why GNSS cannot provide reliable positioning services indoors. Secondly, GNSS is interfered by the multipath effect mainly because the path of the signal bends when it passes through the ionosphere and the propagation speed also changes, that is the ionospheric delay; similarly, the path bends when the signal passes through the troposphere; and reflectors around the receiver reflect the signal to the receiver antenna, which interferes with the signal coming directly from the satellite. The current receiver has been able to compensate the ranging error on the propagation path according to the priori errors, so the problem of NLOS and multipath effect is not considered when DOP is used. Since the receiver compensates for the distance measurements based on a priori errors, allowing for GPS positioning accuracy to be within a few meters. Generally,  $DOP < 3$  is considered to be a better constellation layout, with GPS positioning error being within 5 m. According to PDOP, which is the ratio of positioning error to ranging error, the ranging error that has been compensated for a priori error is  $< 2$  m. At that point, the  $< 2$  m range error is negligible compared to the range of more than 10,000 meters, and the relative range error  $\delta_1 < 1/5000$  or the gradient value of the absolute error is close to zero.

The propagation of electromagnetic waves in an indoor environment is far more complex than in an open outdoor environment, where they are refracted and diffracted from surrounding walls, floors, ceilings, and other indoor objects, making multipath problems more serious and uncontrollable in indoor environments than outdoors. The positioning accuracy of indoor positioning technology, represented by UWB, has been developed to the centimeter level, and although UWB has better resistance to multipath effects, it is still not avoided multipath interference. Taking the cuboid 8-BS configuration as an example, in an  $8 \text{ m} \times 8 \text{ m} \times 3 \text{ m}$  room, when the MS is close to a BS, the distance from that BS to the label is even smaller than the distance difference between other BSs and that BS to the label (i.e.,  $|r_i - r_j| > r_i$ ), where the distances between all BSs and the MS are considered equal is obviously unreasonable. At this time, the ranging error of UWB is about 5 cm, which is sufficient to make the positioning error reach  $> 10$  cm. Although the 5 cm

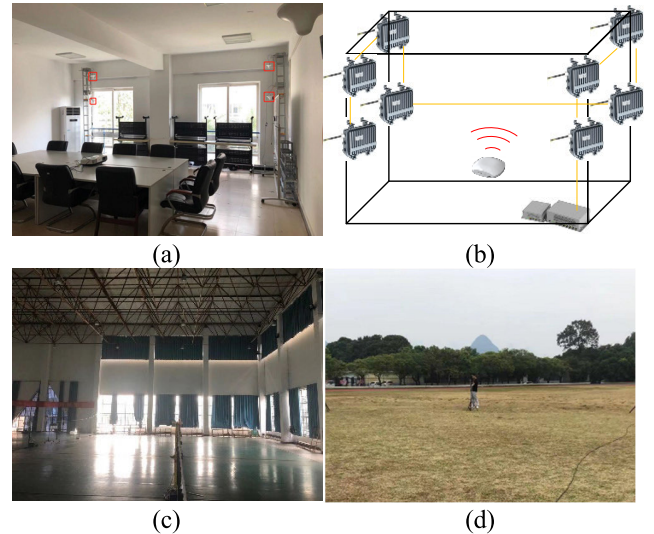
ranging error is lower than the 10 m range, it has not reached a level that can be ignored because the relative range error  $\delta_2 > 1/200$  is larger than the satellite range error  $\delta_1$  by a magnitude. Therefore, the difference in relative distance between each BS and MS must be taken into account in the BS configuration of the indoor positioning to reduce the ranging error and improve the positioning accuracy.

In summary, the use of PDOP for BS configuration optimization is a theoretical possibility, but it is not sufficiently considered, and only considers the effect of angle on positioning, ignoring the NLOS and multipath problems that are far more complex than GNSS in the indoor environment, which has certain limitations. Therefore, PDOP cannot be used as a decisive metric in the BS configuration optimization of indoor positioning, but it can be used as a reference metric.

