Research on Distributed Beamforming Algorithm Based on Inter-satellite Link

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Abstract. The inter-satellite link load belongs to a system with limited power volume, and generally has low antenna gain and weak transmission capacity. Aimed at handling the problem that single-node inter-satellite link systems are often incapable of satisfying long-distance high-bandwidth communication requirements, the distributed beamforming algorithm is applied to the inter satellite design, in order to achieve higher inter-satellite link performance without increasing the inter-satellite link transmission power. This paper analyzes the feasibility and spatial beam pattern of distributed beamforming in inter-satellite links. The improved distributed beamforming algorithms that can be adapted to different channels change are proposed. In a flat stationary channel, the phase weight and correction factor are increased, when the random phase disturbance is 3°, the number of beam retransmissions is reduced by 800 times compared with the classical algorithm; In the time-varying channel, the feedback of the time-varying in-formation of the channel is increased, and the phase compensation is added to alleviate the influence of the dynamic change of the channel. Compared with the traditional algorithm, it can be adapted to the change of the time-varying channel.

Keywords: Distributed beamforming · One-bit feedback · Random perturbation

1 Introduction

Inter-satellite link refers to the communication link between satellites. Through the inter-satellite link, information transmission and precise measurement between satellites can be realized, and multiple satellites can be interconnected into space communication and measurement networks [1, 2]. The inter-satellite link load belongs to the power volume limited system, with low antenna gain and weak transmission capacity. When faced with the cooperative task of perceptual communication, the single node inter-satellite link system is often difficult to meet the requirements of long-distance and high bandwidth communication, and becomes the bottleneck of cooperative task. Multiple forwarding by multi-hop mode will inevitably lead to the increase of communication delay and can not be adapted to the scene with high real-time requirements; In addition, the forwarding by converging satellite node will put forward higher requirements for converging node

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resources, and make the whole inter-satellite network highly dependent on the converging node. In the face of complex environment, the damage of the converging node will lead to the paralysis of the whole network. Therefore, how to rely only on the coordination of the inter-satellite link nodes of the distributed satellite system to enhance the communication measurement capability of the inter-satellite network, to expand the scope of the inter-satellite link, and to improve the anti-interference ability is of great significance to the decentralized space-based system.

Distributed beamforming is independent of each other and the randomly distributed nodes randomly cooperate with each other to form a virtual antenna array which directly communicate with the target receiver through beamforming [3]. Distributed beamforming technology sends a common message and controls the phase of its transmission through multiple information sources at the same time, so that the signals can be constructively combined at the intended destination, and the antenna array with N array elements can obtain N^2 times of the radiant power gain. Distributed beamforming can increase the communication distance of nodes and enhance the communication range of nodes. Unlike multi-hop communication, it reduces the occurrence of problems in the safety and reliability of satellite long-distance communication.

In terms of distributed beamforming research, H. Ochiai first proposed the application of traditional beamforming theory to wireless sensor networks in 2005. Based on the above research results, M.I. Poulakis analyzed and discussed the application of beamforming theory in sensor network and satellite communication scenarios based on ideal environmental conditions [4]. Since 2004, with the support of the US Naval Research Office, DARPA and the National Science Foundation, the R. Mudumbai team at the University of California and the D.R. Brown II team at Worcester Polytechnic have conducted systematic research on distributed beamforming. The R. Mudumbai team's research achievement is mainly to propose a synchronization method based on closed-loop feedback: one-bit feedback synchronization scheme [5–7]. This synchronization scheme was proposed in 2005 [8]. In 2010, R. Mudumbai summarized the one-bit feedback synchronization method [9, 10], proposed a circuit prototype, and verified the algorithm experimentally.

The one-bit feedback algorithm proposed in this paper makes a simple iteration of the feedback from the satellite receiver to achieve satellite transmitter phase coherence, and shows that the process meets the requirements of distributed beamforming. The basic idea is as follows: each satellite transmitter randomly adjusts its phase in each iteration, while the receiver broadcasts a one-bit feedback in each iteration showing that its SNR is better or lower than before. If it is better than before, the transmitter maintains the phase disturbance, and if it is worse, the previous phase disturbance is eliminated. Repeat this random process until the transmitter converges to phase coherence.

