



Research on Evaluation Method of Cooperative Jamming Effect in Cognitive Confrontation

Jing Ma¹, Bin Shi¹, Fei Che², and Sitong Zhang²(✉)

¹ Science and Technology on Special System Simulation Laboratory,
Beijing 100854, China

13301067916@189.cn, shibin1018@sohu.com

² Harbin Engineering University, Harbin 150001, China
chefei0627@126.com, zhangsitong0726@126.com

Abstract. In modern warfare, due to the increasingly complex electromagnetic environment, cognitive confrontation will become the main form of war. Effective interference with enemy radars is of great importance for taking the lead in the battlefield. The evaluation of the synergistic interference effect is an important indicator to measure the performance of the interference equipment. According to the evaluation result, the interference strategy can be changed in time to achieve the best interference revenue and provide a strong guarantee for the successful penetration of the target. In this paper, the discovery probability and positioning accuracy of radar network are used as evaluation indicators to establish an evaluation model. The interference power, interference frequency, interference timing and interference pattern are used as membership functions. The distance, false alarm probability and different interference strategies are studied. The simulation shows that proper false alarm probability, closer distance and proper interference strategy can improve the interference benefit and provide a theoretical basis for obtaining the best interference effect in the actual battlefield.

Keywords: Cognitive confrontation · Jamming effect evaluation · Evaluation index · Jamming strategy

1 Introduction

In the current war, as the battlefield environment becomes more and more complex, cognitive confrontation will become the main form of war in the future battlefield. Radar is an important part of cognitive confrontation, whose main task is to extract target information from the target echo by pulse compression and coherent accumulation, and realize the detection, localization and tracking of the target [1, 2]. As the opposite of the radar, the main task of the jammer is to intercept the radar's transmitted signal and then modulate and forward it, generating a deception or suppressing jamming signal similar to the target echo, so that the radar can not effectively detect the target [3, 4]. Coordination jamming assessment is an important indicator to measure the performance of jamming equipment [5]. According to the evaluation results, it can be

judged whether the distribution of jamming resources is good or bad, which is conducive to the rational use of jamming resources, timely change the jamming strategy according to the evaluation results to achieve the best jamming revenue, and provide a strong guarantee for the successful penetration of the target [6, 7]. Therefore, it is of great significance to conduct a rapid, comprehensive and reasonable evaluation of the radar coordinated jamming effect [8, 9]. This problem has also been discussed in some previous studies. Literature [10] discussed the jamming effectiveness of the IR smoke projectile resist the IR imaging guided missile. Literature [11] proposed an online evaluation method based on support vector machine. The literature [12] evaluated the jamming effect based on the power criterion method. In literature [13], the method based on power criterion is used to study the reduction degree of enemy radar detection distance at different powers to evaluate the effect. Literature [14] uses the magnitude of the lure angle as the evaluation criterion. In the above study, the factors affecting the jamming effect are not comprehensive enough, and the evaluation effect will also change when the evaluation indicators are different. Therefore, when evaluating the jamming effect, it is necessary not only to accurately select the factors affecting the jamming effect, but also to select the appropriate evaluation indicators according to the different jamming objects. In this paper, the jamming effect of jammer on radar signal is studied. Four different membership functions are selected as the factors affecting the jamming effect. According to the characteristics of radar work, the discovery probability and location accuracy of radar are used as evaluation indicators to establish the jamming effect evaluation model.

2 Synergistic Jamming Membership Function

2.1 Jamming Power Membership Function

Firstly, we apply the ratio of jamming and signal (JSR) to describe the power suppression benefit which represents the suppressing effect to radar $R_j(j = 1, 2, \dots, n)$ from jammer $u_i(i = 1, 2, \dots, m)$. The power suppression benefit function can be expressed as q_{1ij} . Only when the ratio of the power of received jamming power and the power of the echo signal is greater than the minimum JSR, it is deemed that the jamming of the jammer is effective. The power of the jammer signal and the effective echo signal power received by the radar R_j are shown in Eq. (1).

$$P_{ji} = \frac{P_j G_j G_t \lambda^2}{(4\pi R_j)^2 L}, P_{js} = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R_s^4} \quad (1)$$

where P_t and P_j separately represent the transmission power of radar and jammer, G_t is the radar main lobe gain, G_A is the gain of the jammer, σ is the scattering area of self-defense aircraft, A is the equivalent receiving area of radar antenna, R_j is the distance between radar and target and R_s is the distance between jammer and target.

