Spectrum Sensing for Weak Signals Based on Satellite Formation

Yu Zhang[1,2], Xiaojin Ding[2(✉)], Chaoran Sun[1,2], Jian Zhu[1], and Gengxin Zhang[1,2]

[1] College of Telecommunications and Information Engineering, Nanjing University of Posts and Telecommunications, Nanjing 210003, China
[2] Telecommunication and Network National Engineering Research Center, Nanjing University of Posts and Communications, Nanjing 210003, China
`dxj@njupt.edu.cn`

Abstract. In this paper, we investigate the spectrum sensing of a weak signal based on multiple low earth orbit (LEO) satellites in the presence of a spectrum-sharing node, which can generate the interference imposed on the sensing LEO satellites. In order to improve the sensing ability of the weak signal, a cooperative spectrum sensing method relying on satellite formation is proposed. Specifically, firstly, some satellites will be chosen from multiple LEO satellites for formation purposes, where the specific number of satellites chosen can be adjusted by evaluating the probability of detection weak signal, as detailed later. Then, considering the object that both restraining the interference and magnifying the weak signal, the weighted value of each satellite for beamforming may be optimized with the aid of genetic algorithm, and the receive gains of the weak signal and the interference can be achieved. Finally, the probability of detecting the weak signal can be evaluated by calculating the signal to interference plus noise ratio (SINR), and the number of the chosen satellites can be decided accordingly. Simulation results show that the proposed method not only can suppress the interference imposed on the sensing satellites, but also can increase SINR of sensing satellites for the weak signal, resulting in improving the probability of detection.

Keywords: Spectrum sensing · Multi-satellite collaboration · Beamforming · Satellite formation

1 Introduction

Spectrum sensing is one of the key technologies in cognitive radio technology, which is mainly used to monitor the frequency usage of primary users. Traditional spectrum sensing technology is mainly divided into two categories: single node spectrum sensing and multi-node cooperative spectrum sensing. The most basic spectrum sensing methods include spectrum sensing based on energy, spectrum sensing based on cyclic-stationary characteristics and spectrum sensing based on matched filter detection [1]. Among these spectrum sensing methods, the energy sensing method is the simplest one, because this method does not need any prior information characteristics of the transmitted signal, and

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it is the most widely used spectrum sensing technology at present [2]. At the beginning of the emergence of cognitive radio technology, the research is based on the ground network, that is, the cognitive users and primary users both are nodes in the ground network, and so far, the research of cognitive radio technology in the ground network has been quite mature [3]. However, due to the fact that the ground network can’t solve the problem of communication obstacles caused by the desert, ocean and other terrain areas, and the high cost of setting up base stations in sparsely populated and remote areas, people have to consider the development of the satellite network [4]. Satellite communication becomes more concentrated because of its large coverage, wide coverage, high communication quality, and it can overcome the communication obstacles caused by the desolate terrain encountered by the ground network [5]. As an extension and supplement of the ground network, satellite network has become one of the leading technologies of the next generation of mobile communication system to construct the satellite ground integrated system and realize the seamless coverage of wireless mobile communication [6]. With the advantages of large carrying capacity of ground system and wide coverage of satellite system, the satellite ground integrated system can provide users with seamless coverage services. At the same time, with the development of the satellite ground integrated system, it is inevitable to face the problem of spectrum resource shortage, so it is necessary to apply cognitive radio technology to the satellite ground integrated system.

Spectrum sensing in the satellite ground integrated system will face another problem. That is, due to the long-distance transmission between the ground network and the satellite, the low signal-to-noise ratio will seriously affect the performance of spectrum sensing [7]. Especially for the proposed scenario, when the satellite perceives a weak signal with strong signal interference, the SINR of the weak signal received by the satellite will be lower. Therefore, the low signal-to-noise ratio of satellite spectrum sensing will become a hot topic. At present, some scholars have also studied related problems, such as in Ref. [8], the author has studied the optimization of different spectrum sensing parameters by using genetic algorithm in the case of low SNR. The simulation results show that this method provides a better practical solution for cognitive radio network. Another example, in Ref. [9], the author proposed an improved energy detection method based on gradient for the change of noise power and low SNR. The simulation results show that the performance of spectrum sensing is improved based on this method.