2 Basic Model of Distributed Beamforming for Inter-satellite Links

Figure 1 shows the communication model of distributed inter-satellite link beamforming based on feedback control. It has N satellite transmitters, and all transmitters are frequency-locked to the reference carrier signal by using the master-slave architecture described in [6]. As a result, the carrier signals of all transmitters are at the same frequency f_c, without frequency offset. However, due to the unknown transmission delay in the master-slave architecture, there is an arbitrary phase difference between the satellite transmitters. The carrier signal of transmitter i is expressed as:

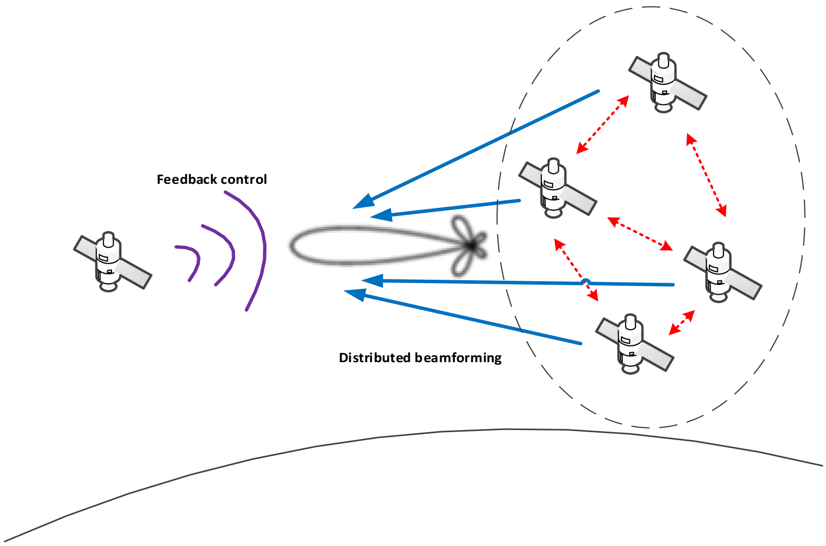

Fig. 1. Diagram of distributed interstellar link beam formation based on feedback control

$$c_i(t) = R\left(e^{j(2\pi f_c t + \varepsilon_i)}\right) \tag{1}$$

Where ε_i is the phase offset.

The modulated signal sent by transmitter i is expressed as:

$$s_i(t) = R\left(m(t)e^{j\theta_i}e^{j(2\pi f_c t + \varepsilon_i)}\right) \tag{2}$$

θ_i is the rotation angle of the modulated signal of the satellite transmitter i.

If the channel transmitted to the receiver is $h_i = a_i e^{j\varphi_i}$, the total received signal of the satellite receiver is:

$$r(t) = R\left(m(t)e^{j2\pi f_c t}\sum\nolimits_{i=1}^{N} a_i e^{j(\varepsilon_i + \theta_i + \varphi_i)}\right) \tag{3}$$

The phase from transmission to reception is $\Phi_i = \varepsilon_i + \theta_i + \varphi_i$. The power of the received signal is expressed as:

$$S_r = \left|\sum\nolimits_i a_i e^{j\Phi_i}\right|^2 \tag{4}$$

The transmitter adjusts its phase rotation θ_i so that the signals from all transmitters are coherently received at the receiving end, and the received power S_r is maximized. At this time, Φ_i is a constant value.

In order to visualize the effect of distributed beamforming, it is assumed that there are 8 transmitting nodes, distributed on a 100 * 100 m plane, and omnidirectional antennas are used, all of which have the same frequency of 1 GHz and the same phase, and are transmitted simultaneously (Fig. 2).

