Optimal Anchor Configuration in UWB Localization via SNR-Weighted A-Optimality

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SNR 가중 A-최적성 기법을 적용한 UWB 최적 앵커 배치 연구

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Abstract

Ultra-Wideband positioning accuracy is deeply tied to the geometric arrangement of anchors. This paper introduces a smart deployment strategy using an SNR-weighted Fisher Information Matrix (FIM) to handle unpredictable environments. By mapping signal quality into weights through a sigmoid function, we effectively filter out unreliable data from blocked paths. Based on 2,000 simulations, A-optimality proved to be the most reliable metric for predicting real-world success. Our results show that adding height variety to anchors can boost accuracy by at least 4 times, ensuring stable performance even in complex indoor buildings.

Ⅰ. Introduction

Ultra-Wideband (UWB) technology is now a leading choice for high-precision indoor positioning in various industrial fields [1]. Many studies focus on improving individual link-level ranging through better protocols or AI [2], [3]. However, the actual placement of anchors remains a major bottleneck for system performance. Effective anchor deployment is vital to ensure stable and accurate positioning within complex 3D spaces. To solve this, we propose a new method using an SNR-weighted Fisher Information Matrix (FIM). By applying a sigmoid function to map signal quality into reliable weights, we offer a practical way to evaluate anchor configurations for superior results.

Ⅱ. Method

The FIM characterizes the information content of the measurements with respect to the unknown position parameters, while its inverse bounds the estimation error covariance through the Cramér–Rao lower bound (CRLB) [4]. Assuming measurements from N anchors are stochastically independent, the total FIM $\mathcal{J}$ is the linear sum of individual contributions $\mathcal{J}_i$:

$$\boldsymbol{\mathcal{J}} = \sum_{i=1}^{N} \boldsymbol{J}_i = \sum_{i=1}^{N} \left(\frac{1}{R_i} \boldsymbol{H}_i^T \boldsymbol{H}_i \right) \tag{1}$$

where $\boldsymbol{H}_i$ is the 1×3 Jacobian vector representing the unit direction from the tag $[x, y, z]^T$ to the i-th anchor $[x_i, y_i, z_i]^T$

$$\boldsymbol{H}_i = \left[\frac{x - x_i}{d_i}, \quad \frac{y - y_i}{d_i}, \quad \frac{z - z_i}{d_i} \right] \tag{2}$$

To ensure the FIM accurately reflects real-world reliability, we identified a key indicator to distinguish between clear paths and blocked paths. Our empirical analysis in Fig. 1 shows that the Signal-to-Noise Ratio (SNR) is the most effective tool for this distinction. We observed a clear change in link quality at a threshold of approximately $90\,dB$, where signal errors begin to increase significantly due to obstacles.

To reflect signal reliability, we define the LOS probability P_{LOS} using a sigmoid function:

$$P_{LOS}(SNR) = \frac{1}{1 + exp(-k(SNR - SNR_{th}))} \tag{3}$$

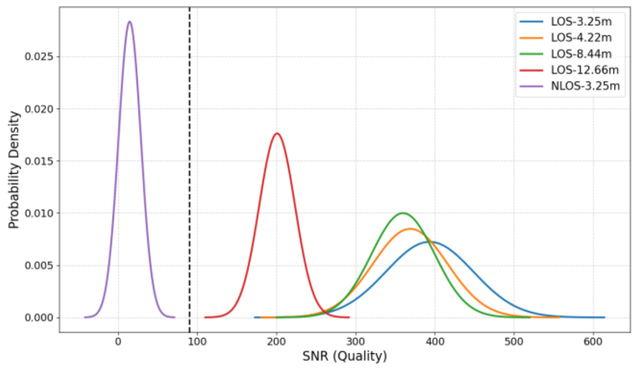

Figure 1. Gaussian Distribution of SNR by Measurement Distance.

Within this model, we set the discrimination threshold $SNR_{th} = 90\,dB$ and the steepness parameter $k = 1$. This function defines P_{LOS} strictly within the range of 0 to 1. Whenever the measured SNR falls below the threshold, the model forces P_{LOS} to converge rapidly toward 0. This mechanism effectively identifies the link as a blocked path by nullifying its contribution to the positioning system.

We weight the measurement variance using P_{LOS} and substitute this relationship into Eq. (1). This process allows us to derive the final SNR-weighted FIM as follows:

$$\mathcal{J} = \sum_{i=1}^{N} \left(\frac{P_{LOS}(SNR_i)}{\sigma^2} \boldsymbol{H}_i^T \boldsymbol{H}_i \right) \tag{4}$$

This enables the FIM calculation to explicitly reflect the inaccuracies associated with NLOS conditions by adaptively weighting each anchor's contribution.

Ⅲ. Conclusion

The framework was validated via 2,000 Monte-Carlo simulations using the SNR-weighted FIM. By evaluating various FIM-based optimality metrics, statistical results in Table 1 show that A-optimality has the highest correlation with actual RMSE and MAE [5]. It outperformed D-optimality, E-optimality, and the condition-number. This confirms that A-optimality is the most reliable metric for predicting positioning robustness in complex 3D structures.

To evaluate robustness in complex settings, we simulated an L-shaped corridor where a wall creates severe signal blockages. In a co-planar setup with all anchors at $2.5\,m$, the A-optimality score reached a massive 10^9, causing large vertical drifts and an RMSE of $1.4103\,m$. However, by simply lowering one anchor to $0.5\,m$ to add vertical diversity, the A-optimality dropped to 349 and the RMSE improved to $0.3697\,m$. These results prove that positioning accuracy changes drastically based on anchor placement, even when using the same hardware. Furthermore, our proposed metric accurately predicts these performance shifts by capturing geometric sensitivity.

In summary, this research proves that A-optimality within an SNR-weighted FIM framework is a powerful tool for designing 3D anchor layouts. Our findings confirm that this approach effectively evaluates positioning potential even when signals are blocked by obstacles. Future work will focus on using global optimization algorithms to automate the placement of the minimum number of anchors. This advancement will enable cost effective and high precision network planning for large-scale industrial infrastructures.

Table 1

Comparison of Spearman Correlation Coefficients

Criterion	RMSE	MAE
A-optimality	**0.8261**	**0.8335**
E-optimality	0.8142	0.8243
D-optimality	0.8242	0.8309
Condition-number	0.8229	0.8575

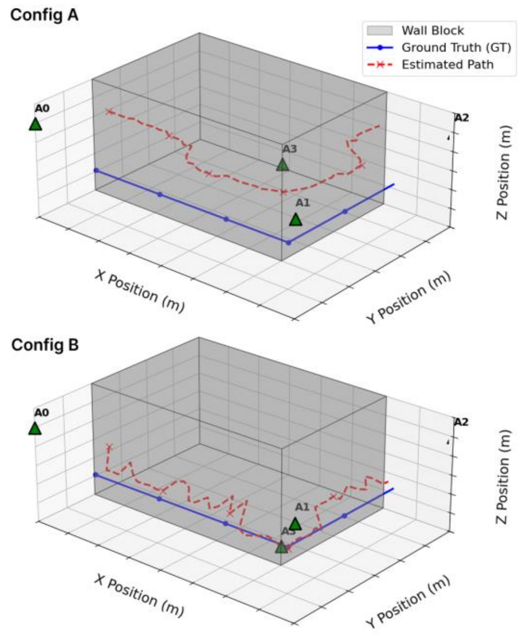

Figure 2. 3D positioning performance and anchor configurations in a NLOS-dense L-shaped corridor.

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