However, there are few researches on the spectrum sensing of a weak signal based on multiple low earth orbit (LEO) satellites in the presence of a spectrum-sharing node, which can generate the interference imposed on the sensing LEO satellites. In this paper, a multiple satellite cooperative spectrum sensing model is proposed, and beamforming technology is introduced to improve the received signal-interference-noise ratio (SINR) of the weak signal when there is strong signal interference on the ground. According to the relevant research, beamforming technology can be used to solve the problem of interference, for example, a scenario of beamforming technology application proposed in Ref. [10], and the simulation results show that beamforming technology plays an important role in canceling the influence of fading and interference. At the same time, in Ref. [11], the author puts forward another application scenario of beamforming technology, and the simulation results show that the design method of beamforming can find the best combination of beamforming, and can deal with interference management problems well, so it is feasible to apply beamforming technology to the scenario proposed in this paper. The method proposed in this paper is to make the satellite form the pattern in the form of formation. In the direction of weak signal, the manifold vectors of each satellite are superposed in the same phase, and in the direction of strong signal, the manifold vectors of each satellite are eliminated in the reverse direction as much as possible, so as to improve the signal-interference-noise ratio (SINR) of satellite reception. The main innovations of this paper are as follows:

1) The system model of satellite sensing weak signal in the presence of strong interference is proposed;
2) Beamforming technology is introduced to improve the received signal-interference-noise ratio (SINR) of satellite;
3) Simulation results show that this method can effectively improve the performance of satellite spectrum sensing.

The rest of this paper is arranged as follows: Sect. 2 is the introduction of the proposed system model and energy perception. In Sect. 3, the beamforming technology proposed in this paper is introduced, and the calculation formula of signal- interference-noise ratio (SINR) of satellite receiving under this technology is given. Section 4 is performance evaluation, and Sect. 5 concludes this paper.

2 The System Model

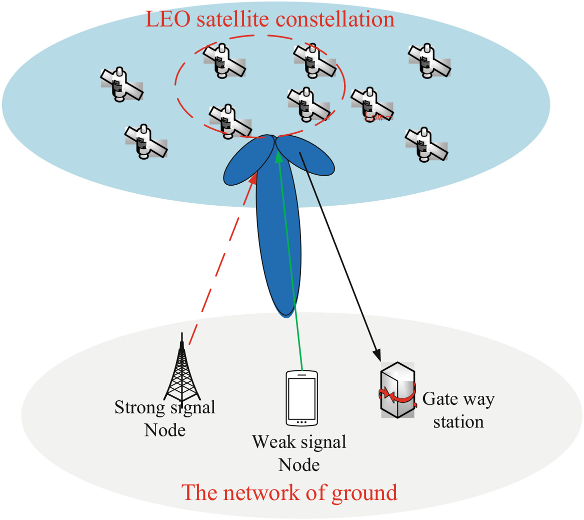


Fig. 1. Illustrative of cooperative sensing model for satellite communications

The model in Fig. 1 is based on a satellite-ground integration scenario in which the satellite acts as a cognitive user to perceive weak signal node on the ground in the presence of strong signal interference. In this scenario, the ground network has a strong signal transmitting node and a weak signal transmitting node as well as a signal gateway for satellite transmitting and receiving signals. The LEO satellites over the nodes are grouped in formation to form a cluster to sense the weak signal node in the ground network when there is strong signal interference. Based on the above model, it is assumed that the transmitting signal of the weak signal node on the ground is s_1, the transmitting power is P_{T1}, the transmitting gain is G_{T1}, and the channel gain between the weak signal node and the satellite i is h_{1i}. Accordingly, the transmitting signal of the strong signal node is s_2, the transmitting power is P_{T2}, the transmitting gain is G_{T2}, the channel gain between the strong signal node and satellite i is h_{2i}, assuming the satellite's receiving gain is G_R, then the received signal of satellite i can be given by the following formula:

$$y_i = \sqrt{G_{T1} \cdot P_{T1} \cdot G_R} \cdot h_{1i} \cdot s_1 + \sqrt{G_{T2} \cdot P_{T2} \cdot G_R} \cdot h_{2i} \cdot s_2 + n_0, \quad 1 \leq \mathrm{i} \leq \mathrm{N} \qquad (1)$$

