Application of time-reversal in electromagnetic power synthesis under distributed motion platform

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Abstract

Space-time adaptive focusing is the most prominent feature of time-reversal electromagnetic waves. This paper studies the spatial power synthesis technology of distributed motion platforms based on time-reversal electromagnetic waves. Firstly, the spatial power synthesis process based on time-reversal on a distributed fixed platform is modeled. Then, the time-reversal signal processing process of a distributed array on the motion platform is deduced, and the feasibility of realizing precise power focusing is verified in theory. Finally, the factors affecting the power synthesis effect in the target area are analyzed. The simulation results indicate that the spatial power synthesis on the distributed motion platform based on the time-reversal can effectively balance between power focusing effect and computational complexity. Also, the proposed method has better efficiency than the existing techniques, and it has strong practicability and feasibility.

1. Introduction

Spatial power synthesis refers to the coherent superposition of signals with the same frequency and a specific phase relationship from multiple scattered signal sources in a specific area through spatial propagation to obtain high-power signals [1]. This technology has been widely used in both military and civilian applications, such as high-power microwave-directed energy weapons [2], cooperative jamming [3], and energy supply for satellite and space platforms [4].

The phase delay-and-sum (DAS) phased array is a common technology for spatial power synthesis, that is, the specific direction of the beam is achieved by controlling the addition of a specific phase shift to each array element [5, 6, 7]. However, there are two prominent difficulties of this technology in practical applications. The first problem is precise power focusing. To meet the requirements of certain tasks, it is often desirable to synthesize power at the specified target position. This requires high-precision positioning of all distributed array elements and then supplementing the corresponding phase shift for each array element through the spatial position relationship to control the precise power focusing. However, considering factors such as the number of distributed nodes, motion speed, formation change, and communication synchronization, the resulting phase error will cause power focusing outside the target area, resulting in power loss and negative effects on the equipment. The second problem is the high computational complexity. To synthesize high power, it is necessary to arrange enough distributed array elements. However, factors such as node positioning, phase compensation, and motion control pose great challenges to the computational efficiency and robustness of distributed structures.

With the development of modern radar technology, inspired by phased array and MIMO radar, the concept of waveform diversity [8, 9] has been introduced in spatial power synthesis to solve the above problems. Reference [10] proposed a semidefinite programming (SDP) model for breast cancer treatment in medical ultrasound hyperthermia. Wireless arrays were used to achieve power focusing in the tumor area while avoiding the influence of hyperthermic ultrasound on other areas. Reference [11] further verified the feasibility of the treatment plan based on waveform diversity technology through various experiments, and the performance indicators in different scenarios were analyzed. Reference [12] proposed an improved SDP model. In the military field, taking precision electronic warfare as the application background, reference [13] transformed the energy focusing problem under ultra-sparse array into an SDP problem and proposed a precise interference focused energy delivery (FED) technology based on a wireless sensor network. By optimizing and solving the autocorrelation matrix of the transmitted signal, the energy of the focal region was maximized, and the energy outside the region was minimized. Reference [14] established the mixed-boolean SDP (MBSDP) model to further improve the energy focusing effect. However, most of the above waveform design prob-

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lems based on waveform diversity technology are NP-hard problems. To address this issue, convex relaxation is often used to convert these problems into P-hard problems and then optimize the solution [15, 16, 17]. Although this technique can effectively improve the precise focusing effect of spatial power, the computational complexity is greatly increased. Especially, when the distributed array elements are on the motion platform, the computational overhead increases exponentially. Therefore, this study uses time-reversal (TR) to perform spatial power synthesis on a distributed motion platform to balance between power focusing performance and computational complexity.

