IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received February 19, 2020, accepted March 6, 2020, date of publication March 12, 2020, date of current version March 20, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.2980418

Detection of Spectrum Misuse Behavior in Satellite-Terrestrial Spectrum Sensing Based on Multi-Hypothesis Tests

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This work was supported in part by the Natural Science Foundation for Distinguished Young Scholars of Jiangsu Province under Grant BK20190030, in part by the National Natural Science Foundation of China under Grant 61871398 and Grant 61931011, in part by the National Key Research and Development Program of China under Grant 2018YFB1801103, and in part by the Equipment Advanced Research Field Foundation under Grant 61403120304.

ABSTRACT As the increasing of both users' demand and the number of communication satellites, spectrum resource is becoming increasingly scarce. Cognitive radio (CR) can effectively alleviate the scarcity of spectrum resource. By using CR technology in the satellite and terrestrial integrated network, the satellite can share the spectrum resource with the terrestrial communication equipment to improve the spectrum utilization. However, due to the satellite communication's inherent openness and the increasing intelligent level of devices, it makes the satellite communication vulnerable to spectrum misuse, which seriously threatens the reliability and efficiency of the satellite communication system. This paper studies the detection of spectrum misuse in the satellite-terrestrial spectrum sharing system. First, we model the problem as a ternary hypothesis test problem by using generalized multi-hypothesis Neyman-Pearson (GMNP). Then, we utilize a two-step method to solve the complex formula problem in the multiple authorized users scenario. Reasonable decision thresholds are derived by means of the generalized likelihood ratio test (GLRT) and maximum a posterior (MAP) criterion, respectively. Finally, the performance of detection is evaluated and analyzed comprehensively to verify the feasibility of the study.

INDEX TERMS Cognitive radio, generalized multi-hypothesis Neyman-Pearson, generalized likelihood ratio test, maximum a posterior.

I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

With the rapid development of space communication technology and the continuous integration of ground Internet, mobile communication and satellite network services, the "integrated information network of earth and sky", which supports the seamless networking and information transmission of space, sky and earth, has gradually become an important trend of future space communication network construction. Satellite communication has the advantages of long transmission distance, wide coverage, wide communication frequency band and low operation and maintenance cost. It is an important support of spatial information network. With the development of aerospace technology, multiple satellites are used for communication, and satellite-terrestrial collaborative communication is also increasingly important [1]–[9]. However, the current satellite spectrum allocation is fixed. As the increasing of both users' demand and the number of communication satellites, spectrum resource is becoming increasingly scarce [10].

CR was first proposed by Dr. Mitola in 1999 [11]. It is a good solution to improve the utilization of spectrum resource, so it can be used in satellite communication system [12]–[17]. It refers to the manner of sharing spectrum resources with cognitive users through the perception of spatial environment spectrum without affecting the normal work of the primary user [18], [19]. In the satellite communication system, there

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Yang.

are similar problems with shortage of spectrum resources, so CR technology can be well used in the satellite communication system. In 2010, Dr. Kandeepan of Italy first proposed the concept of cognitive satellite terrestrial radio (CSTR) [20]. For CSTR systems, it is very important for secondary users to correctly perceive the spectrum of primary users, so secondary users need to have the ability to detect illegal behavior if an illegal user violates the rules of spectrum usage and emotional communication [21], [22]. However, it is difficult to analyze and detect illegal users because of the random appearance of illegal users.

B. RELATED WORK

As for satellite cognitive communication system, reference [23] utilizes hypothesis testing and maximum posteriori to detect NGEO satellite signals which impact GEO system. Reference [12] deduces the protection radius of the earth station by analyzing the interference to the satellite system. Reference [24] suggests that beamforming technology can reduce the interference caused by satellite signals to terrestrial communication systems. In reference [25], a dynamic spectrum access (DSA) decision framework, which can also perceive the spectrum well under interference, is proposed. References [9] proposes a space segment design based on a spectrum-sensing-based cooperative framework, in applying cognitive radio to future broadband satellite communications toward 5G. Reference [17] proposes the concept of weighted cooperative spectrum sensing, which can better cope with the interference to the primary user caused by a secondary user. In fact, the above references only study how to make normal spectral perception under interference, and the interference discussed is predictable. However, illegal frequency users are a priori unknown, the above method cannot be applied.

For the detection of spectrum misuse behavior, reference [26] constructs a joint spectrum sensing and access framework to prevent malicious behavior by rational and irrational malicious users. Reference [27] proposes a malicious user detection framework based on low rank matrix completion. However, their detection method is based on the current frequency state known. In reference [21], a generalized multi-hypothesis Neyman-Pearson (GMNP) is proposed, which can detect illegal behaviors while judging the frequency state of use. However, the above methods are all based on the terrestrial spectrum sharing system. The satellite-terrestrial spectrum sharing system is quite different from the terrestrial spectrum sharing system, the detection method should be designed according to its characteristics.

The main differences between the satellite-terrestrial spectrum sharing system and the terrestrial spectrum sharing system are as follows:

- Satellite-terrestrial channel is very different from terrestrial channel, which is mainly reflected in channel gain. Satellite signal is beam signal, and different antenna gain should be considered in different cognitive scenarios. In this paper, the analysis of the system model is added, and the characteristics of the satellite-terrestrial spectrum sharing system are reflected in more detail.
- For traditional terrestrial spectrum sharing system, the location of the primary user is generally fixed and the beam coverage is small (such as cellular communication systems), so the coverage of the primary users usually do not overlap. However, in the satellite-terrestrial spectrum sharing system, the position of NGEO satellite is generally not fixed. A satellite's beam coverage is greater than that of a base station on the ground. The satellite beam coverage area may also vary as the satellite moves, and beams of multiple primary users may overlap. Therefore it is necessary to consider the spectrum misuse behavior detection scenario under the coverage of multiple primary users.

C. CONTRIBUTIONS

This paper proposes a detection framework for illegal behavior in the satellite-terrestrial spectrum sharing system. The main contributions are as follows:

- We propose the detection of spectrum misuse behavior in satellite-terrestrial spectrum sharing system and model the problem as a multiple hypothesis test problem. Then the hypothesis is reasonably simplified to a ternary hypothesis test problem. Finally, the GLRT is used to solve the problem.
- We analyze the influence of the number of primary users on the detection performance of illegal behaviors by deducing the judgment threshold of illegal behaviors. In addition, the detection of illegal behavior of single and multiple satellites is analyzed and deduced, respectively. Furthermore, the detection method and decision threshold in two scenarios are given.
- We provide detailed simulation under different parameter settings, which validates the feasibility of the detection algorithm and has a high detection probability for illegal behaviors.

D. ORGANIZATION

The rest of this paper is organized as follows. Section II analyzes the system model of the typical spectrum sharing scenario and classifies it into two cases. Then it establishes multiple hypothesis test model when the number of authorized users is one. Section III gives the GMNP criterion and deduces the detection threshold of the illegal behavior when the number of authorized users is one. Section IV establishes multiple hypothesis test model when the number of authorized users exceeds one and deduces the detection threshold of illegal behavior in this scenario. Section V carries on the simulation, Section VI gives the conclusion.

II. SYSTEM MODEL

There are three typical satellite-terrestrial spectrum sharing systems:

- Satellite authorization and terrestrial cognition. The satellite network is the authorization network while the terrestrial network is the cognitive network.
- Terrestrial authorization and satellite cognition. The terrestrial network is the authorization network while the satellite network is the cognitive network.
- Satellite authorization and satellite cognition. The satellite network is both the authorization network and the cognitive network.

Before proceeding further, we make some assumptions as follows:

- The power level sets from the satellite's system are known to cognitive users, since the power level sets are predetermined and could be acquired from ITU (International Telecommunication Union) database.
- The gain patterns of the earth stations and the satellites conform to relevant ITU-R recommendations [28]. The positions of the satellites can be obtained through the electronic fence system [29], which adopts phased array radar to search and track space targets. Its phased array antenna controls the direction of the beam electronically and it can simultaneously search and measure multiple beams of different directions.
- Generally speaking, it is difficult for illegal users to obtain accurate information about the working status of the primary user, and they can only obtain limited information by means of transient time slot perception. So considering an extreme case where an illegal user has no information about the true status of the primary user, illegal users can only attack at random completely, that is to say, the prior probability of the illegal user and the primary user are independent of each other.

A. SATELLITE AUTHORIZATION AND TERRESTRIAL COGNITION

The satellite authorization and terrestrial cognition refers to the scenario that the satellite network is the authorization network while the terrestrial network is the cognitive network. There are two scenarios, satellite uplink sharing and satellite downlink sharing. For the scenario of satellite uplink sharing, the wide area of satellite coverage and the communication elevation angle of the earth station increase the difficulty of spectrum sensing of cognitive users, and it is difficult for terrestrial cognitive users to effectively use the satellite spectrum resources. Therefore, the existing satellite authorization and terrestrial cognition network is mainly applied in the terrestrial cognitive user how to use CR technology to share the channel resources of satellite downlink. Fig. 1 shows a typical scenario of satellite authorization and terrestrial cognition wireless network based on satellite downlink sharing. In this scenario, the ground cognitive user finds and utilizes the idle satellite spectrum resources through spectrum sensing.