K_j denotes the minimum ratio of jamming and signal, which indicates radar R_j required for normal work. Therefore, we can derive the decision-making criterions. After normalization, q_{1ij} can be expressed as Eq. (2)

$$q_{1ij} = \begin{cases} 1 & p_{ji}/p_{js} \geq 2K_j \\ \frac{2}{3} \left(\frac{p_{ji}/p_{js}}{K_j} - 0.5 \right) & 0.5K_j \leq p_{ji}/p_{js} \leq 2K_j \\ 0 & p_{ji}/p_{js} \leq 0.5K_j \end{cases} \quad (2)$$

2.2 Jamming Frequency Membership Function

Then, the frequency alignment benefit function q_{2ij} is addressed to report the jamming suppression effect of jammer $u_i (i = 1, 2, \dots, m)$ on radar $R_j (j = 1, 2, \dots, n)$. The jammer u_i can only jam the radar R_j if the jammer's jamming frequency overlaps with the radar's operating frequency. (f_{i1}, f_{i2}) denotes the operating frequency of the jammer, and (f_{j1}, f_{j2}) denotes the operating frequency of the radar. Consequently, q_{2ij} can be expressed as Eq. (3).

$$q_{2ij} = \begin{cases} 1 & f_{i1} < f_{j1} \text{ and } f_{i2} > f_{j2} \\ 0 & f_{i1} > f_{j2} \text{ or } f_{i2} < f_{j1} \\ \frac{\min(f_{i2}, f_{j2}) - \max(f_{i1}, f_{j1})}{f_{j2} - f_{j1}} & \text{other} \end{cases} \quad (3)$$

2.3 Jamming Timing Membership Function

Next, the time-benefit function is used to express the jamming suppression effect of the jammer $u_i (i = 1, 2, \dots, m)$ on the radar $R_j (j = 1, 2, \dots, n)$. The effect of suppressing time benefit on jamming benefit can be expressed as q_{3ij} . Similar to the frequency alignment benefit function, q_{3ij} can be expressed as Eq. (4).

$$q_{3ij} = \begin{cases} 1 & t_{j1} < t_{r1} \text{ and } t_{j2} > t_{r2} \\ 0 & t_{j1} > t_{r2} \text{ or } t_{j2} < t_{r1} \\ \frac{\min(t_{r2}, t_{j2}) - \max(t_{r1}, t_{j1})}{t_{r2} - t_{r1}} & \text{other} \end{cases} \quad (4)$$

2.4 Jamming Style Membership Function

Finally, the jamming patterns benefit function q_{4ij} is adopted to describe the jamming patterns benefit which represents the jamming suppression effect of jammer $u_i (i = 1, 2, \dots, m)$ on radar $R_j (j = 1, 2, \dots, n)$. Suppose that each radar (possibly of different system type) have valid m types of jamming patterns, and been sorted according to the advantages and disadvantages of theoretical jamming effects. If jammer u_i contains the jamming patterns which are effective for radar R_j , then the higher the jamming pattern is in ranking, the greater the value of the jamming pattern benefit function is. Otherwise, $q_{4ij} = 0$. q_{4ij} can be expressed as Eq. (5).

$$q_{4ij} = \begin{cases} 0 & \text{jammer does not contain the jamming pattern} \\ 1 - \frac{n}{m} & \text{other} \end{cases} \quad (5)$$

In the battlefield environment, there are m jammers to jam the radar network composed of n radars. According to the above membership function calculation, the membership matrix of the m jammers $u_i (i = 1, 2, \dots, m)$ to interfere with a certain radar in the radar R_j network is as Eq. (6).