The channel gain of ground nodes to each satellite is approximately considered to be equal because of the mode array of satellite formation. It means that h_{1i} and h_{2i} all are the same, assuming that, after Gauss decline, the channel gain's mean is 0, and the variance is 1, then that satisfies $h_{1i} = h_{2i} = 1$, and n_0 represents Additive white Gaussian noise. Then after satellites forming, the signal-interference-noise ratio (SINR) of the weak signal by satellite i can be expressed as:

$$SINR_i = \frac{P_{T1} G_R G_{T1} \left(\frac{c}{4\pi d_{ji} f} \right)^2}{P_{T2} G_R G_{T2} \left(\frac{c}{4\pi d_{ji} f} \right)^2 + KBT} \qquad \mathrm{j} = 1{,}2 \qquad (2)$$

Where K is Boltzmann constant, T represents the equivalent noise temperature of the receiver, and B represents the transponder bandwidth, c is the light speed, d_{ji} denotes the distance between the satellite i and the node j, f is the center frequency of the spectrum bands.

According to Ref. [12], the relationship between the correct detection probability of a single satellite perception and SINR is shown in Fig. 2. From Fig. 2, it can be seen that the correct detection of conventional energy sensing method will decrease sharply when SINR is below −4 dB, in the scenario shown in Fig. 1, the SINR will be much lower than −4 dB when the transmitted power of the sensing signal and the Interference signal are 10 dBm and 30 dBm, respectively, there is an urgent need to explore a new perception method to meet the needs of weak signal perception.