TR electromagnetism is an emerging field in recent years. This technology has been widely used in the fields of acoustic waves [18] and electromagnetic waves [19]. It has two main applications in spatial power synthesis. One application is the high-power source. Based on the space-time focusing features of TR electromagnetic waves, reference [20] used a reverberation chamber with an opening on the front to obtain a high-power microwave pulse signal by synthesizing eight signals from a low-power source. Reference [21] used the space-time focusing features of TR electromagnetic waves to determine the focus and feed timing of a multi-source reflector antenna, and a three-source parabolic antenna was designed. The simulation results indicated that the electric-field peak value of its far-field radiation field was 2.38 times that of the standard parabolic antenna with the same aperture. Thus, the designed three-source parabolic antenna can be used for power synthesis. The other application of TR electromagnetism is medical treatment. Reference [22] proposed a high-intensity transcranial ultrasonic therapy for brain treatment based on the multi-channel array and TR adaptive focusing features. Reference [23] proposed to use TR power synthesis to achieve microwave hyperthermia for deep tumors and built the TR-based microwave hyperthermia system. This system was preliminarily calibrated and tested. It can be seen that space-time adaptive focusing is the most prominent feature of TR electromagnetic waves. Its working principle is as follows. When a source fluctuates and propagates outward, for a receiver arranged on the surface surrounding the area, the recorded signal is time-reversed and transmitted into the area as a secondary source, and the resulting signal will achieve spatial and temporal focusing at the original source point. This study analyzes the feasibility and validity of spatial power synthesis of distributed motion platforms based on TR. The results show that the TR-based focusing process is simple to implement because it does not require prior knowledge such as the propagation environment and the spatial location of distributed nodes, does not introduce new signal patterns, and does not require preprocessing such as signal sorting and recognition. Compared with the traditional DAS phased array and waveform diversity technology, it can achieve precise power focusing and greatly reduce computational complexity. After validation by engineering tests, the technology is expected to be widely used in military and civilian applications such as electronic mobile jamming, automotive wireless energy transfer, and battlefield cover for surprise defense.

2. Establishment of spatial power synthesis model under fixed platforms based on TR technique

To conveniently illustrate the feasibility of TR-based spatial power synthesis on a motion platform, the TR-based power synthesis model on a fixed platform under ideal conditions is established first. As shown in Fig. 1, the N node positions of the distributed array antennas scattered in the space are denoted as \( r_1, r_2, \ldots, r_N \), the target point location is denoted as \( r_T \), and the point in the power synthesis area is denoted as \( r_H \). Taking a monochromatic signal as an example, the process of TR signal processing is described in the following.

Assume that the emission signal pattern of the original target radiation source \( r_T \) is expressed by formula (1)

\[
S(t) = A \cdot \cos (2\pi f_0 t + \phi_0)
\]

where \( A \) is the signal amplitude, \( f_0 \) is the center frequency, and \( \phi_0 \) is the initial phase.

The signal pattern received by the node \( j \) is expressed by formula (2)

\[
S_j(t) = \frac{A}{R_T} \cdot f_T(\theta_T, \phi_T) \cdot f_j(\theta_T, \phi_T) \cdot S_T(t - R_T T_f) = A' \cdot \cos \left[ 2\pi f_0 (t - R_T T_f) + \phi_0 \right]
\]

where \( f_T(\theta_T, \phi_T) \) is the directivity function of the target radiation source antenna; \( f_j(\theta_T, \phi_T) \) is the directivity function of the receiving antenna of node \( j \); \( \theta \) represents the angle between the connection line between the node \( r_j \) and the target radiation source \( r_T \), and its projection line on the plane \( \text{soy}_{T} \); \( \phi \) represents the angle between the projection line and the \( x \)-axis; \( A' = \frac{A}{R_T} \cdot f_T(\cdot) f_j(\cdot) \) is the amplitude factor (can be considered as a constant in a short time); \( R_T = \| r_j - r_T \|_2 \) is the Euclidean distance between the node \( j \) and the original target point \( T \); \( T_f = \| r_T - r_H \|_2 \) is the time delay from the signal to the node \( j \); \( c \) is the propagation speed of electromagnetic waves.