$$q_j = \begin{bmatrix} q_{11j} & q_{12j} & \dots & q_{1mj} \\ q_{21j} & q_{22j} & \dots & q_{2mj} \\ q_{31j} & q_{32j} & \dots & q_{3mj} \\ q_{41j} & q_{42j} & \dots & q_{4mj} \end{bmatrix} \quad (6)$$

According to the expert's experience, the weight vector of the four indicators is recorded as $\omega = [\omega_1, \omega_2, \omega_3, \omega_4]$, which represents the weight of the four indicators of jamming power, jamming frequency, jamming timing and jamming pattern. The jamming benefits of the m jammer to a radar in the radar network are as Eq. (7).

$$\begin{aligned} Q_j &= \omega \cdot q_j = [\omega_1, \omega_2, \omega_3, \omega_4] \cdot \begin{bmatrix} q_{11j} & q_{12j} & \dots & q_{1mj} \\ q_{21j} & q_{22j} & \dots & q_{2mj} \\ q_{31j} & q_{32j} & \dots & q_{3mj} \\ q_{41j} & q_{42j} & \dots & q_{4mj} \end{bmatrix} \\ &= [q_{1j}, q_{2j}, \dots, q_{mj}] \end{aligned} \quad (7)$$

Since the jammer can produce effective jamming benefits from the above four aspects at the same time, when solving the jamming benefit of a single jammer to a single radar, the Zadeh “ Λ ” operator should be used to perform small operations.

$$q_{ij} = \omega_1 \cdot q_{1ij} \Lambda \omega_2 \cdot q_{2ij} \Lambda \omega_3 \cdot q_{3ij} \Lambda \omega_4 \cdot q_{4ij} \quad (8)$$

The jamming benefit matrix of the m -frame jammers to the n radars in the radar network can be obtained.

$$Q = [Q_1^T, Q_2^T, \dots, Q_n^T] = \begin{bmatrix} q_{11} & q_{12} & \dots & q_{1n} \\ q_{21} & q_{22} & \dots & q_{2n} \\ \dots & \dots & \dots & \dots \\ q_{m1} & q_{m2} & \dots & q_{mn} \end{bmatrix} \quad (9)$$

3 The Model of Collaborative Jamming Effect Evaluation

According to the role of radar network in cognitive confrontation, this paper selects the radar’s discovery probability and location accuracy as indicators for the evaluation of coordinated jamming effects. The model of collaborative jamming effect evaluation is shown in the Fig. 1.