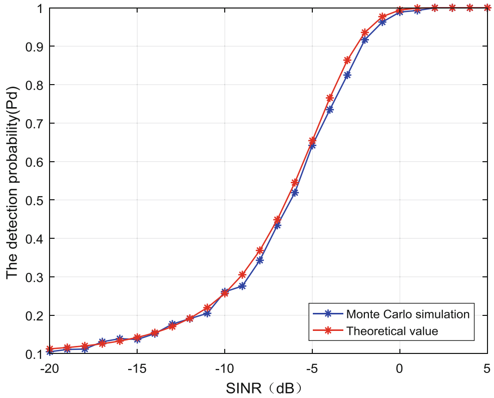


Fig. 2. Single user detection probability varies with SINR in energy perception

3 Spectrum Sensing Based on Multi-satellite Array

3.1 Model of Satellite Array

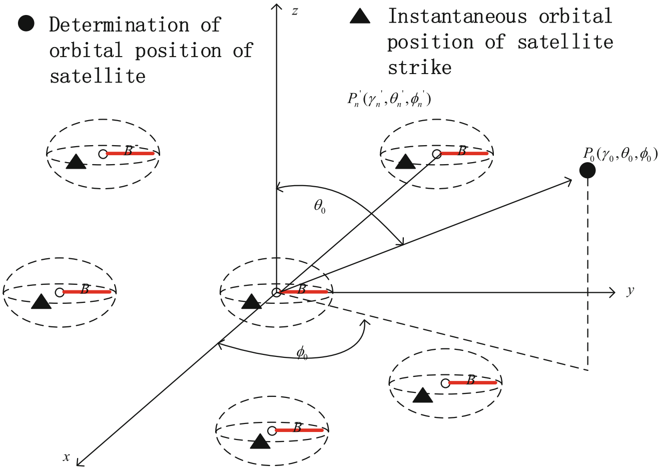


Fig. 3. Distributed satellite cluster array model

As shown in Fig. 3, it is the distributed satellite cluster array model, the orbital position information determined by the nth satellite is set as $P_n(\gamma_n, \theta_n, \phi_n)$, γ_n is the distance from the origin of coordinates of the nth satellite, and the elevation Angle and azimuth Angle of the satellite meet $\theta_n \in [0, \pi]$ and $\phi_n \in [0, 2\pi)$ respectively. Because of the perturbation force, the position of the satellite will wobble randomly. In consideration of satellite wobble, it is assumed that the instantaneous actual position of the nth satellite is randomly distributed in a sphere with determined position information $P_n(\gamma_n, \theta_n, \phi_n)$ as its center and radius B, and the actual coordinates of the satellite are denoted by $P_n'(\gamma_n', \theta_n', \phi_n')$. After the satellite array is assumed, the desired spatial azimuth direction of the main lobe of its orientation graph is set as $P_0(\gamma, \theta_0, \phi_0)$. Based on [13], the following assumptions are also made:

(1) The satellites in the distributed satellite cluster use the same type of antenna, and the array pattern function conforms to the pattern multiplication theorem.
(2) The distance between the distributed satellite cluster and the ground node is much larger than that between the satellites in the distributed cluster, so the electromagnetic signal path attenuation between the ground node and the satellite array elements is roughly the same.
(3) The LOS is the main link for each satellite element to reach the ground node, and only the additive white Gaussian noise channel is considered, not the multipath, fading or shadow caused by reflection or scattering.
(4) The array satellite is perfectly synchronized in carrier frequency, phase and time.

3.2 Cooperative Beamforming Pattern Function

The following is a brief description of the relevant formulas of distributed satellite array pattern function based on random antenna array theory.

$$\begin{aligned} A_n(\theta, \phi) &= \overbrace{\exp\left[jk\gamma_n'\left(cos\psi_n' - cos\psi_{n,0}'\right)\right]}^{\text{random term}} \cdot \overbrace{\exp(jk\gamma_n cos\psi_n)}^{\text{fixed term}} \\ &= \exp\left\{\mathrm{jk}\left(\gamma_n'\left(\cos\psi_n' - \cos\psi_{n,0}'\right) + \gamma_n\cos\psi_n\right)\right\} \qquad \mathrm{n} = 1, 2, \ldots \mathrm{N} \end{aligned} \tag{3}$$

Where, $k = {}^{2\pi}/_{\lambda}$ and λ is wavelength, $n = 1, 2, \ldots N$ (N is the number of satellites). Substitute through the following formula:

$$\cos\psi_n' = \sin\theta\sin\theta_n'\cos(\phi - \phi_n') + \cos\theta\cos\theta_n' \tag{4}$$

$$\cos\psi_n = \sin\theta\sin\theta_n\cos(\phi - \phi_n) + \cos\theta\cos\theta_n \tag{5}$$

$$\cos\psi_{n,0}' = \sin\theta_0\sin\theta_n'\cos(\theta_0 - \varphi_n') + \cos\theta_0\cos\theta_n' \tag{6}$$

$$\rho_0 = \sqrt{(\sin\theta\cos\phi - \sin\theta_0\cos\phi_0)^2 + (\sin\theta\sin\phi - \sin\theta_0\sin\phi_0)^2} \tag{7}$$

$$\cos\delta = \rho_0^{-1}(\sin\theta\cos\phi - \sin\theta_0\cos\phi_0) \tag{8}$$

$$\sin\delta = \rho_0^{-1}(\sin\theta\sin\phi - \sin\theta_0\sin\phi_0) \tag{9}$$

$$\cos\gamma = \rho_0^{-1}(\cos\theta - \cos\theta_0) \tag{10}$$

$$\delta = \tan^{-1}\left[\frac{\sin\theta\sin\phi - \sin\theta_0\sin\phi_0}{\sin\theta\cos\phi - \sin\theta_0\cos\phi_0}\right] \tag{11}$$

$$I_n = R_n \sin\theta_n^{'} \cos(\phi_n^{'} - \delta), \qquad -1 \le \mathrm{I}_n \le 1 \tag{12}$$