### III. MATERIALS AND METHODS

#### A. EXPERIMENTAL SCENE AND EXPERIMENTAL EQUIPMENT

UWB, with its extremely high temporal resolution [23], has a significant advantage in indoor positioning. In this paper, an experimental analysis was conducted using UWB indoor positioning as an example. In order to compare the positioning effect of several BS configurations under different receiving SIR, the experiment is divided into two parts: small-scale positioning experiment and large-scale positioning experiment. The small-scale positioning experiment is used to compare the positioning accuracy of various base station configurations under the condition of high SIR. An 8 m \* 8 m \* 3 m conference room with tables, chairs, and other obstacles was selected as the small-scale experimental scene. The small-scale experimental scene and its mock-up are shown in Fig. 5 (a)(b). The large-scale positioning experiment is used to compare the positioning accuracy of various BS configurations under the condition of low SIR. The large-scale experimental scene is a gymnasium with 100 m \* 30 m \* 10 m, which is shown in the Fig. 5 (c). Due to the limitation of the fiber length of the UWB indoor positioning system, the large-scale positioning experiment is conducted in the range of 20 m \* 17 m according to the limit length of optical fiber. At the same time, in order to compare the interference of multipath effect on positioning accuracy under two kinds of SIR conditions, we also conduct experiments in the same size outdoor, because in the infinitely large space, it can be regarded as no multipath effect interference. Therefore, we limit a range of the same size in the football field according to the small-scale scene, and we conduct experiment in this limited range to compare the effect of multipath on the positioning accuracy of different BS configurations under high SIR conditions. And then, we limit a range of the same size in the football field according to the large-scale scene, and we conduct experiment in this limited range to compare the effect of multipath on the positioning accuracy of different BS configurations under low SIR conditions. The outdoor experimental scene is shown in the Fig. 5 (d).



**FIGURE 5.** The experimental scene. (a) Small-scale experimental scene; (b) Mock-up of the small-scale experimental scene; (c) Large-scale experimental scene; (d) Outdoor experimental scene.

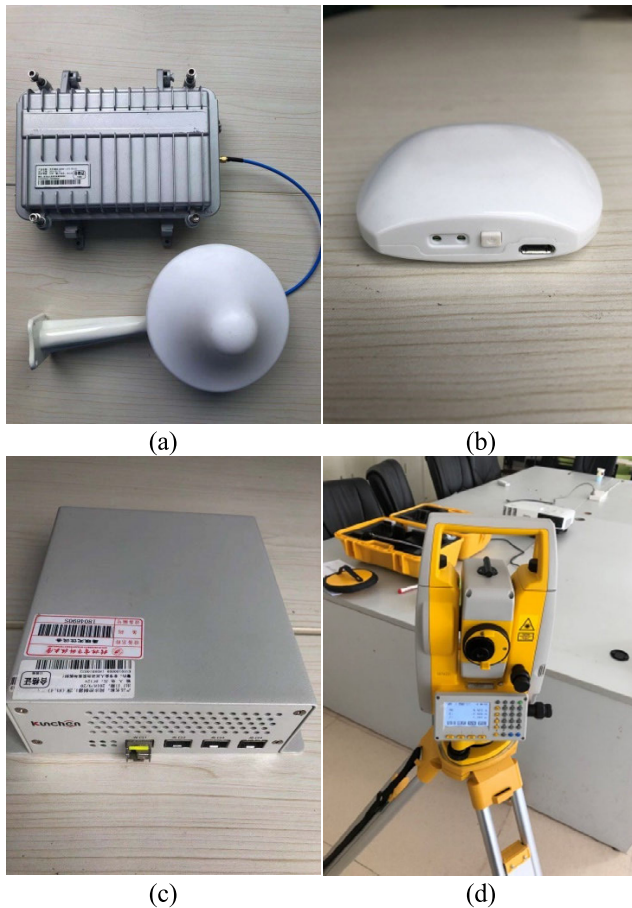
The experimental equipment included an UWB indoor positioning system, an electronic total station and a computer. The UWB indoor positioning system used the Sichuan CLP Kunchen Hawkeye system, which included a fiber synchronization controller, a MS, and eight BSs, which were interconnected by optical fibers and fixed on the truss to facilitate movement. To obtain the actual precise location of the BS antennas and MS, the BS antennas and MS were calibrated using the Southern Mapping NTS-332R4 Electronic Total Station. The BSs transmitted a time stamp of the received MS signal to the fiber synchronization controller through the optical fiber for delay compensation, and then the time stamp was then transmitted to the computer, which calculated the MS coordinates using TDOA. The UWB indoor positioning base station (BS), mobile station (MS), fiber synchronization controller, and the electronic total station are shown in Fig. 6.