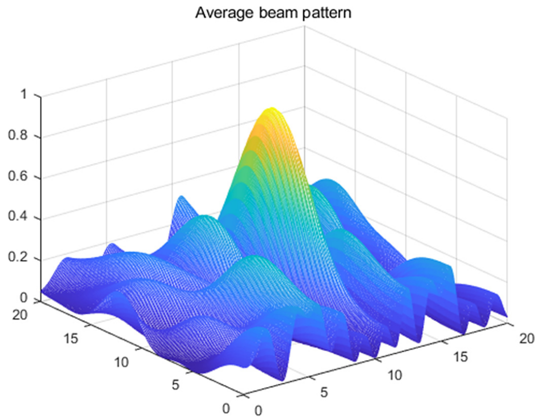

Fig. 2. 8-nodes distributed beamforming average beam pattern

Figure 3 shows that the number of transmitting nodes increases to 110, and the beam synthesis efficiency reaches 98%. Meanwhile, the beam pattern is very sharp, and the side lobe is only 10%, while the side lobe suppression effect is good, and the beam directivity is strong. It can be seen that increasing the number of satellite transmitters can increase the synthesized beam gain, but the number of transmitter nodes is determined. Therefore, it becomes the focus of this paper that how to improve the efficiency of beamforming and increase the communication distance of nodes by changing the phase of transmitter nodes, and increase the communication distance of nodes under a certain number of transmitter nodes.

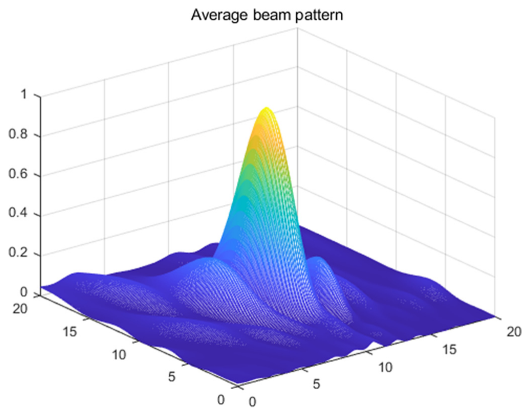

Fig. 3. 110-nodes distributed beamforming average beam pattern

3 One-Bit Feedback Distributed Beamforming Method and Feasibility Simulation

The net complex gain of the receiver is:

$$Y = \sum_{i=1}^{N} a_i e^{j(\varepsilon_i + \theta_i + \varphi_i)} = \sum_{i=1}^{N} a_i e^{j\Phi_i} \tag{5}$$

The amplitude Y $\geq$ 0 indicates the received signal strength (RSS), and $\Phi_i = \varepsilon_i + \theta_i + \varphi_i$ is the phase difference between the satellite receiver and the transmitter i signal.

If the received carrier phases Φ_i are all equal, then:

$$Y = \left| \sum_{i=1}^{N} a_i e^{j\Phi_i} \right| \leq Y_{max} \equiv \left(\sum_{i=1}^{N} a_i \right), \text{ If and only } \Phi_i = \Phi_j \tag{6}$$

The purpose of the feedback control algorithm is to allow the transmitter i to dynamically calculate the optimal value of θ_i without knowing any φ_i or ε_i.

The classic one-bit feedback algorithm proposed in this paper only needs to add a random phase perturbation vector to the starting phase of each transmitter, and then after several iterations, the RSS finally reaches the optimal. First, a brief introduction to the classic distributed beamforming single-bit feedback algorithm is given as follows.

1) Each transmitter retains the best value of its current phase rotation $\theta_{best,i}(n)$. The receiving end measures the received signal strength Y of each time slot n, then the best $Y_{best}(n)$:

$$Y_{best}(n) = \max_{m \leq n} Y(m) \tag{7}$$

$$Y(m) = \left| \sum_{i=1}^{N} a_i e^{j\Phi_i(m)} \right| \tag{8}$$

2) In the n + 1 time slot, each beamforming node transmitter generates random phase disturbance δ_i, subject to the probability distribution $f_\delta(\delta_i)$, so that: $\theta_i(n+1) = \theta_{best,i}(n) + \delta_i$,thereby:

$$\Phi_i(n+1) = \Phi_{best,i}(n) + \delta_i \tag{9}$$

Where $\Phi_{best,i}(n) = \varepsilon_i + \theta_{best,i}(n) + \varphi_i$ is the phase of the signal from the transmitter to the receiver, which corresponds to $\theta_{best,i}(n)$.
3) If the signal strength received by the feedback node satellite is stronger than the best received signal strength of the previous time slot, the satellite receiver will generate a single feedback bit and set it to “1”, otherwise set it to “0”, and then broadcast that feedback.
4) The receiver updates $Y_{best}(n+1)$, and the beamforming node transmitter updates the phase rotation $\theta_{best,i}(n+1)$, and maintains the phase disturbance δ_i when the feedback bit is “1”, otherwise discards it.
5) Repeat the process in the next time slot.