TR processing is to invert the time domain of the signal. Denote the ‘time window length’ of a signal under TR processing as \( T_{\text{win}} \), which includes signal receiving, processing, and transmission. The TR signal generated by node \( j \) can be expressed as formula (3)

\[
S_{TR}(t) = B_j \cdot \cos \left[ 2\pi f_0 (T_{\text{win}} - t - R_T T_f) + \phi_0 \right]
\]

where \( B_j \) is the signal amplitude after modulation, and \( (T_{\text{win}} - t) \) represents the time-domain inversion processing of the signal. Through spatial propagation, when the signal reaches any point \( r_H \) in the power synthesis area, it can be expressed as formula (4)

\[
S_{\text{TR}}(t) = \frac{B_j}{R_T} \cdot f_{\text{TR}}(\theta_{\text{TH}}, \phi_{\text{TH}}) \cos \left[ 2\pi f_0 (T_{\text{win}} - t - R_T T_f - R_H T_f) + \phi_0 \right]
\]

where \( f_{\text{TR}}(\cdot) \) is the directivity function of the transmitting antenna of node \( j \), and the definitions of other parameters are the same as above.

To facilitate discussion, assume that \( \frac{B_j}{R_T} \cdot f_{\text{TR}}(\cdot) = 1 \) is available for all node signals. In this case, the signal synthesis pattern at the \( c \) position is expressed by formula (5)

\[
S_H(t) = \sum_{j=1}^{N} \cos \left[ 2\pi f_0 (T_{\text{win}} - t - R_H T_f - R_j T_f) + \phi_0 \right]
\]

The synthesis power is expressed as formula (6)

\[
P_H = \frac{1}{T_{\text{win}}} \int_{0}^{T_{\text{win}}} |S_H(t)|^2 dt
\]

It can be seen from formula (3) that, at the original target point position, i.e., \( R_H = R_T \), the signal phases of all nodes can be completely

Fig. 1. Spatial distribution relationship between distributed array nodes and target radiation sources.
aligned, and the power synthesis value is the largest. However, around the target point, i.e., $R_{PM} \neq R_{PT}$, due to the phase difference introduced by the path difference, power synthesis will drop.

3. Feasibility analysis of spatial power synthesis under motion platform

Based on the established spatial power synthesis model on the fixed platform, the feasibility of using TR for spatial power synthesis on the motion platform is further analyzed. To facilitate discussion, the power synthesis models in this study are all established when the distributed antenna is on the motion platform and the target point is stationary. Firstly, it is assumed that the target point is in the near-field area of the distributed array antenna. As shown in Fig. 2, the radial velocity $V_j$ of the array element node $j (j = 1, 2, .. N)$ in the array antenna relative to the target point $r_j$ is a constant. Because TR electromagnetic waves have space-time adaptive focusing features, considering the Doppler frequency shift introduced by relative motion, it is only necessary to start the discussion from the moment when each node receives the signal from the original target radiation source. Detailed analysis is presented below.

The original target radiation source still uses the simple signal as expressed in formula (7).

$$S(t) = A \cdot \cos (2\pi f_0 t + \phi_0)$$

Through space propagation, when the signal reaches the $j$-th node, the pattern is expressed as formula (8)

$$S_j(t) = A_j' \cdot \cos \left[ 2\pi f_0 (t - R_j f_0 c) + \phi_0 \right]$$

where $A_j' = \frac{A_j}{R_j} \cdot f_r(\theta_j, \phi_j, \theta_j, \phi_j)$ is the antenna emission direction image of the original target radiation source; $f_r(\cdot)$ is the receiving antenna direction image of node $j$, and it also considers the same polarization direction; $c$ is the propagation speed of the electric waves; $R_j$ is the distance between node $j$ relative to the target point $T$ when node $j$ receives the signal.