#### B. BS CONFIGURATION

In this paper, a genetic algorithm was used to obtain the BS configuration with PDOP as the optimization objective (*PDOP-optimized BS configuration*) according to the mathematical model given in [16]. The optimization objective function of the model is as follows:

$$\begin{aligned} \min f_1(x_1, y_1, z_1, \dots, x_8, y_8, z_8) \\ = \frac{\sum_{i=1}^M \sum_{j=1}^N PDOP(i, j)}{M * N} \\ s.t. \ x_{\min} < x_n < x_{\max}, y_{\min} < y_n < y_{\max}, \\ z_{\min} < z_n < z_{\max}, n = 1, 2, 3, \dots, 8, \end{aligned} \quad (20)$$

where  $(x_n, y_n, z_n)$  are the coordinates of the  $n^{\text{th}}$  BS;  $(x_{\min}, y_{\min}, z_{\min})$  and  $(x_{\max}, y_{\max}, z_{\max})$  indicate the upper and lower bounds of the BS in X, Y, and Z directions in the



**FIGURE 6.** The experimental equipment. (a) Base station; (b) mobile station; (c) fiber synchronization controller; (d) electronic total station.

feasible solution region; the scene is dissected into  $M * N$  tiny regions, and each tiny region can be considered as a sample point.

The TDOA time-difference measurement error model has been proposed in Section 2.2. In practical applications, at least five BSs are required for 3D positioning, but it is not necessary for all BSs to participate in the calculation, so in this paper, the information from the first six BSs to arrive is selected to participate in the calculation. The specific steps are:

- 1) Dissecting the scene into  $M * N$  microregions, each of which can be considered a sample point;
- 2) Calculation of the true distance from the sample points to each BS;
- 3) The true distances from sample points to individual BSs were substituted for the range error model to obtain the observed distances;
- 4) Ranking of observation distances from small to large;
- 5) The information from the first six BSs (i.e. the shortest observation distance) was selected and substituted into the TDOA time-difference measurement error model to obtain the TDOA time-difference measurement error for the sample point;

- 6) The mean of the TDOA time-difference measurement error for all sample points is used as a metric for this BS configuration, so its optimization objective function is:

$$\begin{aligned} \min f_2(x_1, y_1, z_1, \dots, x_8, y_8, z_8) \\ = \frac{\sum_{i=1}^M \sum_{j=1}^N \varphi_{ij}}{M * N} \\ \text{s.t. } x_{\min} < x_n < x_{\max}, y_{\min} < y_n < y_{\max}, \\ z_{\min} < z_n < z_{\max}, n = 1, 2, 3, \dots, 8; \end{aligned} \quad (21)$$

- 7) The BS configuration with the lowest mean value of the TDOA time-difference measurement error is selected as the output, and the *TDOA time-difference measurement error-optimized BS configuration* is obtained.

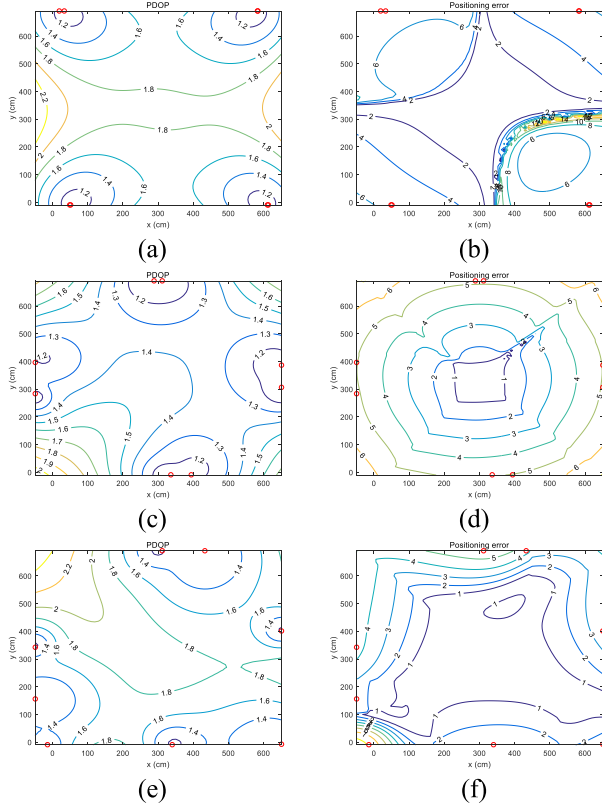
The experiments in this paper are based on practical applications, in order not to affect the daily production and life, the BS can only be deployed along the surrounding walls. Finally, a comparison study in terms of accuracy and applicability was performed between the commonly used *cuboid 8-BS configuration* and the two optimized BS configurations (*PDOP-optimized BS configuration*, and *TDOA time-difference measurement error-optimized BS configuration*).