In traditional CR systems, detecting whether the authorized primary user works on a given frequency band is a binary hypothesis test problem [23]. In this scenario, for this binary hypothesis test problem, the authorized user is

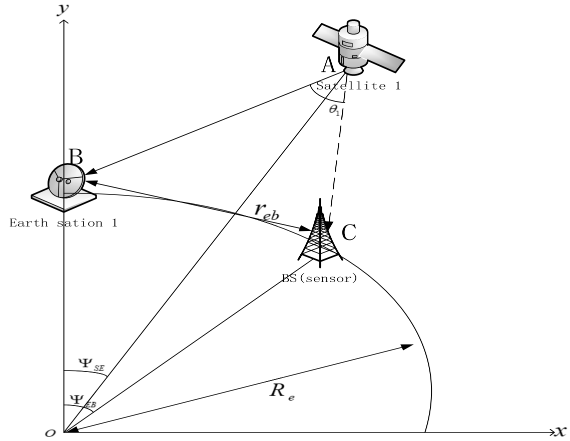

FIGURE 1. Satellite authorization and terrestrial cognition.

a communication satellite, and the cognitive base station needs to perceive whether the signal of the primary user exists or not. Therefore, there are two assumptions here. One is that $\mathcal{H}_0^S$ is not used by the authorized user, i.e. the channel is idle; the other is that $\mathcal{H}_1^S$ is used by the authorized user, i.e. the channel is busy.

$$y_s(t) = \begin{cases} n(t) & \mathcal{H}_0^S, \\ \sqrt{P_s}\sqrt{h_s}e^{i\phi}s_1(t) + n(t) & \mathcal{H}_1^S, \end{cases} \tag{1}$$

where $y_s(t)$ is the received signal of the sensor at sampling time t; $s(t)$ is the primary user's satellite transmission symbol, which follows a circularly symmetric complex gaussian (CSCG) distribution with zero mean and unit variance; P_s is the transmitted power of a satellite, and in a single time slot is constant; h_s for the channel gain, concrete expression as follows, ϕ for channel phase; $n(t)$ for additive white gaussian noise, the variance for σ_n^2.

$$h_s = G_{ner,\max}G_{gst}(\theta_1)\left(\frac{c}{4\pi f d_{S\to B}}\right)^2 10^{-\frac{A_g}{10}}10^{-\frac{A_c}{10}}, \tag{2}$$

where $G_{ner,\max}$ represents the maximum gain of the receiving antenna of the sensor, $G_{gst}(\theta_1)$ represents the gain of the satellite transmitted antenna with the direction angle of θ_1, c represents the speed of light, f represents the central frequency of the spectrum band, and $d_{S\to B}$ represents the distance between the satellite and the sensor. Propagation factors A_g and A_c represent gaseous absorption and cloud or fog attenuation, respectively, [30]. Gaseous absorption A_g (dB) due to the two constituent gases(oxygen and water vapor) is given by [31].

$$A_g = A_\omega + A_o = 0.182 f N''(f), \tag{3}$$

where A_ω and A_ω are the specific attenuations due to dry air and water vapour, respectively, and $N''(f)$ is the imaginary part of the frequency-dependent complex refractivity that the specific expression refers to [31]. On the other hand, the specific attenuation within a cloud or fog A_c (dB) can be written as [32]

$$A_c = K_l M, \tag{4}$$

where $K_l = 0.89 f / \left[\epsilon''(1+\eta)\right]$ is the specific attenuation coefficient with $\eta = \left(2+\epsilon'\right)/\epsilon''$, ϵ'' and ϵ' are the real part and imaginary part of the dielectric permittivity ϵ of water, M represents liquid water density in the cloud or fog.

Vectors $\overrightarrow{AB}$ and $\overrightarrow{AC}$ can be expressed by the following equation:

$$\overrightarrow{AB} = [-(h_{sat}+R_e)\sin\Psi_{SE}, R_e-(h_{sat}+R_e)\cos\Psi_{SE}], \quad (5)$$

$$\overrightarrow{AC} = [R_e\sin\Psi_{EB}-(R_e+h_{sat})\sin\Psi_{SE}, R_e\cos\Psi_{EB} - (R_e+h_{sat})\cos\Psi_{SE}], \quad (6)$$

where h_{sat} represents the altitude of the satellite from the ground, R_e is the radius of the earth, Ψ_{SE} represents the angle between the satellite to the center of the earth and the satellite earth station to the center of the earth, Ψ_{EB} represents the angle between the satellite to the center of the earth and the terrestrial cognitive base station to the center of the earth.

Therefore, θ_1 and $d_{S\to B}$ can be expressed as:

$$\theta_1 = \arccos\left(\frac{\overrightarrow{AB}\cdot\overrightarrow{AC}}{\left|\overrightarrow{AB}\right|\left|\overrightarrow{AC}\right|}\right) \quad (7)$$

$$d_{S\to B} = \overrightarrow{AC} = [R_e\sin\Psi_{EB}-(R_e+h_{sat})\sin\Psi_{SE}, R_e\cos\Psi_{EB}-(R_e+h_{sat})\cos\Psi_{SE}] \quad (8)$$

In addition, ϕ is channel phase, which is independent of the sensing mode that mainly involving signal energy proposed in this paper, n(t) is additive white gaussian noise (AWGN) with mean value of zero and variance of σ_n^2. Therefore, h_s follows a cyclic symmetric complex gaussian (CSCG) distribution, and can be expressed as: $h_s \sim CN(0, h_sP_s+\sigma_n^2)$. In the perceptive slot with time length T, the sensor earth station obtains N sampling values, expressed as $y = (y_0, y_1, \cdots, y_N)$.

For unauthorized users, channels may be used at a time slot. This state can also be described by the following binary hypothesis test:

$$y_I(t) = \begin{cases} n_t & H_0^I \\ \sqrt{P_x}\sqrt{h_x}x(t)+n_t & H_1^I \end{cases} \quad (9)$$

where $\mathcal{H}_0^I$ refers to the assumption that there is no illegal user in the current time slot, $\mathcal{H}_1^I$ refers to the assumption that the illegal user runs with transmitted power of P_x, h_x represents the channel gain, since the prior information of the illegal user is unknown, the transmitted power P_x and channel gain h_x are also unknown. $s(t)$ refers to the signal emitted by the illegal user at time t. Therefore, $y_I(t)$ also follows a CSCG distribution and can be expressed as:

$$y_I(t) \sim CN(0, \sigma_x^2). \quad (10)$$

In practical use, the coverage of multiple satellites using the same frequency band may overlap due to the wide range of satellite coverage and the increase in the number of satellites. The cognition terrestrial user may receive signals from multiple authorized satellites at the same time, as shown in Fig. 2. For this scenario, the detection method of illegal

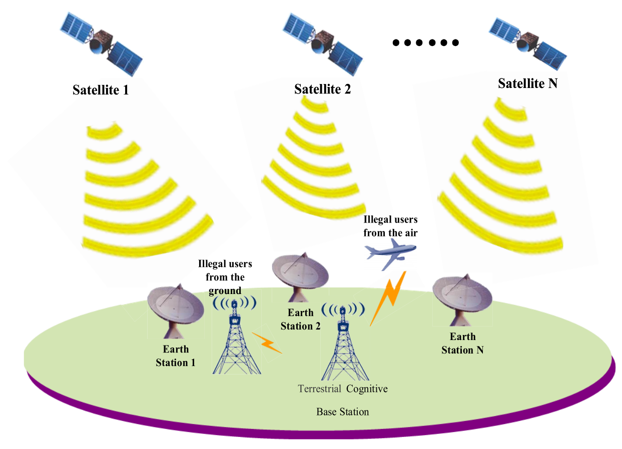

FIGURE 2. Multiple authorized satellite scenarios.

users is different from the previous scenario, which increases the difficulty of detection. The following sections will analyze the problem of illegal user detection in this scenario in detail.

B. TERRESTRIAL AUTHORIZATION AND SATELLITE COGNITION

Terrestrial authorization and satellite cognition network refers to the scenario that the terrestrial network is the authorization network while the satellite network is the cognitive network. Since it will cause serious interference to the terrestrial primary user when the satellite downlink as the cognitive user link, this scenario mainly focuses on the satellite uplink. The typical application of terrestrial authorization and satellite cognition network is shown in Fig. 3.

The cognitive earth station finds and utilizes the free terrestrial spectrum resources through spectrum sensing. The signal $y_B(t)$ received by the cognitive earth station can be modeled as:

$$y_B(t) = \begin{cases} n(t) & H_0^B \\ \sqrt{P_B}\sqrt{h_B}s_2(t)+n(t) & H_1^B, \end{cases} \quad (11)$$

where H_0^B indicates that the authorized user is not working, H_1^B represents the authorized user working. P_B represents the transmitted power of the base station, h_B represents channel gain, $n(t)$ represents noise. $s_2(t)$ is the signal transmitted by the ground station and obeys the gaussian distribution of zero mean value and unit variance. P_B and h_B are known a priori, so $y_B(t)$ also obeys the gaussian process, $y_B(t) \sim N(0, h_BP_B+\sigma_n^2)$.

Again, unauthorized illegal user modeling is the same as before. It follows the same gaussian. Since the beams of the ground communication network do not generally overlap, it makes no sense for this scenario to discuss multiple authorized users. In this scenario, it is a spectrum misuse detection problem with single authorized user.

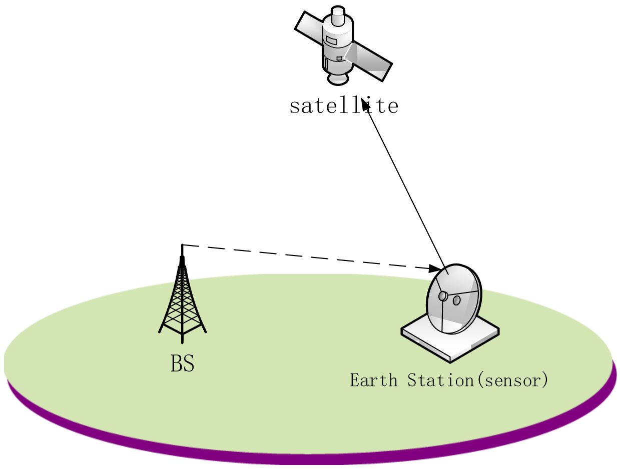

FIGURE 3. Terrestrial authorization and satellite cognition.

