Secure Spectrum Sharing for Satellite Internet-of-Things with Blockchain

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Secure Spectrum Sharing for Satellite Internet-of-Things with Blockchain

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Abstract The introduction of satellite communications will play a key role in next generation communications. However, satellite systems are faced with the challenge of efficiently managing the satellite spectrum resource when supporting the communication needs of massive Internet-of-Things (IoT) devices, which is expected to growth explosively in scale of deployment. To address this issue, we propose a blockchain-based satellite spectrum resource optimization scheme. The scheme is based on a market-driven spectrum trading technique to maximize the benefit of the satellite systems, hence the utilization of the spectrum resource. In specific, the proposed spectrum trading protocol focuses on the heterogeneity of LEO satellite spectrum, which covers a huge band range with varying transmission qualities, by allowing a price differentiation between different spectrum ranges. As a result, different terrestrial IoT systems may select their preferred spectrum range, and price, according to their own application requirements and budgets. Furthermore, data integrity is needed to ensure the proper functioning of the spectrum trading process. In the proposed scheme, we adopt a blockchain mechanism for facilitating spectrum trading with enhanced security, with all essential transaction-related data to be stored in a blockchain, which is used as a distributed and immutable data store for all records of the trading activities. Due to the limited computing power of terrestrial IoT device terminals, the blockchain is based on a Delegated Proof

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of Stake (DPoS) consensus algorithm which is believed to be more suitable for the scenario of satellite-based IoT systems.

Keywords Satellite communications · Internet-of-Things (IoT) · spectrum trading · blockchain

1 Introduction

Next generation communications such as 6G networks, which is anticipated to provide global connectvity coverage with high-speed transmssion, have received great attention of the research community worldwide. To achieve this, 6G networks are expected integrate 5G and satellite communications, hence leading to a global competition for orbit and spectrum resource to meet the needs of 6G communications [1][2]. In this connection, compared to Geostationary Earth Orbit (GEO) satellites which are faced with issues of long delay and low speed, Low Earth Orbit (LEO) satellites are widely believed to play a critical role in 6G communications [3]-[5].

As one of the most important application scenarios for next generation networks, Internet-of-Things (IoT) systems for implementing smart cities, industry 4.0 and environmental monitoring for earth sustainability will rely heavily on the anytime anywhere connectivity offered by 6G networks. As such, satellite communications will need to support and cater for the communication needs of a massive number of IoT devices with truly global and high-speed coverage. Many research efforts have been paid to satellite IoT wherein almost every cutting edge technology raised in recent years, such as edge computing, LoRa protocol, NOMA and massive MIMO etc. has been analyzed and investigated to improve the system performances [6]-[10].

Satellite systems are faced with the increasingly challenging issue of efficiently managing the satellite spectrum resource as terrestrial Internet-of-Things (IoT) is expected to experience explosive growth in scale of deployment. To address this issue, many spectrum management schemes have been proposed, which are based concepts ranging from cooperative values, dynamic spectrum access, power allocation and on-board processing techniques respectively [11]-[14]. In [11], the authors proposed a joint spectrum sensing and power control-forwarded resource sharing solution for LEO satellite communications. In [12], software-defined spectrum optimization method was designed in cognitive satellite systems to improve the utilization of satellite resource and system performance. In [13], a joint interference pricing and power control method was devised to enhance the spectrum efficiency in multibeam satellite systems. In [14], a satellite spectrum trading framework for GEO satellite systems was proposed to improve spectrum sharing by introducing the method of dynamic bargaining.

In this paper, we propose a blockchain-based satellite spectrum resource optimization scheme. The scheme is based on a market-driven spectrum trading technique to maximize the benefit of the satellite systems, and hence the utilization of the spectrum resource. Specifically, we focus on the LEO satellite IoT scenario where the satellite spectrum is heterogeneous and covers a huge band range with varying transmission qualities. The proposed spectrum trading protocol takes advantage of the heterogeneity of LEO satellite spectrum by allowing a price differentiation between different spectrum ranges. Hence, different terrestrial IoT systems may select their preferred spectrum range, and price, according to their own application requirements and budgets. The proposed scheme included the design of a spectrum pool structure, which matches the heterogeneity of the spectrum.