## IV. RESULTS AND ANALYSIS

### A. COMPUTER SIMULATION RESULTS AND ANALYSIS

The simulations were carried out using the cuboid 8-BS configuration, the PDOP-optimized BS configuration, and the TDOA time-difference measurement error-optimized BS configuration. The positioning error distribution and PDOP distribution are shown in Fig. 7, where the red points represent the BS locations and the line represents the contour line of the value. The comparison of results is shown in Tab. 1. According to the simulation experiments, although the PDOP-optimized BS configuration can improve the positioning accuracy, it is not as effective as the TDOA time-difference measurement error-optimized BS configuration, and there is a big difference between the PDOP distribution and the error distribution, which cannot characterize the error distribution in the indoor TDOA positioning system. From Fig. 7 (a), (c), and (e) can be seen, the distribution of PDOP are centered on the BS and radiates all around, because the MS is surrounded by any four BSs can get a good PDOP, in this case the increase in anchor point can bring a slight increase in PDOP. Therefore, it can be seen from Fig. 7, most of the region are surrounded by at least four BSs, whereas the PDOP values outside the region surrounded by BSs are larger, and through the distribution of contour lines can be seen the contour lines outside the region surrounded by BSs are denser, indicating that the PDOP upward gradient is large. Fig. 7 (b), (d), and (f) shows that the error is smaller when the distance between the MS and each BS is relatively close, and larger when the distance is relatively far. This is because in TDOA solving, the use of distance difference can offset part of the distance measurement error, and if the distance between the MS and each BS is relatively close, it can offset most of





**FIGURE 7.** Comparison of the simulation results. (a) (b) The PDOP and error distribution of the cuboid 8-BS configuration; (c) (d) the PDOP and error distribution of the PDOP-optimized BS configuration; (e) (f) the PDOP and error distribution of the TDOA time-difference measurement error-optimized BS configuration.

**TABLE 1.** Pre-optimized and Post-optimized performance comparison (simulation).

| Accuracy metric       | Cuboid 8-BS configuration | PDOP-optimized BS configuration | TDOA time-difference measurement error-optimized BS configuration |
|-----------------------|---------------------------|---------------------------------|---|
| PDOP                  | 1.6579                    | 1.3977                          | 1.6748  |
| Average error(cm)     | 3.9983                    | 3.8533                          | 1.8483  |
| Mean square error(cm) | 21.9362                   | 16.8965                         | 5.4608  |

the distance measurement error, thus reducing the positioning error. The reason for the large positioning errors at all four corners is that the angle between all the BSs and the MS is only 90 degrees, as shown in Figure 4 in Section 2.2, and the small angle between the BSs and the MS will also lead to a decrease in positioning accuracy.