After TR processing, the TR signal generated by the node $j$ is expressed by formula (9)

$$S_{TRj}(t) = B_j \cdot \cos \left[ 2\pi f_0 (T_{win} - t - R_j f_0 c) + \phi_0 \right]$$

where $B_j$ is the signal amplitude after modulation; $T_{win}$ represents the ‘time window length’ that includes signal receiving, processing, and transmission. During this time period, the distance $\Delta r$ of the array element relative to the target point is $\Delta r = V_j \cdot T_{win}$. Through space propagation, relative displacement is generated when the retroreflected signal reaches the original target radiation source position. The signal pattern is expressed by formula (10)

$$S_{TRj}(t) = B_j \cdot \cos \left[ 2\pi f_0 \left( T_{win} - t - \frac{R_j - V_j t}{c} \right) + \phi_0 - 2\pi f_0 \frac{V_j T_{win}}{c} \right]$$

$$= B_j \cdot \cos \left[ 2\pi f_0 \left( T_{win} - t - \frac{V_j t}{c} \right) + \phi_0 - 2\pi f_0 \frac{V_j T_{win}}{c} \right] = B_j \cdot \cos \left[ 2\pi f_0 \left( T_{win} - t - \frac{V_j t}{c} \right) + \phi_0 - 2\pi f_0 \frac{V_j T_{win}}{c} \right]$$

Denote $[2\pi f_0 \left( T_{win} - t - \frac{V_j t}{c} \right) + \phi_0 - 2\pi f_0 \frac{V_j T_{win}}{c}]$ in formula (10) as $\phi_j$. Then, when the TR signals emitted by any two nodes arrive at the original target radiation source, the phase difference can be expressed as formula (11)

$$\Delta \phi = \phi_i - \phi_j$$

$$= \left[ 2\pi f_0 \left( T_{win} - t - \frac{V_i t}{c} \right) + \phi_0 - 2\pi f_0 \frac{V_i T_{win}}{c} \right]$$

$$- \left[ 2\pi f_0 \left( T_{win} - t - \frac{V_j t}{c} \right) + \phi_0 - 2\pi f_0 \frac{V_j T_{win}}{c} \right]$$

$$= 2\pi f_0 \left( (T_{win}) \cdot (V_j - V_i) \right)$$

It can be seen from the above formula that, in the ideal case where there is no time synchronization error $\Delta t$ or positioning error $\Delta r$, whether the TR signals transmitted by each node can achieve accurate in-phase coherent superposition at the target radiation source position only depends on whether the radial velocity of each node relative to the target radiation source is consistent. When there is a speed difference, a phase error will be introduced, and the synthesis efficiency will be reduced. The size of the phase error is not only determined by the speed difference between nodes but also related to the receiving time window $T_{win}$. In this case, it is necessary to select a reference array element node and then estimate the radial velocity difference between each node relative to the target point. Meanwhile, compensation needs to perform based on the above formula to achieve phase alignment.

The above is the feasibility analysis of using TR to perform spatial power synthesis on distributed motion platforms in the near field. In the far field, it is assumed that the distance between the distributed arrays relative to the original target radiation source is far enough. Then, the distance between each node relative to the target point is approximately equal, i.e., $R_1 = R_2 = ... = R_i = R_N$. Meanwhile, it is assumed that the array element is a slow-motion platform. Then, the radial velocity of the node relative to the target point is also approximately equal, that is, $V_1 = V_2 = ... = V_j = V_N$. When the signal reaches the array, it can be regarded as a plane wave. In theory, the TR signal sent back can achieve accurate coherent superposition at the original target radiation source location.

4. Analysis of influencing factors of target point synthesis effect

According to the analysis in Section 3, to realize the coherent superposition of node signals at the target point, based on the characteristics of the distributed motion platform, the ‘cluster’-based master-slave structure shown in Fig. 3 can be adopted. A master node can control the secondary nodes of each sub-array to quickly and effectively control the motion speed, signal processing time, and sending and receiving time of all other slave nodes. However, affected by factors such as atmospheric airflow, time control accuracy, and path avoidance, it is difficult to ensure that the speed of all array element nodes is absolutely the same. The phase error introduced by the speed error $\Delta V$ will decrease the synthesis efficiency during the signal synthesis process.