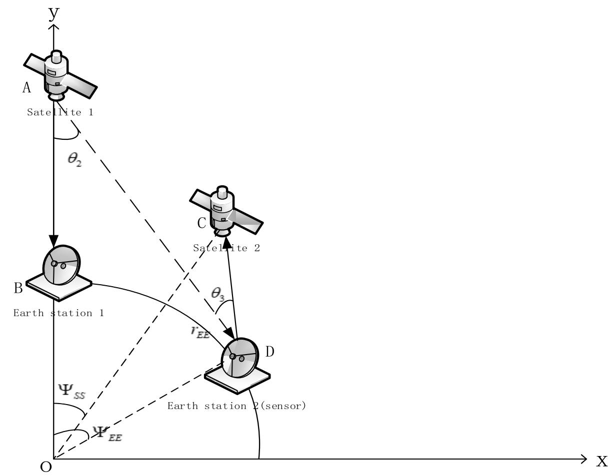

FIGURE 4. Satellite authorization and satellite cognition.

C. SATELLITE AUTHORIZATION AND SATELLITE COGNITION

According to the difference of satellite orbital altitude, the cognitive wireless network constructed by the dual-satellite system is generally composed of the high-orbit satellite network as the authorized user and the low-orbit satellite network as the cognitive user. A typical satellite authorization and satellite cognition network is shown in Fig. 4. In this scenario, the signal $y_{ss}(t)$ received by the earth station of cognitive satellite can be modeled as:

$$y_{ss}(t) = \begin{cases} n(t) & H_0^S \\ \sqrt{P_{ss}}\sqrt{h_{ss}}e^{i\phi}s_3(t) + n(t) & H_1^S, \end{cases} \quad (12)$$

$$h_{ss} = G_{ner}(\theta_3)G_{gst}(\theta_2)\left(\frac{c}{4\pi f d_{S\to E}}\right)^2 10^{-\frac{A_g}{10}}10^{-\frac{A_c}{10}}, \quad (13)$$

where P_{ss} represents the transmitted power of the authorized satellite, h_{ss} represents channel gain, $s_3(t)$ is a symbol for satellite transmission, following a CSCG distribution. $G_{ner}(\theta_3)$ represents the receiver antenna gain of the cognitive earth station, $G_{gst}(\theta_2)$ represents the transmitted antenna gain of the cognitive earth station, $d_{S\to E}$ represents the distance between the authorized satellite and the cognitive earth station.

Vectors $\overrightarrow{AB}$, $\overrightarrow{AD}$ and $\overrightarrow{CD}$ can be expressed as follows:

$$\overrightarrow{AB} = [0, -h_{sat1}], \quad (14)$$

$$\overrightarrow{AD} = [R_e \sin\Psi_{EE}, R_e\cos\Psi_{EE} - R_e - h_{sat1}], \quad (15)$$

$$\overrightarrow{CD} = [R_e\sin\Psi_{EE} - (h_{sat2}+R_e)\sin\Psi_{SS}, R_e\cos\Psi_{EE} - (h_{sat2}+R_e)\cos\Psi_{SS}, \quad (16)$$

where h_{sat1} is the altitude of satellite 1, h_{sat2} is the altitude of satellite 2, Ψ_{EE} represents the angle between the earth station of satellite 1 and the earth station of satellite 2 to the center of the earth, Ψ_{SS} represents the angle between satellite 1 to the center of the earth and satellite 2 to the center of the earth.

Therefore, θ_2, θ_3 and $d_{S\to E}$ can be expressed as:

$$\theta_2 = \arccos\left(\frac{\overrightarrow{AB}\cdot\overrightarrow{AD}}{\left|\overrightarrow{AB}\right|\left|\overrightarrow{AD}\right|}\right), \quad (17)$$

$$\theta_3 = \arccos\left(\frac{\overrightarrow{AD}\cdot\overrightarrow{CD}}{\left|\overrightarrow{AD}\right|\left|\overrightarrow{CD}\right|}\right), \quad (18)$$

$$d_{S\to E} = \overrightarrow{AD} = [R_e\sin\Psi_{EE}, R_e\cos\Psi_{EE} - R_e - h_{sat1}]. \quad (19)$$

Similarly, $y_{ss}(t)$ also follows a CSCG distribution and can be expressed as: $y_{ss}(t) \sim CN(0, h_{ss}P_{ss} + \sigma_n^2)$. Again, unauthorized illegal user modeling is the same as before. It follows the same gaussian distribution.

In the same way, the cognition earth station may receive signals from multiple authorized satellites at the same time, as shown in Fig. 5. For this scenario, the detection method of illegal users is different from the previous scenario, which increases the difficulty of detection. The following sections will analyze the problem of illegal user detection in this scenario in detail.

Through the analysis of the previous three scenarios, we can divide the detection of spectrum misuse behavior in the satellite-terrestrial spectrum sharing system into two situations:

- When the number of authorized users is one, the detection of spectrum misuse behavior.
- When the number of authorized users exceeds one, the detection of spectrum misuse behavior.

Next, in the case of satellite authorized ground cognition, the detection methods of illegal frequency behavior in the above two cases will be analyzed. The detection methods in the other two scenarios are basically the same, so the analysis is not repeated.

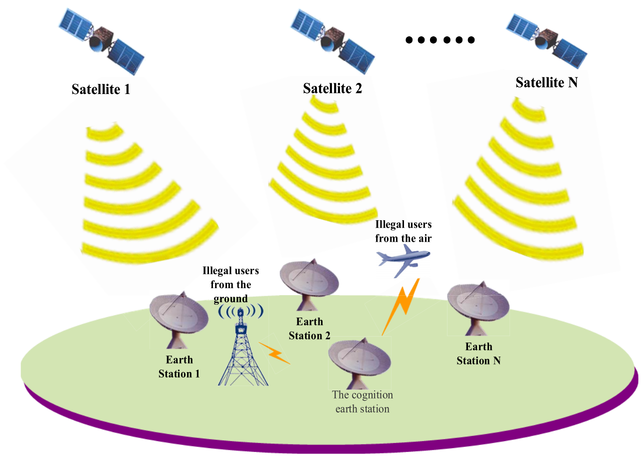

FIGURE 5. Multiple authorized satellite scenarios.

D. MULTIPLE HYPOTHESIS TEST MODEL WHEN THE NUMBER OF AUTHORIZED USERS IS ONE

In the scenarios of satellite authorizing terrestrial to recognize only a single satellite is considered as the primary user, the perception of the system by the sensor can be modeled as the following quaternion hypothesis test problem:

$$\begin{cases} \mathcal{S}_0 : y(t) = n(t), \\ \mathcal{S}_1 : y(t) = \sqrt{P_s}s(t) + n(t), \\ \mathcal{S}_2 : y(t) = \sqrt{P_x}x(t) + n(t), \\ \mathcal{S}_3 : y(t) = \sqrt{P_s}s(t) + \sqrt{P_x}x(t) + n(t), \end{cases} \tag{20}$$

where $\mathcal{S}_0$ means the channel is idle, $\mathcal{S}_1$ means the channel is used by the primary user satellite, $\mathcal{S}_2$ means the channel is occupied by illegal users, and $\mathcal{S}_3$ means that both the primary user and illegal users exist. $y(t)$ represents the observation of the earth station for sensing at time t.

From the signal received by the earth station for sensing, it can be seen that both primary users and illegal users are subject to CSCG distribution and are independent of each other. By analyzing the characteristics of each hypothesis, it can be found that the difference of each hypothesis lies in the variance of observed values.

Because $y(t) \sim CN(0, \sigma^2)$, if $\mathcal{S}_0$ is true, $\sigma^2 = \sigma_n^2$; when $\mathcal{S}_1$ is assumed to be true, $\sigma^2 = P_s + \sigma_n^2$; when $\mathcal{S}_2$ is assumed to be true, $\sigma^2 = P_x + \sigma_n^2$; when $\mathcal{S}_3$ is assumed to be true, $\sigma^2 = P_s + P_x + \sigma_n^2$. Because the illegal user's received power p_x is unknown, the above model can be reformulated as:

$$\begin{cases} \mathcal{S}_0 : \sigma^2 = \sigma_0^2, \\ \mathcal{S}_1 : \sigma^2 = \sigma_1^2, \\ \mathcal{S}_2 : \sigma^2 > \sigma_0^2, \quad \sigma^2 \neq \sigma_1^2, \\ \mathcal{S}_3 : \sigma^2 > \sigma_1^2, \end{cases} \tag{21}$$

where $\sigma_0^2 = \sigma_n^2$, $\sigma_1^2 = P_s + \sigma_n^2$. In $\mathcal{S}_3$, $\sigma^2 > \sigma_1^2$ when both primary and illegal users are received. When $\mathcal{S}_2$ is true, because the parameter space is continuous and the probability of $\sigma^2 = \sigma_1^2$ is 0, it can be distinguished from the assumption $\mathcal{S}_1$.