**B. ACTUAL TESTING RESULTS AND ANALYSIS**

**1) RESULTS AND ANALYSIS OF SMALL-SCALE POSITIONING EXPERIMENTS**

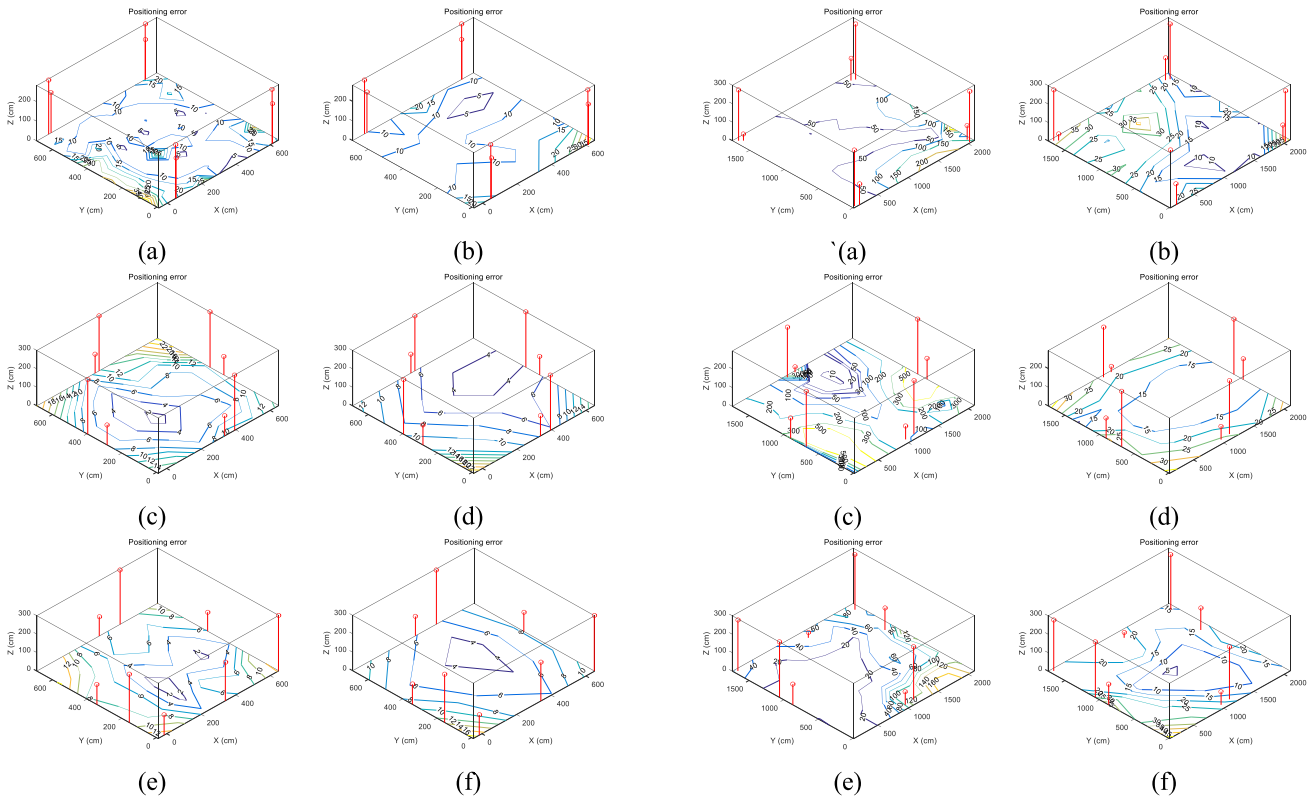
Based on the PDOP-optimized BS configuration and the TDOA positioning error-optimized BS configuration

**TABLE 2.** Pre-optimized and Post-optimized performance comparison (small-scale positioning experiment).

| Accuracy metric               | Cuboid 8-BS configuration | PDOP-optimized BS configuration | TDOA time-difference measurement error-optimized BS configuration |
|-------------------------------|---------------------------|---------------------------------|---|
| Indoor average error(cm)      | 13.6491                   | 9.9599                          | 7.1709  |
| Outdoor average error(cm)     | 12.6558                   | 9.1238                          | 8.1596  |
| Indoor mean square error(cm)  | 265.0826                  | 129.3889                        | 64.1111   |
| Outdoor mean square error(cm) | 232.4800                  | 117.5625                        | 81.4375   |
| Indoor variance               | 79.7696                   | 30.1888                         | 12.6897   |
| Outdoor variance              | 72.3101                   | 34.3193                         | 14.8577   |

obtained in Section 3.2, the BS were deployed separately, and then compared with the cuboid 8-BS configuration. The experimental scene setup and execution process ensures that the MS at each location exists in an LOS path with each BS to exclude NLOS interference. The experimental results show that the performance of the PDOP-optimized BS configuration and the TDOA time-difference measurement error-optimized BS configuration are improved compared to the cuboid 8-BS configuration, with the optimization effect of the TDOA time-difference measurement error-optimized BS configuration being more pronounced. The experiments were conducted within the same size range of the conference room in a standard outdoor football field, and the results were similar to those in the room. The data comparison of the three BS configurations is shown in Tab. 2, and the distribution of the actual errors of the three BS configurations in small-scale scene are shown in Fig. 8 (a), (c), and (e), and the distribution of the actual errors in outdoor scene are shown in Fig. 8 (b), (d), and (f), where the red points represent the BS positions.