To analyze the impact of speed error on the synthetic signal, the synthetic efficiency function of the TR signal sent back by the distributed array elements at the target point is defined as formula (12)
\[ \eta_T (t) = \frac{S_{\text{sum}}' (t)}{S_{\text{sum}} (t)} = \frac{\sum_{j=1}^{N} S_{j} T_{j} (t)}{\sum_{j=1}^{N} S_{j}'} T_{j} (t) \]  

where \( S_{\text{sum}} (t) \) is the actual synthetic signal when there is an error, and \( S_{\text{sum}}' (t) \) is the ideal synthetic signal when there is no error. It is assumed that the signal transmission powers of all array elements are equal, i.e., \( B_1 = B_2 = ... = B_i \). Ideally, the speed of all nodes is \( V_0 \), i.e., \( V_j = V_0 = \ldots = V_j = V_0 \). Then, based on formulas (10) and (12), the signal synthesis efficiency can be expressed as formula (13)

\[
\eta_T (t) = \frac{\sum_{j=1}^{N} \cos \left( 2 \pi f_0 \left( T_{\text{win}} - t - \frac{V_j t}{c} \right) + \phi_0 - 2 \pi f_0 \frac{V_j T_{\text{win}}}{c} \right) }{\sum_{j=1}^{N} \cos \left( 2 \pi f_0 \left( T_{\text{win}} - t - \frac{V_j t}{c} \right) + \phi_0 - 2 \pi f_0 \frac{V_j T_{\text{win}}}{c} \right)^{-1}} 
\]

This function can measure the change of the signal synthesis efficiency at the target position caused by the speed difference of the distributed array element nodes at different times. Considering the purpose of power synthesis at the target point, the moment of the maximum signal synthesis amplitude under the ideal condition is taken for analysis, i.e., \( t = \frac{n \pi f_0}{f_0 c} \). Then, the random variable is expressed as formula (14)

\[
\eta_{T_{\text{max}}} = \eta_T (t = \frac{n \pi f_0}{f_0 c}) = \frac{\sum_{j=1}^{N} \cos \left( 2 \pi f_0 \left( T_{\text{win}} - t - \frac{V_j t}{c} \right) + \phi_0 - 2 \pi f_0 \frac{V_j T_{\text{win}}}{c} \right) }{\sum_{j=1}^{N} \cos \left( 2 \pi f_0 \left( T_{\text{win}} - t - \frac{V_j t}{c} \right) + \phi_0 - 2 \pi f_0 \frac{V_j T_{\text{win}}}{c} \right)^{-1}} 
\]

Compared to the propagation speed of electromagnetic waves, the motion speed of the unmanned aerial vehicle (UAV) is extremely small and can be ignored. Then, the even symmetry characteristic of the cos function is used to simplify the above formula as formula (15).

\[
\eta_{T_{\text{max}}} = \frac{1}{N} \cdot \sum_{j=1}^{N} \cos \left( \pm K \cdot 2 \pi f_0 T_{\text{win}} \cdot \frac{V_0 - V_j}{c} \right) 
\]

\[
= \frac{1}{N} \cdot \sum_{j=1}^{N} \cos \left( 4 \pi f_0 T_{\text{win}} \cdot \frac{V_j - V_0}{c} \right) 
\]

\[
= \frac{1}{N} \cdot \sum_{j=1}^{N} \cos \left( \Delta V_j \right) 
\]

\[
= \frac{1}{N} \cdot \sum_{j=1}^{N} \cos \left( \Delta f_j \right) 
\]

where \( \Delta V_j \) represents the speed error of each node, and \( \Delta f_j = \frac{4 \pi f_0 T_{\text{win}}}{c} \cdot \Delta V_j \) represents the phase error caused by the speed error. It can be seen that, when \( \Delta f_j = 0 \), the synthesis efficiency is \( \eta_{T_{\text{max}}} = 1 \); when \( \Delta f_j \neq 0 \), both the center frequency of the signal \( f_0 \) and the value of the receiving time window \( T_{\text{win}} \) affect \( \eta_{T_{\text{max}}} \).