Back to the purpose of this paper, that is to detect whether the channel is occupied, and if it is occupied, determine whether there are illegal users. Among them, the first part is to find out the spectrum opportunity, while the second part is to protect the scarce spectrum resources from being occupied illegally. In order to implement part one, $\mathcal{S}_0$ needs to be distinguished from other states, and in order to implement part two, $\mathcal{S}_0$ and $\mathcal{S}_1$ need to be distinguished from other states. Therefore, detection targets can be achieved even if $\mathcal{S}_2$ and $\mathcal{S}_3$ are not distinguished. Therefore, the original quaternion hypothesis test problem can be transformed into a ternary hypothesis test problem, that is, $\mathcal{S}_2$ and $\mathcal{S}_3$ can be merged into one term. Then the original problem can be modeled as the following ternary hypothesis test [21]:

$$\begin{cases} \mathcal{H}_0 : \sigma^2 = \sigma_0^2, \\ \mathcal{H}_1 : \sigma^2 = \sigma_1^2, \\ \mathcal{H}_2 : \sigma^2 \in \left(\sigma_0^2, \sigma_1^2\right) \cup \left(\sigma_1^2, +\infty\right), \end{cases} \tag{22}$$

where $\mathcal{H}_0$ and $\mathcal{H}_1$ represent channel idle and channel occupied by the main user satellite respectively, while the mixed assumption $\mathcal{H}_2$ indicates the existence of illegal users. To facilitate subsequent statements, σ^2 is used to represent the unknown variance of the observed data in $\mathcal{H}_2$.

III. DETECTION OF ILLEGAL BEHAVIOR

A. GENERALIZED MULTI-HYPOTHESIS NEYMAN-PEARSON CRITERION

In the ternary hypothesis model, not only the prior probability is unknown, but also it is difficult to obtain the prior distribution of the unknown variance of the observed data. At the same time, there are conflicts among various state detection probabilities. To solve these problems, we can use the following generalized multi-hypothesis Neyman-Pearson (GMNP) criterion [21]:

Under the constraint of the detection probability of $\mathcal{H}_0$ and $\mathcal{H}_1$ ($\Pr(\mathcal{H}_0|\mathcal{H}_0)$ and $\Pr(\mathcal{H}_1|\mathcal{H}_1)$), the detection probability of illegal behavior is maximized, i.e.

$$\begin{aligned} &\max_{\mathcal{R}_0,\mathcal{R}_1,\mathcal{R}_2} \Pr(\mathcal{H}_2|\mathcal{H}_2), \\ &s.t. \Pr(\mathcal{H}_0|\mathcal{H}_0) \geq \alpha, \quad \Pr(\mathcal{H}_1|\mathcal{H}_1) \geq \beta, \end{aligned} \tag{23}$$

where $\Pr(\mathcal{H}_i|\mathcal{H}_j)$ represents the probability that judgment $\mathcal{H}_i$ is true when the true state is $\mathcal{H}_j$, $i, j \in \{0, 1\}$, both α and β are the performance constraint parameters, $0.5 < \alpha < 1$, $0.5 < \beta < 1$. In addition, $\mathcal{R}_i$ represents the decision domain of $\mathcal{H}_i$, including:

$$\Pr(\mathcal{H}_i|\mathcal{H}_j) \triangleq \int_{\mathcal{R}_i} p(y; \mathcal{H}_j)dy, \tag{24}$$

where $p(y; H_j)$ is the probability density function of observation sequence y when j is true. Next, Lemma 1 is obtained by equivalent simplification of optimization criterion (23).

Lemma 1: The optimization criterion in (23) can be equivalent to: [21]

$$\begin{aligned} &\max_{\mathcal{R}_0,\mathcal{R}_1,\mathcal{R}_2} \Pr(\mathcal{H}_2|\mathcal{H}_2), \\ &s.t. \Pr(\mathcal{H}_0|\mathcal{H}_0) = \alpha, \quad \Pr(\mathcal{H}_1|\mathcal{H}_1) = \beta. \end{aligned} \tag{25}$$

Remark 2: In the Neyman-Pearson criterion of traditional binary hypothesis test, the detection probability of the alternative hypothesis is maximized under false alarm constraint of the original hypothesis [33]. Therefore, the GMNP criterion proposed in Eq.23 and Eq.25 can be regarded as an extension of the Neyman-Pearson criterion in the generalized multivariate hypothesis test. The main difference between the two is that the multivariate hypothesis contains the mixed hypothesis. Multiple hypothesis increases the complexity of decision domain division, while mixed hypothesis increases its difficulty. The following part focuses on how to design corresponding detection methods.

B. DETECTION METHOD WHEN THE NUMBER OF AUTHORIZED USERS IS ONE

First, in order to maximize the detection probability of illegal behaviors under given constraints, the Lagrange factor method is used to construct the objective function [21]:

$$\mathcal{F} = \Pr(\mathcal{H}_2|\mathcal{H}_2) + \lambda_0 (\Pr(\mathcal{H}_0|\mathcal{H}_0) - \alpha) + \lambda_1 (\Pr(\mathcal{H}_1|\mathcal{H}_1) - \beta). \quad (26)$$

Then:

$$\begin{aligned}\mathcal{F} &= 1 - \int_{\mathcal{R}_0} p(y;\mathcal{H}_2)\,dy - \int_{\mathcal{R}_1} p(y;\mathcal{H}_2)\,dy \\ &\quad + \lambda_0\left(\int_{\mathcal{R}_0} p(y;\mathcal{H}_0)\,dy - \alpha\right) + \lambda_1\left(\int_{\mathcal{R}_1} p(y;\mathcal{H}_1)\,dy - \beta\right) \\ &= \int_{\mathcal{R}_0} [\lambda_0 p(y;\mathcal{H}_0) - p(y;\mathcal{H}_2)]dy \\ &\quad + \int_{\mathcal{R}_1} [\lambda_1 p(y;\mathcal{H}_1) - p(y;\mathcal{H}_2)]dy + 1 - \lambda_0\alpha - \lambda_1\beta.\end{aligned} \quad (27)$$

According to the above equation, if $\mathcal{F}$ is to be maximized, $\lambda_0 p(y;\mathcal{H}_0) - p(y;\mathcal{H}_2) > 0$ when the decision domain is $\mathcal{R}_0$; when the decision domain is $\mathcal{R}_1$, $\lambda_1 p(y;\mathcal{H}_1) - p(y;\mathcal{H}_2) > 0$, where λ_0 and λ_1 are determined by the constraint in the equation. Therefore, in order to maximize $\Pr(\mathcal{H}_2|\mathcal{H}_2)$, judge $\mathcal{H}_2$ as true if and only if:

$$\begin{cases} \dfrac{p(y;\mathcal{H}_2)}{p(y;\mathcal{H}_0)} > \lambda_0, \\ \dfrac{p(y;\mathcal{H}_2)}{p(y;\mathcal{H}_1)} > \lambda_1. \end{cases} \quad (28)$$

In order to realize the GMNP criterion, two likelihood ratios $\frac{p(y;\mathcal{H}_2)}{p(y;\mathcal{H}_0)}$ and $\frac{p(y;\mathcal{H}_2)}{p(y;\mathcal{H}_1)}$ need to be considered in the detection process. By comparing the two equations, it can be seen that in the constraint, $\Pr(\mathcal{H}_0|\mathcal{H}_0)$ is related to the former likelihood ratio, while $\Pr(\mathcal{H}_1|\mathcal{H}_1)$ is related to the latter likelihood ratio. Therefore, the optimization problem can be decomposed into two sub-problems: [21]

$$\begin{aligned}&\max_{\mathcal{R}_0,\mathcal{R}_2} \Pr(\mathcal{H}_2|\mathcal{H}_2), \\ &s.t.\Pr(\mathcal{H}_0|\mathcal{H}_0) = \alpha,\end{aligned} \quad (29)$$

and

$$\begin{aligned}&\max_{\mathcal{R}_1,\mathcal{R}_2} \Pr(\mathcal{H}_2|\mathcal{H}_2), \\ &s.t.\Pr(\mathcal{H}_1|\mathcal{H}_1) = \beta.\end{aligned} \quad (30)$$

The final solution is the intersection of two subproblems. Therefore, the original problem can be simplified by decomposition. Moreover, the two problems have significant physical significance, which can be called detection subproblems and identification subproblems.

1) DETECT SUBPROBLEMS (IDLE OR BUSY)

The subproblems in the equation can be regarded as derived from the following binary hypothesis:

$$\begin{cases} \mathcal{H}_0 : \sigma^2 = \sigma_0^2, \\ \mathcal{H}_2 : \sigma^2 > \sigma_0^2, \sigma^2 \neq \sigma_1^2. \end{cases} \quad (31)$$

Let σ_x^2 represent the variance of observation data under $\mathcal{H}_2$. The above problem is unilateral detection because $\sigma_x^2 > \sigma_0^2$. Therefore, under the limit of $\Pr(\mathcal{H}_0|\mathcal{H}_0) = \alpha$, in order to maximize $\Pr(\mathcal{H}_2|\mathcal{H}_2)$, likelihood ratio detection is used:

$$\begin{aligned}L_0(y) &= \frac{p(y;\hat{\sigma}_x^2,\mathcal{H}_2)}{p(y;\mathcal{H}_0)} \\ &= \frac{\frac{1}{(2\pi\hat{\sigma}_x^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\hat{\sigma}_x^2})}{\frac{1}{(2\pi\sigma_0^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\sigma_0^2})} \\ &= (\frac{\sigma_0^2}{\sigma_x^2})^{\frac{N}{2}}\exp(\frac{\sigma_x^2-\sigma_0^2}{2\sigma_0^2\sigma_x^2}\sum_{n=0}^{N-1} y_n^2) \underset{H_0}{\overset{H_2}{\gtrless}} \lambda_0.\end{aligned} \quad (32)$$