On the other hand, our scheme adopts a blockchain mechanism for facilitating spectrum trading in order to enhance the security of the trading process. When terrestrial IoT device terminals make randomly access satellite channels, data integrity is need to ensure the proper functioning of the spectrum trading process. In the proposal, all essential transaction-related data, including trading information, transmission parameters, user power, etc. are in a blockchain which is used as a distributed and immutable data store for all transaction records of the trading activities. Due to the limited computing power of terrestrial IoT device terminals, the blockchain is based on a Delegated Proof of Stake (DPoS) consensus algorithm which is believed to be more suitable for the scenario of LEO satellite IoT systems.

The rest of this paper is organized as follows. In Section II, the model of the spectrum trading system is provided. In Section III, the pricing mechanism of spectrum sharing scheme is introduced. The detailed blockchain operation is presented in Section IV. Numerical results are presented in Section V to show the performance of the system. This paper is concluded in Section VI.

2 Pricing Mechanism for Spectrum Trading

The spectrum trading scheme proposed in this paper is achieved through spectrum transactions between satellite systems and terrestrial users. The scenario considered is that the LEO satellite systems rent part of the idle spectrum to the ground satellite users, so as to improve its own revenue and share the idle spectrum with the terrestrial users. It is beneficial to encourage spectrum providers to take out more idle spectrum to generate benefits. Besides, it is also beneficial to regulate the supply and demand of satellite spectrum and improve the spectrum efficiency through marketization. In this case, we take into account the oblique projector of LEO multibeam satellite when identifying the terrestrial user's transmission capacity. As shown in Fig. 1, in the multibeam satellite transmission mode, the oblique projector model is given. Thus, the deviation angle between terrestrial user c and the cell center o is as $\theta = \arccos\left(\{(d_o^s)^2 + (d_{c2}^s)^2 - 2R^2[1-\cos(d_{c2}^o/R)]\} \times (2d_o^s d_{c2}^s)^{-1}\right)$, wherein d_o^s denotes the distance between cell center o and the satellite as shown in Fig. 1. d_c^s denotes the distance between user c and cell the subastral point, d_c^o denotes the distance between user c and cell center o and R means the earth radius.

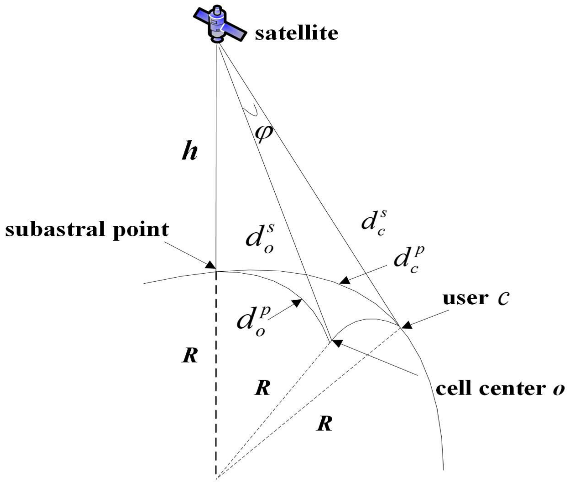

Fig. 1 Orientation angle with oblique projector

Then, for a satellite user n, the transmission capacity can be expressed as

$$C_n = B\log_2(1 + \frac{\rho_n g_n(\varepsilon_n) G(\varphi_n)}{d_n^2 f_n(\varepsilon_n) \sum_{\tau=1}^{l} \frac{\rho_c g_n(\varepsilon_n) G \varphi_n \mu_n \rho}{(4\pi d_c/\gamma)^2 f_n(\varepsilon_n)} + BN_0(\varepsilon_c)}). \tag{1}$$

LEO satellites can work in K, S, C, L, Ka, etc., satellite bands. In the process of dynamic utilization of satellite spectrum, accessing to different spectrum means different benefits for terrestrial users. Low frequency satellite spectrum means less channel fading, while high frequency satellite spectrum faces higher channel attenuation. For terrestrial users, the difference of channel quality will lead to different channel capacity. Therefore, the heterogeneity of satellite spectrum should be considered when developing the satellite spectrum pricing of dynamic spectrum access. In addition, there are significant differences in the flow of different beam cells on the ground, that is, the number of users and traffic flow in different beamcells on the ground are different. The flow in hot spot is large and interference is also large. At the same time, the flow in the unpopular area is small, and the system resources are likely to form idle and waste. At this time, if the spectrum purchased by the satellite users is reused with the hot spot, or the user is located in the hot spot, the spectrum will face greater interference and the transmission income will be affected. However, the satellite users in the unpopular area can obtain relatively high quality spectrum.