According to Fig. 8, after actual testing, the actual error and variance of the PDOP-optimized BS configuration and TDOA time-difference measurement error-optimized BS configuration are smaller than that of the cuboid 8-BS configuration. While the average error decreases, the error of boundary area is larger than that of central area, but it is significantly improved compared with Cuboid 8-BS configuration, and the positioning stability of the whole target scene is also good. Among them, the TDOA time-difference measurement error-optimized BS configuration is better than the PDOP-optimized BS configuration, and it can be seen from the Fig. 8 that the error increase gradient of the PDOP-optimized BS configuration at the four corners is larger than that of the TDOA time-difference measurement error-optimized



**FIGURE 8. Actual error distribution. (a) (b) The error distribution of the cuboid 8-BS configuration; (c) (d) the error distribution of the PDOP-optimized BS configuration; (e) (f) the error distribution of the TDOA time-difference measurement error-optimized BS configuration.**

BS configuration. Therefore, the TDOA time-difference measurement error-optimized BS configuration is more suitable for UWB indoor TDOA positioning system than the PDOP-optimized BS configuration.

The comparison between small-scale scene indoor and outdoor experiments shows that the multipath effect on UWB positioning is not obvious under the conditions of high receiving SIR, mainly because the UWB signal from transmission to reception of the direct path distance is shorter, the direct path signal decay is smaller, whereas the multipath signal due to the increase in propagation distance and refraction rapidly decay, so that the direct path signal and the multipath signal is easy to distinguish.

## 2) RESULTS AND ANALYSIS OF LARGE-SCALE POSITIONING EXPERIMENTS

The three BS configurations (cuboid 8-BS configuration, PDOP-optimized BS configuration, and TDOA time-difference measurement error-optimized BS configuration) are still used for comparison in this experiment. The experimental results show that the PDOP-optimized BS configuration is not as accurate as the cuboid 8-BS configuration in large scale indoor positioning with low receiving SIR, whereas the TDOA time-difference measurement error-optimized BS configuration is more accurate than the cuboid 8-BS configuration. However, the results of

**FIGURE 9. Actual error distribution. (a) (b) The error distribution of the cuboid 8-BS configuration; (c) (d) the error distribution of the PDOP-optimized BS configuration; (e) (f) the error distribution of the TDOA time-difference measurement error-optimized BS configuration.**

the outdoor experiments without multipath interference are significantly better than those conducted in the stadium, and both the PDOP-optimized BS configuration and the TDOA time-difference measurement error-optimized BS configuration can improve the positioning accuracy, especially the TDOA time-difference measurement error-optimized BS configuration. The distribution of the actual errors of the three BS configurations in large-scale scene are shown in Fig. 9 (a), (c), and (e), and the distribution of the actual errors in outdoor scene are shown in Fig. 9 (b), (d), and (f), and the data pairs are shown in Tab. 3.

According to Fig. 9, the multipath effect has a serious impact on the positioning accuracy under the condition of low receiving SIR, and the positioning accuracy of the three BS configurations are poor, especially the average positioning error of the PDOP-optimized BS configuration has exceeded 2 m. In large-scale indoor positioning, the propagation distance of the UWB signal is much longer than in small indoor scenes such as meeting rooms, the signal rapidly decays as the propagation distance increases, so in the stadium where the UWB signal propagation distance is longer, even though the direct path signal reaches the receiving antenna before other multipath signal, the energy difference between the direct path signal and the multipath signal are very small and more difficult to distinguish. At this time, the main component of the received signal is no longer a direct path signal, the

**TABLE 3. Pre-optimized and Post-optimized performance comparison (large-scale positioning experiment).**

| Accuracy metric                      | Cuboid 8-BS configuration | PDOP-optimized BS configuration | TDOA time-difference measurement error-optimized BS configuration |
|--------------------------------------|---------------------------|---------------------------------|---|
| <i>Indoor average error(cm)</i>      | 69.8686                   | 279.3465                        | 51.1422   |
| <i>Outdoor average error(cm)</i>     | 21.9797                   | 21.3833                         | 19.3040   |
| <i>Indoor mean square error(cm)</i>  | 7966.2593                 | 26557.1153                      | 4560.6111   |
| <i>Outdoor mean square error(cm)</i> | 605.6000                  | 528.8400                        | 488.2800  |
| <i>Indoor variance</i>               | 3084.6307                 | 18753.6708                      | 1945.0897   |
| <i>Outdoor variance</i>              | 122.4947                  | 71.5933                         | 115.6352  |

receiving SIR is poor, and the Ricean K-factor is close to 0, so the signal also changes from a Ricean distribution to a Rayleigh distribution.