Since the observed data y plays a role in the form of $\sum_{n=0}^{N-1} y_n^2$, the test statistic is $Y = \sum_{n=0}^{N-1} y_n^2$, and since $\sigma_x^2 > \sigma_0^2$, $L_0(y)$ increases with the increase of Y. So $L_0(y) < \lambda_0$ is the same thing as $Y < \eta_0$ and η_0 is the threshold for λ_0. At the same time, since H_0 is true, $Y = \sum_{n=0}^{N-1} y_n^2 \sim \chi_N^2(\sigma_0^2)$, so,

$$\Pr(\mathcal{H}_0|\mathcal{H}_0) = \Pr(Y < \eta_0|\mathcal{H}_0) = 1 - \frac{\Gamma(\frac{N}{2},\frac{\eta_0}{\sigma_0^2})}{\Gamma(\frac{N}{2})} = \alpha, \quad (33)$$

where $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are Gamma functions and upper bound incomplete Gamma functions respectively. Therefore, the judgment threshold is

$$\eta_0 = \Gamma^{-1}(\frac{N}{2},(1-\alpha)\Gamma(\frac{N}{2}))\sigma_0^2, \quad (34)$$

where, $\Gamma^{-1}(\cdot,\cdot)$ is the inverse function of the incomplete Gamma function. Therefore, the detection subproblem is determined as

$$Y \underset{\mathcal{H}_0}{\overset{\mathcal{H}_2}{\gtrless}} \eta_0. \quad (35)$$

2) RECOGNITION SUBPROBLEM (LEGAL OR ILLEGAL)

The second subproblem in the equation is believed to come from the following binary hypothesis test problem:

$$\begin{cases} \mathcal{H}_1 : \sigma^2 = \sigma_1^2, \\ \mathcal{H}_2 : \sigma^2 > \sigma_0^2, \quad \sigma^2 \neq \sigma_1^2. \end{cases} \tag{36}$$

Different from detecting subproblems, identification subproblem bilateral detection means that unknown parameters σ_x^2 may be higher or lower than σ_1^2. Then, the GLRT is used to solve the bilateral problem.

First, the maximum likelihood estimation of unknown variance $\hat{\sigma}_x^2$ is calculated:

$$\hat{\sigma}_x^2 = \arg\max_{\sigma_x^2} p(y; \sigma_x^2). \tag{37}$$

Let $\frac{\partial p(y;\hat{\sigma}_x^2)}{\partial \hat{\sigma}_x^2} = 0$, we get

$$\hat{\sigma}_x^2 = \frac{1}{N} \sum_{n=0}^{N-1} y_n^2. \tag{38}$$

The generalized likelihood ratio can be obtained

$$\begin{aligned} L_1(y) &= \frac{p(y; \hat{\sigma}_x^2, \mathcal{H}_2)}{p(y; \mathcal{H}_1)} \\ &= \left(\frac{N\sigma_1^2}{\sum_{n=0}^{N-1} y_n^2} \right)^{\frac{N}{2}} \exp\left(\frac{\sum_{n=0}^{N-1} y_n^2}{2\sigma_1^2} - \frac{N}{2} \right) \underset{\mathcal{H}_1}{\overset{\mathcal{H}_2}{\gtrless}} \lambda_1. \end{aligned} \tag{39}$$

Since the test statistic is $Y = \sum_{n=0}^{N-1} y_n^2$ and $L_1(y)$ are functions of Y, it can be obtained that:

$$\frac{dL_1}{dY} = \frac{1}{2} \left(N \frac{\sigma_1^2}{Y} \right)^{\frac{N}{2}} e^{\frac{Y}{2\sigma_1^2}} \frac{Y - N\sigma_1^2}{Y\sigma_1^2}. \tag{40}$$

So at $Y > N\sigma_1^2$, $L_1(y)$ increases as Y increases; otherwise it decreases as Y increases. Therefore, the minimum value of likelihood ratio 1 can be obtained at $N\sigma_1^2$. Therefore, $L_1(y) < \lambda_1$ is equivalent to $\eta_1 < Y < \eta_2$, where η_1 and η_2 are the two solutions of $L_1(y) = \lambda_1$:

$$\begin{aligned} &\left(\frac{N\sigma_1^2}{\eta_1} \right)^{\frac{N}{2}} \exp\left(\frac{\eta_1}{2\sigma_1^2} - \frac{N}{2} \right) \\ &\quad = \left(\frac{N\sigma_1^2}{\eta_2} \right)^{\frac{N}{2}} \exp\left(\frac{\eta_2}{2\sigma_1^2} - \frac{N}{2} \right) = \lambda_1. \end{aligned} \tag{41}$$

At the same time, when only the primary user exists, that is, if $\mathcal{H}_1$ is true, $Y = \sum_{n=0}^{N-1} y_n^2 \sim \chi_N^2 \left(\sigma_1^2\right)$. Therefore, in order to satisfy the constraint

$$\begin{aligned} \Pr(\mathcal{H}_1|\mathcal{H}_1) &= \Pr(\eta_1 < Y < \eta_2) \\ &= \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_1}{\sigma_1^2}\right) - \Gamma\left(\frac{N}{2}, \frac{\eta_2}{\sigma_1^2}\right)}{\Gamma\left(\frac{N}{2}\right)} = \beta. \end{aligned} \tag{42}$$

Therefore, the thresholds η_1 and η_2 can be solved. Therefore, this part is determined as

$$d = \begin{cases} \mathcal{H}_1, & \eta_1 < Y < \eta_2 \\ \mathcal{H}_2, & otherwise. \end{cases} \tag{43}$$

Considering the complexity of GLRT, it is difficult to get a closed form of the threshold. However, the asymptotic properties of the proposed method can be obtained by proper approximation.

First, when N is sufficiently large and the channel is occupied by the primary user, $2\ln L_1(y) \sim \chi_1^2$.

Let $z^2 = 2\ln L_1$, where z obeys the gaussian distribution of zero mean and unit variance, namely, $z \sim \mathcal{N}(0, 1)$, and the approximate test probability can be obtained

$$\begin{aligned} \Pr(\mathcal{H}_1|\mathcal{H}_1) &= \Pr(2\ln L_1 < 2\ln\lambda_1|\mathcal{H}_1) \\ &= \int_{-\sqrt{2\ln\lambda_1}}^{\sqrt{2\ln\lambda_1}} \frac{1}{\sqrt{2\pi}} \rho^{\frac{z^2}{2}} dz \\ &= 2Q(-\sqrt{2\ln\lambda_1}) - 1 = \beta, \end{aligned} \tag{44}$$

where $Q(\cdot)$ is the complementary cumulative distribution function of the standard normal distribution. Therefore, the asymptotic solution of λ_1 is

$$\lambda_1 = \exp\left[\frac{1}{2} \left(Q^{-1}\left(\frac{1+\beta}{2} \right) \right)^2 \right]. \tag{45}$$

In addition, based on equation (41), the approximate solutions of the thresholds η_1 and η_2 can be obtained.

Although the complexity of calculating threshold is reduced, the closed solution of threshold cannot be obtained, which hinders the evaluation of detection performance. However, asymptotic detection performance can be obtained by following propositions.

When N is sufficiently large and $\mathcal{H}_2$ is true, then $z^2 = 2\ln L_1(y) \sim \chi_1^2(\theta)$, where $\chi_1^2(\theta)$ is the non-central chi-square distribution, and the non-central parameter is $\theta = \left(\sigma_2^2 - \sigma_1^2\right)^2 I\left(\sigma_1^2\right)$, $\left(\sigma_1^2\right)$ is Fisher information. Specifically, Fisher information is calculated as follows:

$$\begin{aligned} I\left(\sigma_1^2\right) &= -E\left(\frac{\partial^2 \ln p\left(y; \sigma_1^2\right)}{\partial^2 \sigma_1^2} \right) \\ &= -E\left(\frac{\partial}{\partial \sigma_1^2} \left(\frac{\sum_{1=0}^{N-1} y_t^2}{2\sigma_1^4} - \frac{N}{2\sigma_1^2} \right) \right) \\ &= -E\left(\frac{N}{2\sigma_1^4} - \frac{\sum_{i=0}^{N-1} y_i^2}{\sigma_1^6} \right) = \frac{N}{2\sigma_1^4}. \end{aligned} \tag{46}$$

Then $z \sim \mathcal{N}(\mu, 1)$, $\mu = \sqrt{\left(\frac{\sigma_2^2}{\sigma_1^2} - 1\right)^2 \frac{N}{2}}$. So the gradual probability that $\mathcal{H}_2$ is misjudged as $\mathcal{H}_1$ is

$$\begin{aligned}
&\Pr(\mathcal{H}_1|\mathcal{H}_2) \\
&= \Pr\left(-\sqrt{2\ln\lambda_1} < z < \sqrt{2\ln\lambda_1}|\mathcal{H}_2\right) \\
&= \Pr\left(Q^{-1}\left(\frac{1+\beta}{2}\right) < z < -Q^{-1}\left(\frac{1+\beta}{2}\right)|\mathcal{H}_2\right) \\
&= \int_{Q^{-1}\left(\frac{1+\beta}{2}\right)}^{-Q^{-1}\left(\frac{1+\beta}{2}\right)} \frac{1}{\sqrt{2\pi}} e^{\frac{(z-\mu)^2}{2}} dz, \qquad (47)
\end{aligned}$$

where, based on Eq. 45), $2\ln\lambda_1 = \left(Q^{-1}\left(\frac{1+\beta}{2}\right)\right)^2$. $\beta < 1$ tells us that $0.5 < \frac{1+\beta}{2} < 1$, $Q^{-1}\left(\frac{1+\beta}{2}\right) < 0$, so $\sqrt{2\ln\lambda_1} = -Q^{-1}\left(\frac{1+\beta}{2}\right)$

Based on the Eq. 35 and Eq. 43, the decision domain can be obtained:

$$\mathcal{R}_i = \begin{cases} Y < \eta_0, & i = 0 \\ \eta_1 < Y < \eta_2, & i = 1 \\ \eta_0 < Y < \eta_1, or Y > \eta_2, & i = 2, \end{cases} \qquad (48)$$

where in order to meet the detection performance constraint, $\mathcal{R}_2$ is the intersection of the decision domain of $\mathcal{H}_2$ in two subproblems.