5. Simulation analysis

The analysis in Section 4 suggests that the study of the impact of speed error on the power synthesis effect under the motion state of distributed nodes can be transformed into the study of the impact of the phase error caused by the speed error on the synthesis effect. In this way, the boundary conditions of the speed error can be determined under the premise of meeting certain power synthesis requirements.

It can be seen from formula (15) that the power synthesis efficiency at the target position is not related to the node formation and signal style. Only the influence of the number of nodes \( N \) and the phase error \( \Delta f_j \) need to be investigated. It is assumed that the phase error \( \Delta f_j \) obeys a normal distribution with a mean value of 0 and a variance of \( \sigma^2 \). It is difficult to obtain the variation law of the target point synthesis efficiency with the phase error either in theory. Thus, by taking a fan-shaped array that conforms to the actual application scenario as an example, statistical analysis is conducted by performing 10,000 Monte Carlo experiments under typical parameter settings with different array element numbers \( N \) and different phase error standard deviations \( \sigma \) (within the range of 0–2\( \pi \)). It is assumed that each sub-array consists of five motion nodes, the sub-arrays are evenly distributed, and the number of sub-arrays is set to 3, 5, 7, and 9 respectively as shown in Fig. 4. Then, the total number of nodes is \( N = 15, 25, 35, 45 \), respectively.

Additionally, to facilitate the investigation of the influence of speed error, it is assumed that at the current moment, the control commands of the control unit to all nodes are synchronized in real-time, and the time error is \( \Delta t_1 = \Delta t_2 = \ldots = \Delta t_N = 0 \). Also, it is assumed that the position accuracy of all nodes is measurable in real-time, and the positioning error is \( \Delta r_1 = \Delta r_2 = \ldots = \Delta r_N = 0 \). Given the center frequency \( f_0 \) and receiving time window length \( T_{\text{win}} \), the phase error only comes from the node speed error. Then, Fig. 5 shows the variation law of the mean value \( \mu_{\Delta f} \) and variance \( \sigma^2_{\Delta f} \) of the synthetic efficiency at the target point position with the number of array elements \( N \) and the standard deviation of phase error \( \sigma \).

It can be seen from Fig. 5(a) that the mean value \( \mu_{\Delta f} \) of the synthesis efficiency at the target point position is not affected by the number of nodes \( N \), and it is only related to \( \sigma \). As the value of \( \sigma \) increases, the mean value of the target point synthesis efficiency decreases. Fig. 5(b) also indicates that the variance \( \sigma^2_{\Delta f} \) of the target point synthesis efficiency is not affected by the number of nodes \( N \). When \( \sigma < 0.25 \pi \), \( \sigma^2_{\Delta f} \) increases with the value of \( \sigma \), and it reaches the maximum value near \( \sigma = 0.25 \pi \); when \( \sigma > 0.25 \pi \), \( \sigma^2_{\Delta f} \) decreases with the increase of \( \sigma \) value; when \( \sigma \geq 1.25 \pi \), \( \sigma^2_{\Delta f} \) drops to 0, and then no longer changes.

The analysis suggests that the variance \( \sigma^2_{\Delta f} \) of the target point synthesis efficiency having a peak inflection point at \( \sigma = 0.25 \pi \) is related to the \( 3 \sigma \) rule in the normal distribution features. Within the range of the normal variable of \( (-\infty, +\infty) \), the phase error variable will fall within its mean plus or minus \( 3 \sigma \), i.e., \( P[\mu - 3 \sigma < \Delta \phi < \mu + 3 \sigma] = 0.9974 \). According to this, it can be seen from Fig. 5 that, when \( \sigma < 0.25 \pi \) and \( |\Delta \phi| < 0.75 \pi \), the mean value of the target point synthesis efficiency decreases the fastest. This is because affected by the phase error, the possibility that the signal error of each array element node reaches the target position in the reverse direction is extremely high. However, when \( \sigma > 0.25 \pi \) and \( |\Delta \phi| > 0.75 \pi \), the dispersion interval of the phase error variable expands, and the possibility that the signal sent by each array element node reaches the target position in the reverse direction decreases. Also, the variance \( \sigma^2_{\Delta f} \) of the synthetic efficiency decreases, and the decreasing trend of the mean value \( \mu_{\Delta f} \) of the synthetic efficiency gradually flattens.