$$Q(\theta, \phi) = 2\pi\beta\rho_0 \tag{13}$$

$$T_n = R_n \cos\theta_n^{'}, \qquad -1 \le \mathrm{T}_n \le 1 \tag{14}$$

$$G(\theta) = 2\pi\beta\rho_0 \cos\gamma \tag{15}$$

$$L_n = \frac{\gamma_n}{\lambda} \tag{16}$$

Where $R_n = {}^{\gamma_n}\!/_{B}$, $\beta = {}^{B}\!/_{\lambda}$ represents the normalization of wavelength by perturbation radius of array satellite, and L_n represents the normalization of wavelength by the distance from the nth satellite to the origin of coordinates. After the above formula is substituted, the average manifold vector formula of the nth satellite is obtained as follows:

$$\begin{aligned}\overline{A_n}(\theta,\phi) =& 6tinc(\mathrm{Q}(\theta,\phi))jinc(\mathrm{G}(\theta))\times \\ & \exp\left[j2\pi \mathrm{L}_n(\sin\theta\sin\theta_n\cos(\phi-\phi_n)+\cos\theta\cos\theta_n)\right]\end{aligned} \tag{17}$$

Where $tinc(x) = {}^{J_1(x)}\!/_{x}$, $jinc(x) = {}^{j_1(x)}\!/_{x}$, $J_1(x)$ denotes the first spherical Bessel function of the first order, and $j_1(x)$ denotes the first Bessel function of the first order. Then the corresponding average beam pattern function of a distributed cluster can be expressed as:

$$F(\phi) = \frac{1}{N}\sum_{n=1}^{N} w_n \overline{A_n}(\phi) \tag{18}$$

Where w_n is the weighted value of the nth satellite array, $w_n \in C$(C denotes the complex field). The corresponding average power pattern formula is as follows:

$$S(\phi) = |F(\phi)|^2 \tag{19}$$

3.3 A Spectrum Sensing Method Based on Satellite Array

The above two sections introduce the satellite array model and the relevant knowledge of the beam pattern function. In order to apply this beamforming method to the proposed model, the expected direction of the main lobe of the average power pattern of the satellite cluster array should be aligned with the direction of the weak signal node in the model. In this direction, the manifold vectors of each satellite participating in the array are superimposed in the same phase. So the weighted value of each satellite should meet formula (20):

$$w_n = \exp(-\mathrm{j}2\pi \mathrm{L}_n \sin\theta_n \cos(\phi_0 - \phi_n)), \qquad n = 1, 2, \ldots\mathrm{N} \tag{20}$$

The formula (20) can be substituted into the above formula (10) for the average power pattern, and the final formula for the average power pattern can be obtained. In order to improve the SINR of the weak signal node, the null region direction of the array satellite pattern is aligned with the direction of the strong signal node on the ground and the genetic algorithm is combined to make the value as small as possible. So as to maximize the signal- interference-noise ratio (SINR) of satellite reception. For convenience, we set the desired direction of the array (direction of weak ground signal) as $(\theta_0, \phi_0) = (90°, 0°)$, then the formula of the average power beam pattern can be expressed as follows [14]:

$$S(\phi) = \frac{1}{N^2}\left|\sum_{n=1}^{N} 3tinc(\alpha(\phi) \cdot \exp(j2\pi L_n \sin\theta_n[\cos(\theta - \theta_n) - \cos\phi_n])\right|^2 \tag{21}$$

Where $\alpha(\phi) = 4\pi\beta\sin(\phi/2)$. Assuming that the satellites in the array are in the same perturbation condition (the perturbation of the satellites is taken into account), the perturbation radius of the satellites is set to be 15, it satisfies $\beta = 15$. In order to improve the performance of the satellite array, we can select suitable satellites to participate in the formation. The detailed selection process is as follows:

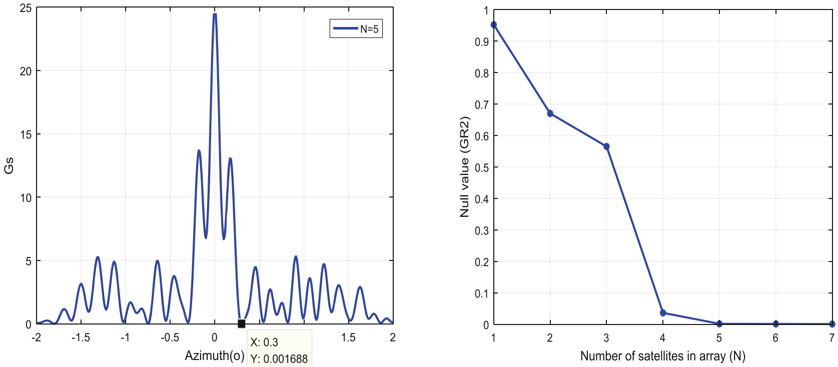
(1) According to the distribution structure of the formation satellites, the first step is to initialize the position information of the formation satellites.
(2) Given the location information of both strong signal node and weak signal node on the ground.
(3) Given the number of satellites participating in the collaboration. In the progress of determining the number of satellites, we can adjust the number of satellites by evaluating the probability of detection weak signal. Objective function is to maximize the received power in the direction of weak signal node and to minimize the received power in the direction of strong signal node, the satellite nodes with the best position information are selected from the satellite formation by genetic algorithm to co-operate to detect the weak signal node in the presence of strong signal interference.

In the above process, the purpose of minimizing the receiving power of strong signal node and maximizing the receiving power of weak signal node is to improve the signal-interference-noise ratio (SINR) of array satellites when they perceive weak signal with strong signal interference.

After optimizing, when the main lobe of the array is aligned to the direction of weak signal, the manifold vector of the array are superimposed in the same phase, and null region gain is generated in the direction of strong signal. In this process, when the number of array satellites is N, it will get N times of gain in the desired direction of the received signal, correspondingly, it will also have a gain of N^2 times in power value of the received signal. That is, the receiving power gain of the sensor signal and the jamming signal are $G_s = N^2$ and G_{R2} respectively. Then the signal-interference-noise ratio (SINR) of the corresponding array satellites cluster receiving weak signal with strong signal interference can be further expressed as:

$$SINR = \frac{G_{T1}P_{T1}N^2G_R(\frac{c}{4\pi df})^2}{G_{T2}P_{T2}G_RG_{R2}(\frac{c}{4\pi df})^2 + KBT} \tag{22}$$

Supposing the null region direction of the pattern formed by the array satellites (the direction of the strong signal on the ground) is $(\theta, \phi) = (90°, 0.3°)$.Under the above conditions, when $L = 2000$, $M = 500$ and $N = 5$,the patterns of the formation of the array satellites and the curves of the nulls in the pattern with the number of the array satellites are shown in Figs. 4(a) and (b) below respectively:



(a) (b)

Fig. 4. Experimental simulation results

In Fig. 4(a), it can be seen that when the number of array satellites in the satellite cluster is N = 5, the null region of the beam pattern is about $1.6e-3$. In addition, it can be seen from Fig. 4(b) that the null region of the beam pattern decreases with the increase in the number of array satellites, which means that with the increase in the number of array satellites, the satellite cluster is more capable of suppressing strong signal.

4 Performance Evaluation

Based on the above formula, the parameter setting table is given (Table 1):

The value of the unknown quantity G_{R2}, in the formula of signal-interference-noise ratio (SINR) is obtained by combining genetic algorithm with the given number of satellites participating in formation. The implementation is described in the previous section, so we will not repeat it again. In order to highlight the proposed method that can improve the SINR of the weak signal node when the satellite perceiving with the strong signal interference on the ground. The following data show the comparison diagram of the spectral sensing method proposed in this paper and the “Or criterion” used in multi-satellite coordination. About the “Or criterion”, this paper, due to limited space, will not be repeated, more details can be seen in Ref. [15].