The update process can be written mathematically:

$$Y_{best}(n+1) = \begin{cases} Y(n+1), & Y(n+1) > Y_{best}(n) \\ Y_{best}(n), & otherwise \end{cases} \quad (10)$$

$$\theta_{best,i}(n+1) = \begin{cases} \theta_{best,i}(n) + \delta_i(n), & Y(n+1) > Y_{best}(n) \\ \theta_{best,i}(n), & otherwise \end{cases} \quad (11)$$

The performance of the algorithm has a great relationship with the selected maximum random phase disturbance δ_i. The second step of the classic algorithm indicates that different phase disturbances have an effect on the final beamforming effect. Choosing the appropriate phase disturbance will help the algorithm to converge faster and the combined power efficiency becomes better. Suppose that there are 30 transmitting nodes with equal amplitude transmission power, the phase disturbance δ_i is subject to two-point distribution and uniform distribution, respectively.

1) The phase disturbance δ_i follows a uniform distribution. When $\delta_i = 30°, 10°, 5°$. The simulation results are shown in Fig. 4. The larger the phase disturbance δ_i, the faster the convergence speed, but the lower the final synthesis efficiency. Conversely, the smaller the phase disturbance δ_i, the slower the convergence speed, the higher the final synthesis efficiency. The reason is that the greater the phase disturbance, in the fourth step of the classic algorithm, the optimal received signal strength obtained by the destination receiver is difficult to be fine-tune to the maximum received strength.

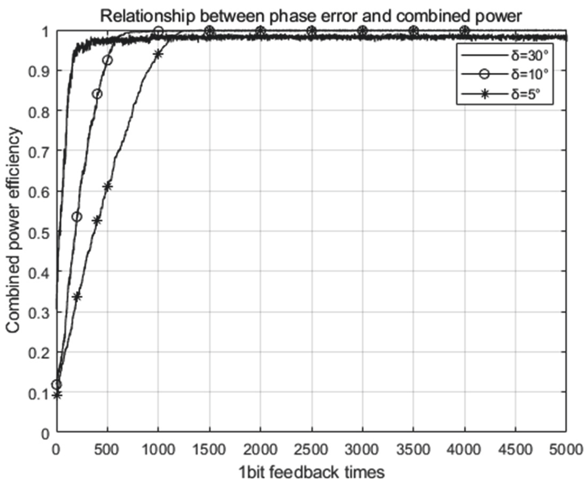

Fig. 4. Phase disturbances follow uniform distribution

2) The phase disturbance δ_i follows two points. Set the phase disturbance $\delta_i = 30°$, $10°$, $5°$. The simulation results are shown in Fig. 5, When the phase disturbance $\delta_i = 10°$, the two-point distribution only needs 550 iterations to converge to the optimal value, and the uniform distribution requires 800 iterations In order to achieve convergence,

the two-point distribution needs 800 iterations to converge to the optimal value when the phase disturbance $\delta_i = 5°$, and the uniform distribution requires 1100 iterations to achieve convergence, indicating that the smaller the phase disturbance, the greater the cost of uniform distribution and the slower the convergence rate.