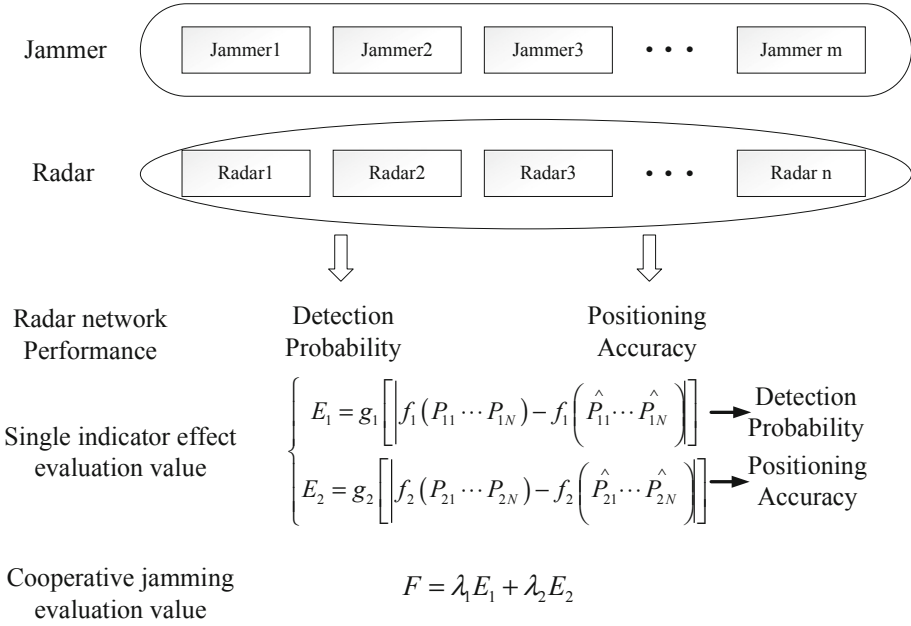


Fig. 1. The model of collaborative jamming effect evaluation

3.1 Effectiveness Evaluation Based on Radar Discovery Probability

The discovery of the probability is one of the important factors to measure the performance of a radar detection. This paper chooses the discovery probability as the evaluation index of radar network detection performance.

Under the condition of false alarm probability P_{fa} , let $x = \frac{r^2}{2\sigma^2}$ denote the ratio of signal plus noise to noise in the radar receiver. According to the Niemann-Pearson criterion used in radar detection, the probability of finding the false alarm probability and the envelope r can be obtained. The function is as Eq. (10)

$$P_d = \exp\left(-\frac{S}{N}\right) \int_{-\ln P_{fa}}^{\infty} \exp(-x) I_0\left(2\sqrt{x} \cdot \frac{S}{N}\right) dx \tag{10}$$

We bring the jamming benefit matrix into the radar discovery probability. Then, the signal-to-jamming ratio received by the radar is:

$$\frac{S}{J} = \frac{P_t G_t \sigma L_1 \sqrt{n}}{4\pi R^2 P_j G_j L q_{ij}} \quad (11)$$

At this time, the expression of the radar discovery probability P_{dj} under the influence of the jamming signal is as Eq. (12).

$$P_{dj} = \exp\left(-\frac{K}{R^2 q_{ij}}\right) \int_{-\ln P_{ja}}^{\infty} \exp(-x) I_0\left(\frac{2}{R} \sqrt{x \cdot \frac{K}{q_{ij}}}\right) dx \quad (12)$$

At this point, the estimated jamming effect under the probability indicator is found to be:

$$E_1 = P_d - P_{dj} \quad (13)$$

3.2 Effectiveness Evaluation Based on Radar Positioning Accuracy

In addition to finding the probability, the positioning accuracy is also one of the important factors to measure the performance of a radar. It represents the accuracy level of the radar network to determine the target position. This paper chooses the positioning accuracy as another evaluation index of radar network detection performance. Geometric accuracy factor GDOP (Geometric Dilution of Precision) is one of the important criteria for measuring the accuracy of positioning systems.

The GDOP expression of the radar network is as Eq. (14).

$$P_g = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \quad (14)$$

Where σ_x , σ_y , σ_z is the positioning error mean square error in the x, y, and z axis directions, and x, y, and z are the position vector of the target.

When the radar network is cooperatively interfered, the signal received by the radar receiver is affected by the jamming signal, and the dry signal ratio of the received signal changes with different jamming strategies. The positioning error of the radar detection distance, azimuth and elevation angle The mean square error also changes, and the positioning accuracy of the radar network is affected.

The radar positioning accuracy expression under certain jamming strategy is as Eq. (15).

$$\hat{p}_g = \sqrt{\sigma_{xj}^2 + \sigma_{yj}^2 + \sigma_{zj}^2} \quad (15)$$

At this point, the estimated jamming effect under the positioning accuracy index is found to be:

$$E_2 = \hat{p}_g - p_g \quad (16)$$

4 Simulation Analysis

We set up two sets of experiments to verify the impact of different influencing factors on radar network discovery probability and positioning accuracy.

Experiment 1: The typical radar and jammer parameters are selected for simulation to verify the influence of different factors on the probability of radar discovery. The parameters of the three radars are:

$$P_t = 630 \text{ kw}, G_t = 33 \text{ dB}, \sigma = 5, L = 3 \text{ dB}, n = 10$$

The parameters of the three radars are:

$$P_j = 150 \text{ w}, G_j = 9 \text{ dB}, L = 3 \text{ dB}, n = 10$$

Under different false alarm probabilities, the relationship between radar discovery probability and signal-to-jamming ratio is simulated as Fig. 2.