Table 1. Relevant parameter settings of SINR calculation

Parameter	Value
Satellite orbit height	1000 km
Satellite antenna revenue	$G_R = 25$ dbi
Satellite quality factors	$G/_T = 5\ \text{dBk}^{-1}$
Transmission frequency	2 GHZ
Transmitting power of weak signal node	$P_{T1} = 10$ dBm
Transmitting power of strong signal node	$P_{T2} = 30$ dBm
Signal transmission bandwidth	30 MHZ
Transmission gain of weak signal node	$G_{T1} = 1$
Transmitting gain of strong signal node	$G_{T2} = 1$
K (Boltzmann constant)	$K = -228.6$(dB)
N	Number of satellites participating in satellite array

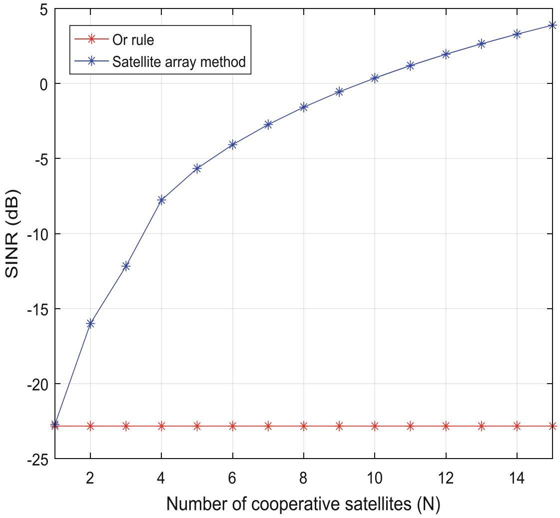


Fig. 5. SINR versus *N*

In Fig. 5, Compared with the "Or criterion" method in the multi-satellite cooperative spectrum sensing, you can see that under the same conditions, the method proposed in this paper has obvious advantages in the signal-interference-noise ratio (SINR) of weak signal node in the presence of strong signal interference on the ground. Besides that, with the increase of the number of cooperative satellites, the SINR of the satellite receiving weak signal with strong signal interference is gradually increasing. Finally, the detection probability under different number of cooperative satellites is researched, and the method proposed in this paper is compared with the traditional “Or criterion” method, as shown in Fig. 6. Although the “Or criterion” can’t improve the SINR, according to its fusion rules $P_D = 1 - \prod_{i=1}^{M} \left(1 - P_{d,i}\right)$, the detection probability of satellites will increase with the increase of cooperative satellite nodes. Figure 6 shows that there is a big gap between the proposed method and the “Or criterion”, which is mainly due to the introduction of beamforming in the multi-satellite cooperative spectrum sensing scenario, this method improves the receiving power gain of the weak signal and decreases the receiving power gain of the strong interference signal, and improves the whole spectrum sensing performance of the array satellites. The simulation result is as follows:

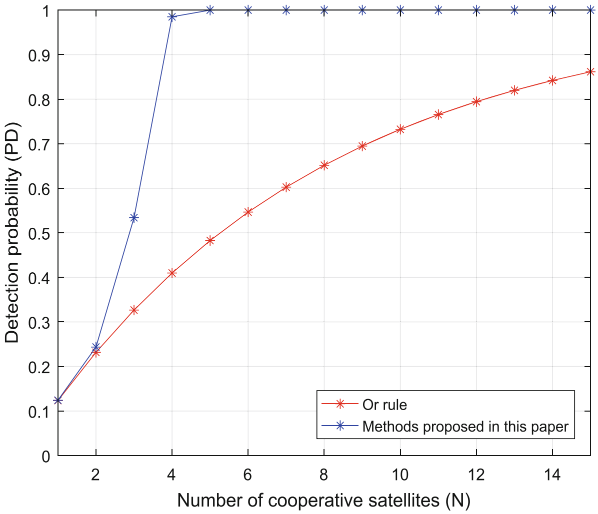


Fig. 6. Detection probability (P_D) versus N

5 Conclusions

In this paper, we propose a cooperative spectrum sensing method relying on satellite formation to improve the sensing ability of the weak signal. Specifically, firstly, we select some LEO satellites to form a formation, and adjust the specific number of selected satellites by evaluating the detection probability of weak signal. Furthermore, by using genetic algorithm to optimize the beamforming weight of each satellite, the receive gains of the weak signal and the interference can be obtained. Finally, the detection probability of the weak signal is evaluated by calculating the SINR after the satellite formation, and the number of selected satellites is determined accordingly. Simulation results show that the proposed method not only can suppress the interference imposed on the sensing satellites, but also can increase SINR of sensing satellites for the weak signal, resulting in improving the probability of detection.

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