To meet the power synthesis size under different task requirements, the ratio of the power synthesis variable \( P_{\text{syn}} \) at any point in the target area to the target point power synthesis variable \( P_T \) should be greater than a given threshold \( \gamma \), and the point \( H \) when \( P_{\text{syn}}/P_T > \gamma \) is defined as the effective power point. The effective power points are calculated and marked to illustrate the effective power focusing in the target area.

The simulation conditions are as follows. LFM signal is adopted, and the signal frequency is set at \( f_0 = 10 \) GHz, the modulation bandwidth is 30 MHz, the receiving time window length is set to 0.1 ms, the target position is set to \( (0, 0, 0) \); the array adopts a uniform fan-shaped array composed of nine sub-arrays, and each sub-array has five array element nodes, the polarization mode and polarization direction of all array element antennas are the same; the total number of nodes is \( N = 45 \); the effective power synthesis threshold \( \gamma \) is set to 0.7; the phase error obeys a zero-mean normal distribution; the standard deviation is set to 0.2\( \pi \), 0.3\( \pi \), 0.5\( \pi \), and 0.8\( \pi \) respectively. Monte Carlo experiments are performed on four groups of values. The comparison with the traditional effective power synthesis effect is shown in Fig. 6.
As shown in Fig. 6, as the phase error increases, the effective power focusing aperture in the target area becomes larger. This is because the phase error results in incomplete alignment of the phases when each node signal is synthesized at the target point position. This not only reduces the synthesis efficiency but also intensifies the energy around the target point. Table 1 shows the power synthesis efficiency of the target position and the corresponding maximum speed error under several sets of phase errors.

It can be seen from the comparison and analysis of Fig. 5 and Table 1 that, for different task needs, to ensure that the target position achieves a certain power synthesis efficiency, the speed error of the array element node needs to be controlled within the corresponding interval. For example, when the synthesis efficiency is required to be more than 90%, the maximum speed error between nodes should not be higher than 15 m/s, and this is easy to achieve on slow-motion platforms such as rotary-wing UAV. The time synchronization error and positioning error are assumed to be ideal for the discussion of this study. Therefore, when the impact of various errors is fully considered in actual applications, the speed error should be controlled within a strict range.

6. Conclusion

In this study, the problem of spatial power synthesis on the distributed motion platform was studied by using the space-time adaptive
focusing feature of time-reversal electromagnetic waves. By installing a time-reversal signal processing device on the distributed motion platform, the signal of the original target radiation source can be received, processed, and then sent back to achieve precise power focusing in the target area. The essence of time-reversal is to perform time-domain reversal or frequency-domain conjugate processing on the signal. Compared with the traditional phase delay superposition phased array and waveform diversity technology, the method proposed in this study has a simple signal processing mode and low computational complexity during spatial power synthesis. The simulation results indicate that the distributed motion platform based on time-reversal electromagnetic waves can also achieve a good power synthesis effect under a certain phase error. The power synthesis changes of the target area under different distributed formations and different phase errors are also presented in this study, which provides a theoretical reference for the practical application of the proposed method.

Declarations

Author contribution statement

Long Tana: Performed the experiments; Analyzed and interpreted the data; Contributed regents, materials, analysis tools or data; Wrote the paper.

Jifei Pana, Qiuxi Jianga: Conceived and designed the experiments. Fangzheng Liu: Contributed regents, materials, analysis tools or data.

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Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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