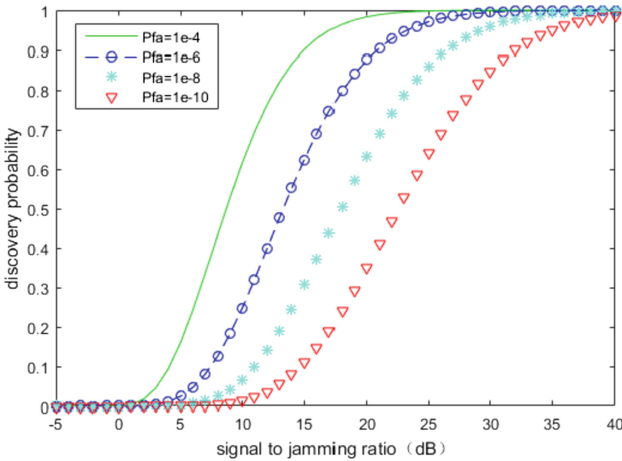


Fig. 2. The curve of radar discovery probability and signal to jamming ratio

At present, it is generally found that the probability of less than or equal to 0.1 is effective as an opaque jamming standard. It can be seen from the figure that this standard can be achieved. As can be seen from Fig. 2, in the case where the signal-to-jamming ratio is constant, as the probability of false alarm decreases, the probability of discovery decreases, and the radar detection performance becomes weak, and the more obvious the jamming effect is.

Fix the value of q_{ij} to 0.6, the simulation result of the relationship between radar probability and distance under different false alarm probabilities is as Fig. 3.

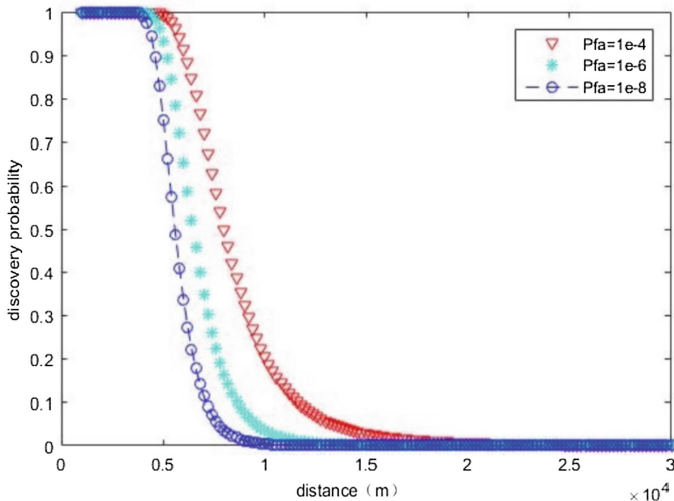


Fig. 3. The curve of radar probability and distance

It can be seen from the Fig. 3 that under a certain false alarm probability, as the distance increases, the probability of discovery gradually decreases. After the distance between the two reaches 12 km or more, the probability of radar discovery drops below 0.1, meeting the standard.

In order to study the influence of jamming benefit on the probability of discovery, the false alarm probability is fixed to $P_{fa} = 10^{-6}$. Under different jamming benefit values, the relationship between radar probability and distance is as Fig. 4.