In Eq. 48, there is a problem that η_0 may be less than η_1. This means that there may be overlaps between decision domains $\mathcal{R}_0$ and $\mathcal{R}_1$, making the performance constraints in the target function unsatisfied. Specifically, when constraint parameters α and β satisfy certain conditions, the overlap of decision fields occurs, for which theorem 1 is given.

Theorem 1: If GLRT is adopted, the decision domain $\mathcal{R}_0$ and $\mathcal{R}_1$ will overlap if and only if constraint parameters α and β meet the following conditions: [21]

$$\beta > \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_1^*}{\sigma_1^2}\right)}{\Gamma\left(\frac{N}{2}\right)} - \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_2^*}{\sigma_1^2}\right)}{\Gamma\left(\frac{N}{2}\right)}, \qquad (49)$$

where $\eta_1^* = \Gamma^{-1}\left(\frac{N}{2}, (1-\alpha)\Gamma\left(\frac{N}{2}\right)\right)\sigma_0^2$ and η_2^* are solutions to $\left(\frac{\eta_1^*}{\eta_2^*}\right)^{\frac{N}{2}} \exp\left(\frac{\eta_2^*-\eta_1^*}{2\sigma_1^2}\right) = 1, \ \eta_2^* \neq \eta_1^*$.

Proof: see appendix for detailed proof process.

When the conditions in theorem 1 are not satisfied and there is no mutual influence between the two subproblems, the asymptotic value of the probability of the illegal behavior being correctly detected can be deduced:

$$\begin{aligned}
\Pr(\mathcal{H}_2|\mathcal{H}_2) &= 1 - \Pr(\mathcal{H}_1|\mathcal{H}_2) - \Pr(\mathcal{H}_0|\mathcal{H}_2) \\
&= 1 - \begin{bmatrix} Q\left(Q^{-1}\left(\frac{1+\beta}{2}\right) - \mu\right) \\ -Q\left(-Q^{-1}\left(\frac{1+\beta}{2}\right) - \mu\right) \end{bmatrix} \\
&\quad - \left(1 - \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_0}{\sigma_2^2}\right)}{\Gamma\left(\frac{N}{2}\right)}\right) \\
&= \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_0}{\sigma_2^2}\right)}{\Gamma\left(\frac{N}{2}\right)} \\
&\quad - \begin{bmatrix} Q\left(Q^{-1}\left(\frac{1+\beta}{2}\right) - \mu\right) \\ -Q\left(-Q^{-1}\left(\frac{1+\beta}{2}\right) - \mu\right) \end{bmatrix}. \qquad (50)
\end{aligned}$$

On the other hand, when overlap occurs, the decision domain needs to be adjusted to avoid overlap and meet performance constraints. Returning to Eq. 27, it can be seen that, in order to meet the performance constraint, the thresholds λ_0 and λ_1 need to be improved. However, since the overlap has occurred, an increase of λ_0 would lead to an increase of η_0, thus increasing the overlap area, while η_1 and η_2 in Eq. 48 would increase with the increase of λ_1, and the decision domain $\mathcal{R}_1$ would further expand. Therefore, when the condition in theorem 1 is satisfied, η_1 needs to be the same as η_0 in order for the constraint condition $\Pr(\mathcal{H}_0|\mathcal{H}_0) = \alpha$ to be satisfied, and in order for the other constraint condition to be satisfied

$$\Pr(\mathcal{H}_1|\mathcal{H}_1) = \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_1}{\sigma_1^2}\right)}{\Gamma\left(\frac{N}{2}\right)} - \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_2}{\sigma_1^2}\right)}{\Gamma\left(\frac{N}{2}\right)} = \beta. \qquad (51)$$

The threshold for η_2

$$\eta_2 = \Gamma^{-1}\left(\frac{N}{2}, \Gamma\left(\frac{N}{2}, \frac{\eta_1}{\sigma_1^2}\right) - \Gamma\left(\frac{N}{2}\right)\beta\right)\sigma_1^2. \qquad (52)$$

Finally, in the case of overlap, the decision domain is:

$$\mathcal{R}_i = \begin{cases} Y < \eta_0, & i = 0 \\ \eta_1 < Y < \eta_2, & i = 1 \\ Y > \eta_2, & i = 2, \end{cases} \qquad (53)$$

where, η_0 is calculated from Eq. 34, and $\eta_0 = \eta_1$, and η_2 is obtained from Eq. 52.

IV. ILLEGAL BEHAVIOR DETECTION WHEN THE NUMBER OF AUTHORIZED USERS EXCEEDS ONE

A. MULTIPLE HYPOTHESIS TEST MODEL WHEN THE NUMBER OF AUTHORIZED USERS EXCEEDS ONE

In the case that multiple satellites are the primary users and there are j satellites, the signals received by the sensing earth station for each satellite can also be modeled as a binary hypothesis test problem:

$$y_s^j(t) = \begin{cases} n(t) & \mathcal{H}_0^S, \\ \sqrt{P_s^j}\sqrt{h_s^j}e^{i\phi_j}s_j(t) + n(t) & \mathcal{H}_1^S, \end{cases} \qquad (54)$$

where $y_s^j(t)$ to perceive earth station in the sampling time t to receive the j-th satellite signal; $s_j(t)$ is the j-th primary user satellite transmission symbol, it follows a CSCG distribution, with zero mean and unit variance; P_s^j for transmitted power of the j-th satellite, and in a single time slot is constant; h_s^j for the j-th satellite channel gain, concrete expression as follows; ϕ_j for the j-th satellite channel phase; $n(t)$ for AWGN, the variance of σ_n^2.

$$h_s^j = G_{ner,\max} G_{gst}^j(\theta_j)\left(\frac{c}{4\pi f d_{gs\to ne}^j}\right)^2 10^{-\frac{A_g}{10}} 10^{-\frac{A_c}{10}}, \quad (55)$$

where $G_{ner,\max}$ represents the maximum gain of the receiving antenna of the sensing earth station; $G_{gst}^j(\theta_j)$ represents the gain of the j-th satellite transmitted antenna with the direction angle of θ; c represents the speed of light; f represents the central frequency of the spectrum band; $d_{gs\to ne}^j$ represents the distance between the satellite and the sensing earth station. Propagation factors A_g and A_c represent gaseous absorption and cloud or fog attenuation, respectively.

The problem is modeled by taking into account the existence of all satellites and illegal users and linear combination. Considering the probability of all possible scenarios, the multiple hypothesis test model is as follows:

$$\begin{cases} \mathcal{H}_0 : \text{Only noise exists}, \\ \mathcal{H}_1 : \text{Only satellite1 and noise exist}, \\ \mathcal{H}_2 : \text{Only satellite2 and noise exist}, \\ \cdots\cdots \\ \mathcal{H}_j : \text{Only satellitej and noise exist}, \\ \mathcal{H}_{j+1} : \text{Satellite1,satellite2 and noise exist}, \\ \mathcal{H}_{j+2} : \text{Satellite1,satellite3 and noise exist}, \\ \cdots\cdots \\ \mathcal{H}_{k+1} : \text{Only illegal users and noise exist}, \\ \mathcal{H}_{k+2} : \text{Satellite1,illegal users} \\ \qquad\quad \text{and noise exist}, \\ \mathcal{H}_{k+3} : \text{Satellite1,satellite2,illegal users} \\ \qquad\quad \text{and noise exist}, \\ \cdots\cdots \\ \mathcal{H}_M : \text{All signal exsit}. \end{cases}$$

From the above model, it can be seen that the model is too complex, assuming too many combinations, and it is very difficult to solve. Therefore, it is necessary to simplify the above model. Through the above derivation, the difference of each hypothesis is still reflected in the variance of observed values.

We assume that the variance of the signal received from the j-th satellite is σ_j^2, and the variance of the noise is σ_0^2. The variance of the illegal user is unknown as σ_x^2.

Then the above hypothesis can be changed into:

$$\begin{cases} \mathcal{H}_0 : \sigma^2 = \sigma_0^2 & \text{noise}, \\ \mathcal{H}_1 : \sigma^2 = \sigma_1^2 + \sigma_0^2 & \text{satellite1 + noise}, \\ \mathcal{H}_2 : \sigma^2 = \sigma_2^2 + \sigma_0^2 & \text{satellite2 + noise}, \\ \cdots\cdots \\ \mathcal{H}_j : \sigma^2 = \sigma_j^2 + \sigma_0^2 & \text{satellitej + noise}, \\ \mathcal{H}_{j+1} : \sigma^2 = \sigma_1^2 + \sigma_2^2 + \sigma_0^2 & \text{satellite1+satellite2+noise}, \\ \mathcal{H}_{j+2} : \sigma^2 = \sigma_1^2 + \sigma_3^2 + \sigma_0^2 & \text{satellite1+satellite3+noise}, \\ \cdots\cdots \\ \mathcal{H}_k : \sigma^2 = \sigma_x^2 + \sigma_0^2 & \text{illegal users+noise}, \\ \mathcal{H}_{k+1} : \sigma^2 = \sigma_1^2 + \sigma_x^2 + \sigma_0^2 & \text{satellite1+illegal users+noise}, \\ \cdots\cdots \\ \mathcal{H}_M : \sigma^2 = \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_j^2 + \sigma_x^2 + \sigma_0^2 & \text{all}, \end{cases}$$

where $\mathcal{H}_0$ means the channel is idle, $\mathcal{H}_{1\sim j}$ means the channel is occupied by the first to j-th primary user, $\mathcal{H}_{j+1\sim k-1}$ means the channel is occupied by multiple primary users, $\mathcal{H}_{k\sim M-1}$ means the channel is occupied by illegal users, and $\mathcal{H}_M$ means the channel is occupied by both primary users and illegal users.