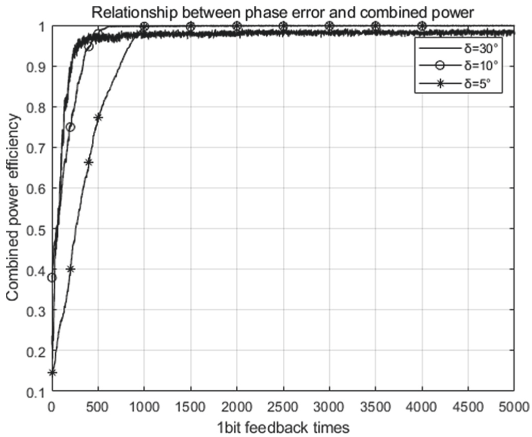

Fig. 5. Phase disturbances follow uniform distribution

In order to improve the adjustment speed of the algorithm and the stability of the channel change, we make certain improvements of the classic algorithm.

Improved algorithm 1: Improve the second step of the classic algorithm, so that the added random phase disturbance changes dynamically with the function convergence. At the beginning of synchronization, phase disturbances can be increased to speed up the convergence of the transmitting node. When approaching convergence, random phase disturbances can be reduced to make the convergence more stable and the synthesis efficiency higher.

Improved algorithm 2: The phase of the distributed beamforming node at the time slot n mentioned above is $\Phi_i = \varepsilon_i + \theta_i + \varphi_i$, After operating the phase, adding the phase weight and the correction factor $\tau_i(n)$, the initial n-slot beamforming phase is expressed as:

$$\Phi_i(n) = \varepsilon_i + \varphi_i + \theta_i(n) + \delta_i(n) + \tau_i(n) \tag{12}$$

When the phase disturbance added by time slot n is successful, that is $Y(n+1) > Y_{best}(n)$ satisfied, the initial n-slot beamforming phase can be expressed as:

$$\Phi_i(n) = \varepsilon_i + \varphi_i + \theta_i(n) + \delta_i(n) + \delta_i(n+1) + \left(1 + \frac{1}{R_D}\right)\tau_i(n) \tag{13}$$

When the phase disturbance of the n-slot fails, that is, $Y(n+1) \le Y_{best}(n)$ is satisfied, the initial n-slot beamforming phase can be expressed as:

$$\Phi_i(n) = \varepsilon_i + \varphi_i + \theta_i(n) - \delta_i(n) + \delta_i(n+1) \tag{14}$$

Figure 6 shows the convergence process of the three algorithms when $\delta_i = 10°$: Initially, the improved algorithm 1 and improved algorithm 2 converge faster than the classic algorithm. After 500 iterations, the improved algorithm 2 has a better convergence rate than the classic algorithm and the improved algorithm 1. Finally, the combined power efficiency of the three algorithms is almost 100%.

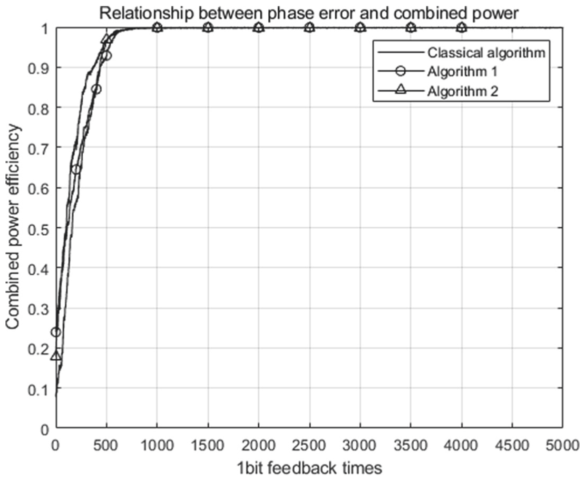

Fig. 6. $\delta_i = 10°$ convergence of the three algorithms

Figure 7 shows the convergence process of the three algorithms when $\delta_i = 3°$: it can be seen that the improved algorithm 2 is significantly better than the improved algorithm 1 and the classic algorithm. The combined power efficiency is almost 100%.