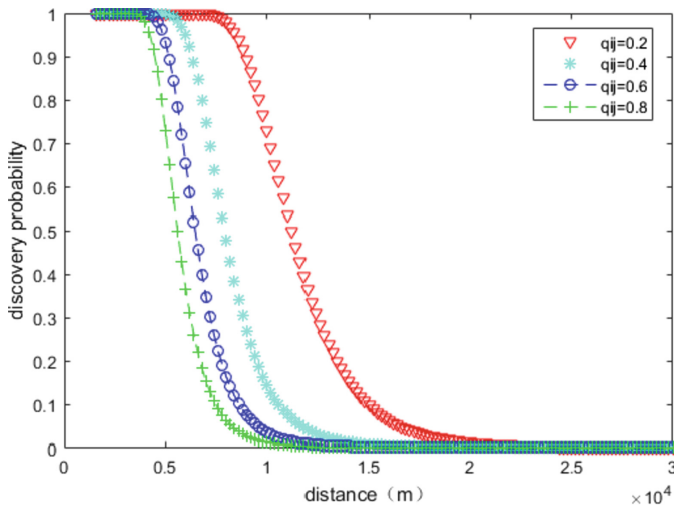


Fig. 4. The curve of radar discovery probability and jamming benefit value

It can be seen from the figure that in the case of false alarm probability and distance determination, with the increase of the jamming benefit value, the radar discovery probability is significantly reduced. The simulation shows that increasing the jamming benefit value plays an important role in reducing the radar discovery probability.

Experiment 2: We select typical radar and jammer parameters for simulation. The parameters of the three radars are:

$$P_t = 500 \text{ kw}, G_t = 40 \text{ dB}, f_c = 2.4 \text{ GHz},$$

$$B_r = 10^6 \text{ Hz}, L_t = 6 \text{ dB}, n = 10$$

The parameters of jammers are shown in the following Table 1

Table 1. Parameters of jammers

Number	Transmit power P_j (kw)	Transmit gain G_j (dB)	Center frequency f_c (GHz)	Bandwidth B_j (MHz)	Jammer loss L_j (dB)	Jammer pattern n
1	40	10	2.4	4	6	1
2	60	10	2.4	2	6	3
3	110	10	2.4	0.5	6	4

In the absence of jamming to the radar network, the two-dimensional plane simulation of the GDOP value of the radar network as a function of the distance between the radar and the target is shown in Fig. 5.

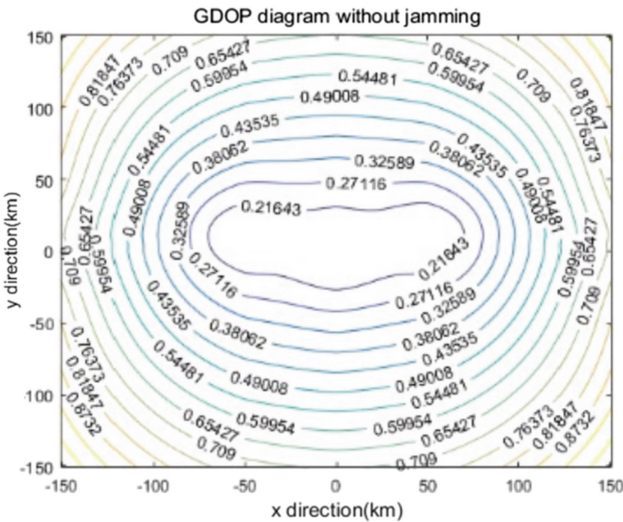


Fig. 5. GDOP diagram without jamming

We apply jamming to the radar network. Due to the different parameters of the jammer, the jamming effects of different jamming strategies are different. The three different jamming strategies and their corresponding jamming benefit values are shown in Table 2.

Table 2. The corresponding jamming benefit values of different jamming strategies

Radar \ Jammer	1	2	3	Jamming benefit
Strategy 1	1	2	3	0.8406
Strategy 2	3	1	2	0.8655
Strategy 3	2	1	3	0.8679

The GDOP diagram of the radar network under different jamming strategies is shown in Figs. 6, 7 and 8.