The above model is too complicated to solve. Since the purpose of this paper is to detect spectrum opportunity and further detect whether there are illegal users, the above multiple hypothesis test models can be merged without affecting the detection results. Then, the above hypothesis can be further simplified into a ternary hypothesis test model:

$$\begin{cases} \mathcal{H}_0 : \sigma^2 = \sigma_0^2, \\ \mathcal{H}_1 : \sigma^2 = \sigma_1^2, \sigma_2^2, \cdots, \\ \qquad \sigma_j^2, \sigma_1^2 + \sigma_2^2, \sigma_1^2 + \sigma_3^2 \cdots, \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_j^2, \\ \mathcal{H}_2 : \sigma^2 > \sigma_0^2, \\ \qquad \sigma^2 \neq \sigma_1^2, \sigma_2^2, \cdots, \\ \qquad \sigma_j^2, \sigma_1^2 + \sigma_2^2, \sigma_1^2 + \sigma_3^2 \cdots, \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_j^2, \end{cases}$$

where $\mathcal{H}_0$ means that the spectrum is not used, $\mathcal{H}_1$ means that the spectrum is occupied by legitimate users (namely the primary users), and $\mathcal{H}_2$ means that illegal users exist.

B. DETECTION METHOD WHEN THE NUMBER OF AUTHORIZED USERS EXCEEDS ONE

Since the model with multiple satellites as the primary user is also built as a ternary hypothesis test model, the analysis method in the previous section is used for processing first.

As can be seen from the above analysis, this ternary hypothesis test problem can also be optimized and decomposed into two sub-problems:

$$\max_{\mathcal{R}_0,\mathcal{R}_2} \Pr(\mathcal{H}_2|\mathcal{H}_2), \quad s.t.\ \Pr(\mathcal{H}_0|\mathcal{H}_0) = \alpha, \quad (56)$$

and

$$\max_{\mathcal{R}_1,\mathcal{R}_2} \Pr(\mathcal{H}_2|\mathcal{H}_2), \quad s.t.\ \Pr(\mathcal{H}_1|\mathcal{H}_1) = \beta. \quad (57)$$

Similarly, the final solution is the intersection of two subproblems. Therefore, the original problem can be simplified by decomposition. Moreover, the two problems have significant physical significance, which can be called detection subproblems and identification subproblems.

1) DETECT SUBPROBLEMS (IDLE OR BUSY)

The subproblems in the equation can be regarded as derived from the following binary hypothesis test problem:

$$\begin{cases} \mathcal{H}_0 : \sigma^2 = \sigma_0^2, \\ \mathcal{H}_2 : \sigma^2 > \sigma_0^2, \\ \quad \sigma^2 \neq \sigma_1^2, \sigma_2^2, \cdots, \sigma_j^2, \sigma_1^2 + \sigma_2^2, \sigma_1^2 + \sigma_3^2, \\ \quad \cdots, \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_j^2. \end{cases} \tag{58}$$

For detection subproblems, the number of primary users has no effect on idle or busy detection of the channel, so the detection method for detection subproblems is the same as before, which is not repeated here.

Therefore, the judgment threshold is:

$$\eta_0 = \Gamma^{-1}(\frac{N}{2}, (1-\alpha)\Gamma(\frac{N}{2}))\sigma_0^2, \tag{59}$$

where, $\Gamma^{-1}(\cdot, \cdot)$ is the inverse function of the incomplete Gamma function. Therefore, the detection subproblem is determined as:

$$Y \underset{\mathcal{H}_0}{\overset{\mathcal{H}_2}{\gtrless}} \eta_0. \tag{60}$$

2) RECOGNITION SUBPROBLEM (LEGAL OR ILLEGAL)

The second subproblem in the equation is believed to come from the following binary hypothesis test problem:

$$\begin{cases} \mathcal{H}_1 : \sigma^2 = \sigma_1^2, \sigma_2^2, \cdots, \\ \sigma_j^2, \sigma_1^2 + \sigma_2^2, \sigma_1^2 + \sigma_3^2 \cdots, \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_j^2 \\ \mathcal{H}_2 : \sigma^2 > \sigma_0^2, \sigma^2 \neq \sigma_1^2, \sigma_2^2, \cdots, \\ \sigma_j^2, \sigma_1^2 + \sigma_2^2, \sigma_1^2 + \sigma_3^2 \cdots, \sigma_1^2 + \sigma_2^2 + \cdots + \sigma_j^2. \end{cases} \tag{61}$$

First, the maximum likelihood estimation of unknown variance σ_x^2 is calculated

$$\hat{\sigma}_x^2 = \arg\max_{\sigma_x^2} p(y; \sigma_x^2). \tag{62}$$

If $\frac{\partial p(y;\hat{\sigma}_x^2)}{\partial \hat{\sigma}_x^2} = 0$, we get

$$\hat{\sigma}_x^2 = \frac{1}{N}\sum_{n=0}^{N-1} y_n^2. \tag{63}$$

Generalized likelihood ratio can be obtained in Eq.64, as shown at the bottom of this page.

Due to the complexity of the detector, it is difficult to carry out theoretical analysis. So you need to think about simpler detectors.

In order to simplify the above detection methods and design a detection method that is easy to theoretical analysis, which can well realize the detection purpose with multiple satellites as the primary user, this section proposes a two-step detector. The core idea is to select the most likely variance and then determine whether there are illegal users.

Specifically, the first step is to adopt the maximum likelihood criterion

$$\sigma_n^2 = \arg\max_{\sigma}(-\left|\sigma_n^2 - \sigma_x^2\right|). \tag{65}$$

The second step is to derive the generalized likelihood ratio

$$L_1(y) = \frac{p(y; \hat{\sigma}_x^2, \mathcal{H}_2)}{p(y; \sigma_n^2, \mathcal{H}_1)} = \frac{\frac{1}{(2\pi\hat{\sigma}_x^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\hat{\sigma}_x^2})}{\frac{1}{(2\pi\sigma_n^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\sigma_n^2})} \underset{H_1}{\overset{H_2}{\gtrless}} \lambda_1. \tag{66}$$

Through the maximum likelihood criterion of variance, the above formula can be well simplified. Similarly, this is also a bilateral detection problem. The detection threshold can be deduced by continuing to use the above method.

$$L_1(y) = \frac{p(y; \hat{\sigma}_x^2, \mathcal{H}_2)}{p(y; \mathcal{H}_1)} = \frac{\frac{1}{(2\pi\hat{\sigma}_x^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\hat{\sigma}_x^2})}{\begin{array}{l}\frac{1}{(2\pi\sigma_1^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\sigma_1^2}) + \frac{1}{(2\pi\sigma_2^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\sigma_2^2}) + \cdots + \frac{1}{(2\pi\sigma_j^2)^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2\sigma_j^2}) \\ + \frac{1}{(2\pi(\sigma_1^2+\sigma_2^2))^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2(\sigma_1^2+\sigma_2^2)}) + \frac{1}{(2\pi(\sigma_1^2+\sigma_3^2))^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2(\sigma_1^2+\sigma_3^2)}) + \cdots + \frac{1}{(2\pi(\sigma_1^2+\sigma_2^2+\cdots+\sigma_j^2))^{\frac{N}{2}}}\exp(-\frac{\sum_{n=0}^{N-1} y_n^2}{2(\sigma_1^2+\sigma_2^2+\cdots+\sigma_j^2)})\end{array}} \underset{H_1}{\overset{H_2}{\gtrless}} \lambda_1. \tag{64}$$

The decision thresholds η_1 and η_2 are the solutions of the following two equations

$$\left(\frac{N\sigma_n^2}{\eta_1}\right)^{\frac{N}{2}} \exp\left(\frac{\eta_1}{2\sigma_n^2}-\frac{N}{2}\right) = \left(\frac{N\sigma_n^2}{\eta_2}\right)^{\frac{N}{2}} \exp\left(\frac{\eta_2}{2\sigma_n^2}-\frac{N}{2}\right) = \lambda_1, \quad (67)$$

$$\Pr(\mathcal{H}_1|\mathcal{H}_1) = \Pr(\eta_1 < Y < \eta_2) = \frac{\Gamma\left(\frac{N}{2},\frac{\eta_1}{\sigma_n^2}\right)-\Gamma\left(\frac{N}{2},\frac{\eta_2}{\sigma_n^2}\right)}{\Gamma\left(\frac{N}{2}\right)} = \beta. \quad (68)$$

The verdict is

$$d = \begin{cases} \mathcal{H}_1, & \eta_1 < Y < \eta_2 \\ \mathcal{H}_2, & otherwise. \end{cases} \quad (69)$$

So the total decision domain is

$$\mathcal{R}_i = \begin{cases} Y < \eta_0, & i = 0 \\ \eta_1 < Y < \eta_2, & i = 1 \\ \eta_0 < Y < \eta_1, or Y > \eta_2, & i = 2. \end{cases} \quad (70)$$

Similarly, there is also the possibility of overlap in the decision domain, and the derivation and analysis of overlap are the same as above, which will not be repeated here. Finally, if there is overlap, the threshold for η_2

$$\eta_2 = \Gamma^{-1}\left(\frac{N}{2}, \Gamma\left(\frac{N}{2},\frac{\eta_1}{\sigma_n^2}\right) - \Gamma\left(\frac{N}{2}\right)\beta\right)\sigma_n^2. \quad (71)$$

The decision domain becomes

$$\mathcal{R}_i = \begin{cases} Y < \eta_0, & i = 0 \\ \eta_1 < Y < \eta_2, & i = 1 \\ Y > \eta_2, & i = 2, \end{cases} \quad (72)$$

where η_0 is calculated from Eq. 59, $\eta_0 = \eta_1$, and η_2 is obtained from Eq. 71.