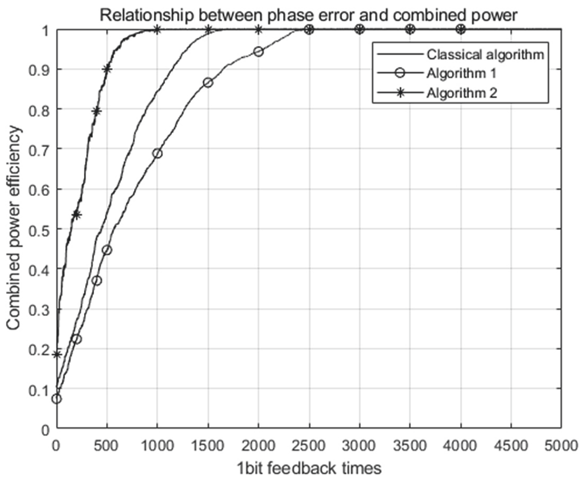

Fig. 7. $\delta_i = 3°$ convergence of the three algorithms

Figure 8 shows the convergence process of the improved algorithm 2 under different initial disturbance step sizes: the phase perturbation corresponding to the convergence speed from fast to slow is 30°, 10°, 5° and 3°, When the number of iterations is 900 The power efficiency is almost 100%, indicating the final value of the received signal strength is the largest.

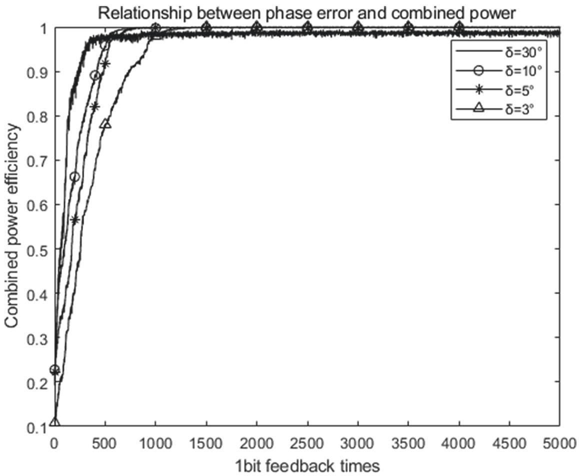

Fig. 8. Convergence process of the improved second algorithm under different δ_i conditions

The above simulation is assumed that the wireless channel from each transmitter to the receiver is static, and the phase synchronization convergence model. For such a channel, it can be proved that the single-bit feedback algorithm asymptotically converges to perfect coherence with probability 1. Once converged, the transmitter can use the optimal value $\theta_{best,i}$ obtained from the algorithm to maintain coherent transmission in subsequent time slots. But in actual situations, the channel phase response changes with time, for example. Due to the Doppler effect of moving scatterers. For such channels, channel changes will cause the transmitted signal to lose coherence over time: Even when the transmitter uses the same phase rotation $\theta_{best,i}$, the received phase $\Phi_{best,i}(n) = \varepsilon_i + \theta_{best,i}(n) + \varphi_i(n)$ will not remain unchanged due to the change of the channel phase response $\varphi_i(n)$. As a result, the received signal strength $Y_{best}(n) = \left|\sum_{i=1}^{N} a_i e^{j\Phi_{best,i}(n)}\right|$ decreases gradually. The one-bit feedback algorithm can be adjusted to dynamically adjust the transmission phase $\theta_{best,i}(n)$. The two-bit feedback algorithm adds feedback information, feeds back the time-varying information of the channel, and adds additional phase compensation to alleviate the adverse effects caused by the dynamic change of the channel, so that the receiving end node receives better quality of RSS.

The following will compare the convergence rate and the final value of the received signal strength of the time-varying channel simulation algorithm and the two-bit feedback algorithm at different channel drift speeds to better show the final stability of each algorithm.

The channel drift Δ_i of the three images is from small to large, and the time-varying channel is from weak to strong. When Δ_i is small, the combined power efficiency of the two algorithms can reach more than 95%; When Δ_i gradually increases, the convergence speed of the two algorithms also decreases, but the two-bit feedback algorithm is time-varying relative to the classic one. The advantages of the channel simulation algorithm are also reflected, especially when $\Delta_i \sim U\left(-\frac{\pi}{18}, \frac{\pi}{18}\right)$, the convergence speed and beamforming efficiency of the two-bit feedback algorithm are the best (Figs. 9 and 10).