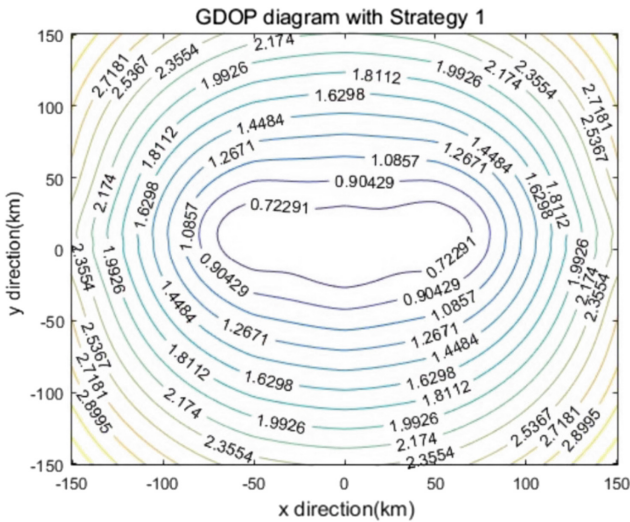


Fig. 6. GDOP diagram with Strategy 1

As can be seen from the figure, different jamming strategies have a great influence on the positioning accuracy of the radar network. Taking (0, 50, 0) as an example, the positioning accuracy of the point is 0.27 km without jamming, and the positioning accuracy of the point under the three jamming strategies is 0.90 km, 2.66 km and 7.17 km, respectively.

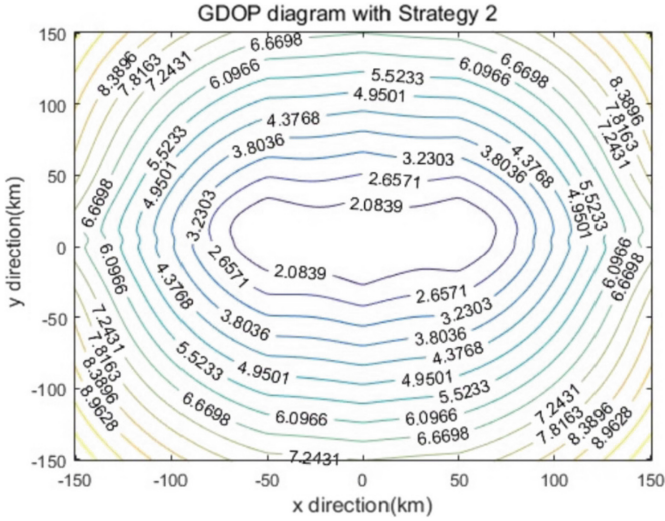


Fig. 7. GDOP diagram with Strategy 2

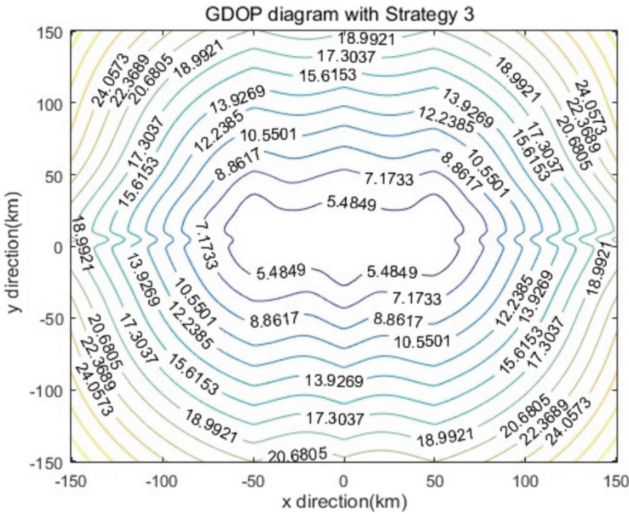


Fig. 8. GDOP diagram with Strategy 3

5 Conclusion

In cognitive confrontation, due to the wider application of radar networking, as an interfering party, the importance of jamming to radar networking is increasing. In order to measure the jamming effect, the evaluation of the jamming benefit has been paid more and more attention. In this paper, we take the discovery probability and location accuracy of radar network as evaluation indicators, and study the effects of distance,

false alarm probability and different jamming strategies on the jamming benefit. Simulations show that proper false alarm probability, closer distance and proper jamming strategy can improve the jamming benefit. Since the false alarm probability and distance are not easy to change in the actual battlefield, it is an effective means to improve the jamming effect by making the appropriate decision to get the maximum jamming benefit.

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