From the small-scale positioning experiment and the large-scale positioning experiment, it can be seen that the PDOP-optimized BS configuration can improve the positioning accuracy in the environment with a high receiving SIR, but is more severely disturbed by the multipath effect in the environment with a low receiving SIR. Therefore, we believe that the DOP cannot be used as a decisive metric for the BS configuration optimization of UWB indoor positioning, mainly because DOP is designed to evaluate the performance of satellite systems in satellite positioning. The satellite positioning systems are used in outdoor large-scale positioning scenes, in which the measurement distances are easily tens of thousands of meters, and a slight measurement error in positioning accuracy can be negligible. At the same time, the observation matrix  $H$  of DOP is normalized, and the distance from each BS to the MS is considered equal, only the angles between BSs and the MS are considered, ignoring the influence of the difference of the ranging error on its positioning. However, UWB is applied to small-scale positioning scenes indoors. In indoor positioning scenes, NLOS and multipath problems are more serious than satellite positioning and are not easily solved, whereas any time measurement error caused by any factor can have a serious impact on the positioning results. Although the DOP is valuable in objectively evaluating the impact of angle on positioning results, its lack of comprehensive consideration leads to its application in indoor positioning has certain limitations. The use of the TDOA time-difference measurement error model can fully take into account the influence of the distance measurement error caused by physical measurement and multipath on positioning accuracy in the indoor environment, and at the same time, the influence of the angle between the BS and the MS

on positioning accuracy can be taken into account. Therefore, in the BS configuration optimization of UWB indoor positioning, the TDOA time-difference measurement error model is more suitable than PDOP as the decisive metric for BS configuration optimization.

## V. CONCLUSION

In the complex indoor environments, important issues affecting indoor positioning accuracy, such as NLOS identification, multipath interference and geometric planning of BS configurations need to be resolved. In this paper, the relationship between DOP and the indoor positioning systems is analyzed based on the recent researchers' common use of DOP to measure the quality of BS configuration for indoor positioning. The relationship between DOP and BS configuration is deduced according to the formula for solving DOP, and the limitations of DOP in the UWB indoor TDOA positioning system are demonstrated from various analyses. The TDOA time-difference measurement error model is then deduced from the UWB ranging error, which is used as an optimization target to establish a mathematical model for the BS configuration optimization. Finally, we use the cuboid 8-BS configuration, the PDOP-optimized BS configuration and the TDOA positioning error-optimized BS configuration to compare the positioning accuracy of the BS configurations under different receiving SIR conditions in  $8\text{ m} \times 8\text{ m} \times 3\text{ m}$  conference room and  $100\text{ m} \times 30\text{ m} \times 10\text{ m}$  gymnasium. At the same time, the experiment is conducted in outdoor standard football field to compare the influence of multipath on the positioning accuracy of the three BS configurations under the conditions of two SIR. The results of small-scale indoor positioning experiments with high receiving SIR show that the positioning accuracy of PDOP-optimized BS configuration and TDOA time-difference measurement error-optimized BS configuration are both improved, and the variance of the positioning error is reduced, which improves the positioning stability of the target scene, and the TDOA time-difference measurement error-optimized BS configuration is more effective. However, the results of the large-scale indoor positioning experiments with low SIR show that the PDOP-optimized BS configuration, which only considers the effect of angle on positioning accuracy, has limitations and is significantly inferior to the cuboid 8-BS configuration and the TDOA time-difference measurement error-optimized BS configuration. The experimental results of the outdoor scene show that multipath does not have a significant effect on the positioning accuracy under the condition of high SIR, whereas multipath has a serious effect on the positioning accuracy under the condition of low SIR, and the anti-multipath capability of the PDOP-optimized BS configuration is obviously inferior to the TDOA time-difference measurement error-optimized BS configuration. It is shown that DOP cannot be used as a decisive metric for the BS configuration optimization of indoor positioning, but its objective evaluation of the angle allows it to be used as a reference index in the BS configuration optimization.

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