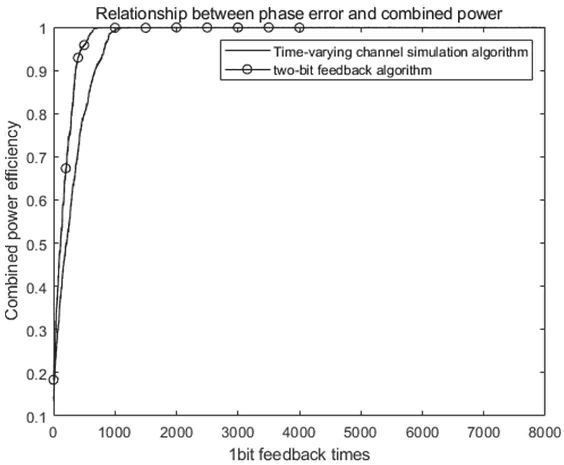

Fig. 9. The convergence process of the two algorithms when the channel drift is $\Delta_i \sim U\left(-\frac{\pi}{125}, \frac{\pi}{125}\right)$

The conclusion of the simulation comparison analysis is that two-bit feedback algrithmms proposed in this paper are suitable for distributed beamforming in time-varying channels. Compared with the existing algorithm, it can overcome the problem that the existing algorithm cannot converge due to channel drift, and has the advantages of fast convergence speed and large final value of received signal strength (Fig. 11).

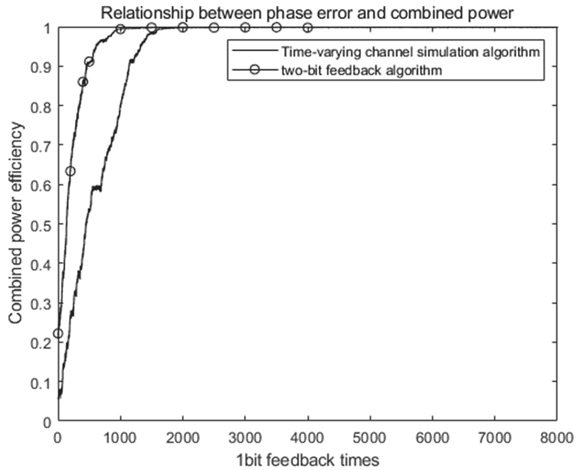

Fig. 10. The convergence process of the two algorithms when the channel drift is $\Delta_i \sim U\left(-\frac{\pi}{125}, \frac{\pi}{125}\right)$

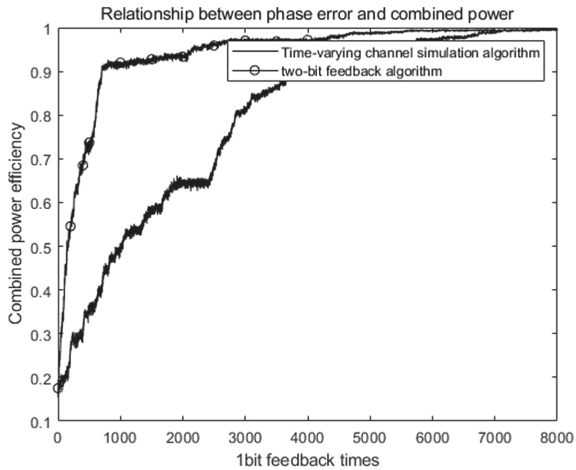

Fig. 11. The convergence process of the two algorithms when the channel drift is $\Delta_i \sim U\left(-\frac{\pi}{18}, \frac{\pi}{18}\right)$

4 Conclusion

This paper studies and analyzes the idea of using distributed beamforming in inter-satellite links from a theoretical perspective. This method can increase the satellite communication distance and improve the confidentiality of satellite communication. A single-bit feedback algorithm is proposed to solve the core problem of its implementation: carrier synchronization. Compared with other synchronization algorithms, the receiver has less feedback and strong scalability. For the stationary channel and the time-varying channel, the distributed beamforming algorithms designed separately have a faster convergence rate and a better final value of the received signal strength than the classic algorithm.

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