V. SIMULATION RESULTS AND ANALYSIS

All satellite and earth station parameters are referred to O3b and OneWeb, respectively. The downlink transmission frequency is 18.48GHz, satellite 1 is a GEO satellite with an altitude of 35678Km, the satellite transmission antenna gain is 52dBi, the earth station antenna gain is 55.4dBi, the earth station antenna diameter is 2.4m, and the earth station noise temperature is 200k. Satellite 2 is an 8062Km NGEO satellite with a transmission gain of 35dBi and a transmission antenna gain of 37.2dBi for the earth station. Satellite 3 is an NGEO satellite with an altitude of 6000Km, the satellite transmission gain is 31.5dBi, and the earth station transmission antenna gain is 36.7dBi. Satellite 4 is an NGEO satellite with an altitude of 10000Km, the satellite transmission gain is 37.3dBi, and the earth station transmission antenna gain is 38.4dBi. The spectrum bandwidth is 6MHz, the sampling number is generally $N = 300$, and the sampling time is 0.05ms. The noise variance is $\sigma_0^2 = 10^{-5}$Watt.

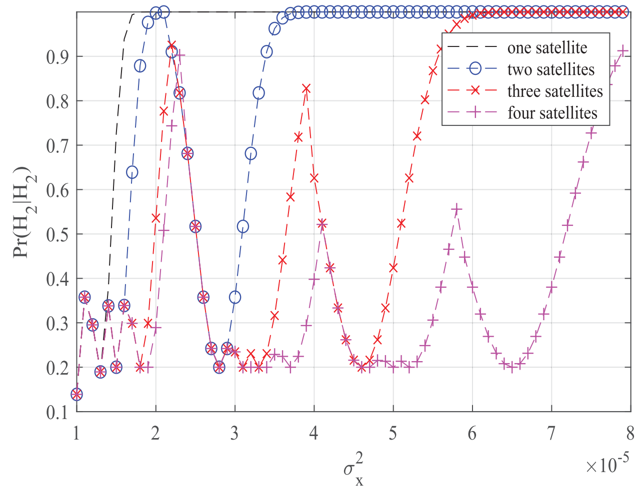

FIGURE 6. Detection probability under different illegal behavior parameters.

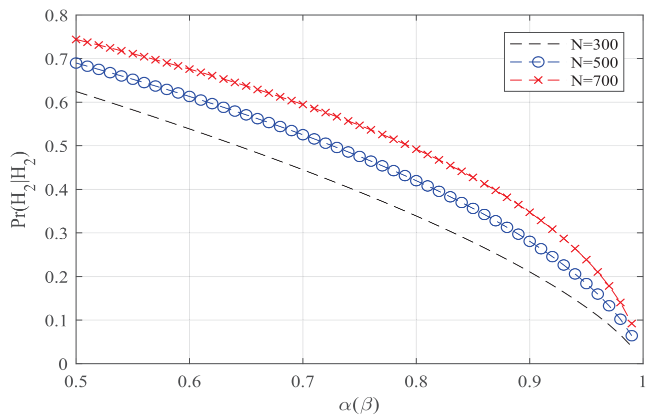

FIGURE 7. Detection probability under different performance constraints.

Fig. 6 shows the detection performance under different variances σ_x^2 when the number of satellites is from 1 to 4, where $\alpha = \beta = 0.8$. As can be seen, when σ_x^2 is close to the variance of the primary user, the detection performance decreases significantly. This is because the similarity between various states is too high, which makes it difficult to distinguish. Therefore, when the number of satellites increases, the number of detection performance degradation will increase obviously due to the combination of variance. On the other hand, when the distance between the variances of the primary users increases, the detection performance can be significantly improved.

Fig. 7 shows the relationship between detection performance and constraint parameter α and β, where $\alpha = \beta$ and $N = 300$. As can be seen, the detection performance will decline with the improvement. Fig. 8 shows the relationship between detection performance and sample number N, where $\alpha = \beta = 0.8$. It can be seen that when N increases, detection performance is improved.

Fig. 9 and Fig. 10 show the detection performance under different performance constraints and samples when the number of primary user satellites is 2, 3 and 4, respectively. As can

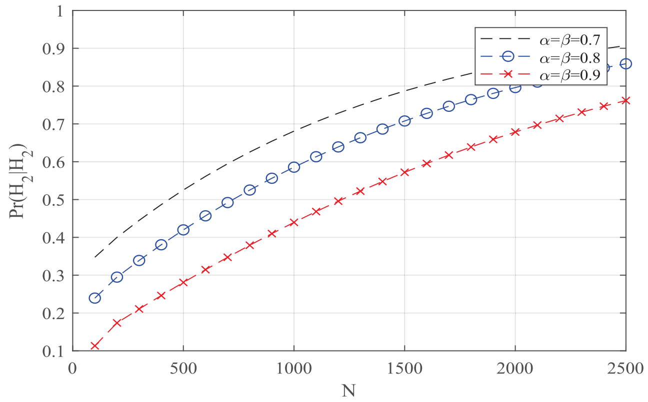

FIGURE 8. Test performance under different sample Numbers.

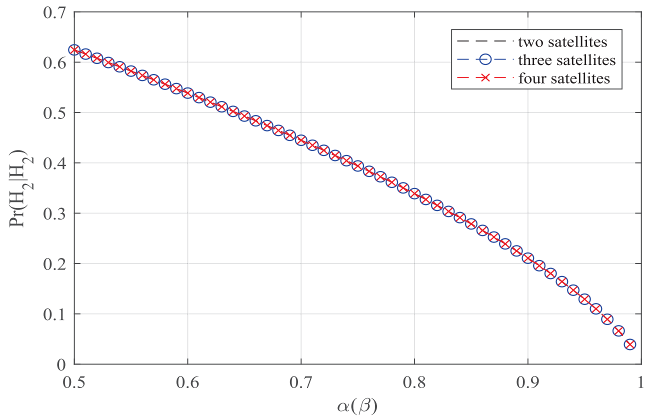

FIGURE 9. Influence of number of primary user satellites on detection probability.

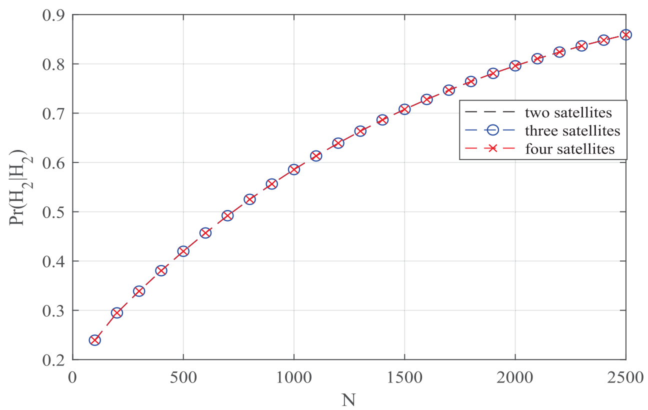

FIGURE 10. Influence of number of primary user satellites on detection probability.

be seen from the figures, the number of satellites has no impact on the detection performance. This is because the maximum likelihood criterion is adopted for variance, and the variance closest to the estimated variance is chosen for judgment. Therefore, when the estimated variance remains unchanged, changing the number of satellites will not affect the detection performance.

VI. CONCLUSION

In this paper, we investigate the detection of illegal spectrum access behavior through spectrum perception in the satellite-terrestrial spectrum sharing system. First we establish a model of multiple hypothesis test, and use the GMNP criteria to solve the problem. Then, we deduce the judgment threshold formula. Finally, through simulation, the performance of the detection method is evaluated and analyzed. The results show that the method has a high detection rate for illegal spectrum access behavior.

APPENDIX

PROOF OF THEOREM 1

Firstly, we consider the critical point (α_c, β_c) which makes the overlapping just happens, i.e., $\eta_0 = \eta_1 = \eta_1^*$. First, based on (36), η_1^* is formulated

$$\eta_1^* = \Gamma^{-1}\left(\frac{N}{2}, (1-\alpha_c)\,\Gamma\left(\frac{N}{2}\right)\right)\sigma_0^2.$$

Substitute η_1^* for η_1 in (43), and we have

$$\left(\frac{\eta_1^*}{\eta_2}\right)^{\frac{N}{2}} \exp\left(\frac{\eta_2 - \eta_1^*}{2\sigma_1^2}\right) = 1.$$

So, we can obtain η_2^* that is the solution to the equation above, $\eta_2 \neq \eta_1$. Then, $\Pr(\mathcal{H}_1|\mathcal{H}_1)$ is formulated as follows

$$\beta_C = \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_1^*}{\sigma_1^2}\right)}{\Gamma\left(\frac{N}{2}\right)} - \frac{\Gamma\left(\frac{N}{2}, \frac{\eta_2^*}{\sigma_1^2}\right)}{\Gamma\left(\frac{N}{2}\right)}. \tag{73}$$

Further, it is found that when β increases, λ_1 increases, η_1 decreases, and the area of the overlapping region increases. On the other side, when α increases, η_0 decreases and the area of the overlapping region increases. This means that once β is over the value in Eq.73 the overlapping happen. In conclusion, the overlapping condition is obtained just as formulated in Eq.49.

This completes the proof.

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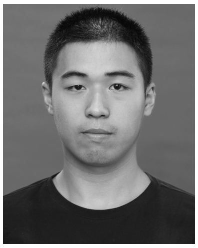

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