As the LEO satellite spectrum is heterogeneous, its corresponding pricing mechanism should be carefully designed. As shown in Fig. 2, the spectrum pool architecture is given in which four kinds of spectrum with different qualities are sold simultaneously. In Fig. 2, four kinds of satellite spectrum are labeled

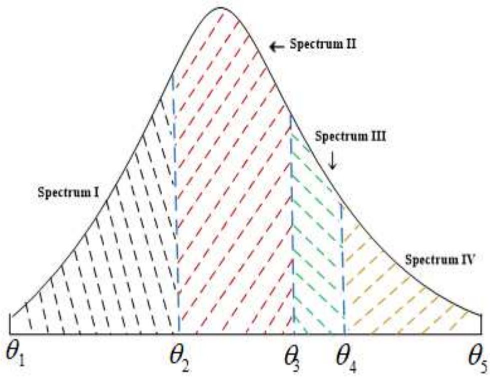

Fig. 2 User spectrum preference distribution

by Spectrum I to Spectrum IV with increasing spectrum quality which means lower inter-cell interference or path fading. In this case, the satellite systems need to segment the spectrum to be sold, and the reasonable pricing should be carried out according to the characteristics of the scene to promote the spectrum sales and increase the system revenue.

For the terrestrial users, they should pick one kind of spectrum to purchase. In this model, we assume that all the satellite idle spectrum can be divided into uniform channel to lease and one terrestrial user can choose one channel with four kinds of potential types for usage. In this case, we define user spectrum preference parameter $\theta \in [\theta_1, \theta_5]$. As shown in Fig. 2, it can be expected that when the preference parameter falls in a given region, the terrestrial user will pick the corresponding kind of spectrum, e.g. when $\theta \in [\theta_2, \theta_3]$, the terrestrial user prefers to use Spectrum II or Spectrum III. In this situation, we define that the terrestrial user will choose Spectrum I only when $\theta \in [\theta_1, \frac{\theta_1+\theta_2}{2}]$, Spectrum II in case of $\theta \in (\frac{\theta_1+\theta_2}{2}, \frac{\theta_2+\theta_3}{2}]$, Spectrum III in case of $\theta \in (\frac{\theta_2+\theta_3}{2}, \frac{\theta_3+\theta_4}{2}]$, and Spectrum IV in case of $\theta \in (\frac{\theta_4+\theta_5}{2}, \theta_5]$. Thus, the utility function of satellite systems can be given as

$$U_s^i = (p_i - M_i)D_i = N(p_i - M_i)\int_{\theta'}^{\theta''} g(\theta)d\theta \tag{2}$$

where p_i denotes the price of spectrum $i(i = 1, 2, 3, or, 4)$, M_i denotes the marginal cost for the satellite systems on spectrum i which means the satellite system needs to discard the potential income in future if it agrees to participant in current spectrum trading. $g(\theta)$ denotes the probability density function (PDF) of the terrestrial user's preference parameter. It can be expected that for Spectrum I, the utility function of satellite systems is as follows

$$U_s^1 = (p_1 - M_1)D_1 = N(p_1 - M_1)\int_{\theta_1}^{\frac{\theta_1+\theta_2}{2}} g(\theta)d\theta \tag{3}$$

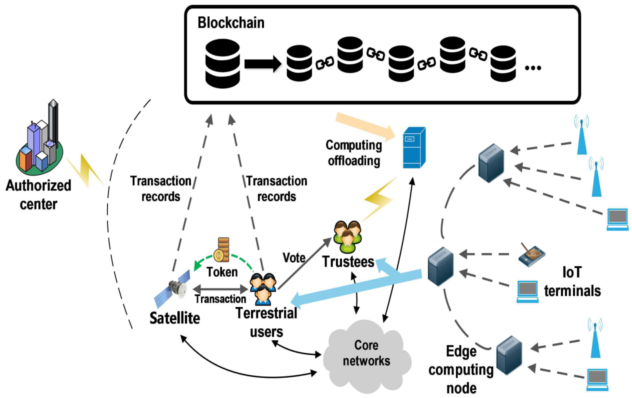

Fig. 3 Framework of the blockchain

On the other hand, for spectrum i, the utility function of a terrestrial user in this spectrum trading can be given as

$$U_t^i = \beta\theta C_i - p_i \tag{4}$$

where θ denotes the terrestrial user's spectrum preference and C_i denote the transmission capacity received by the terrestrial user in given spectrum i. p_i denotes the spectrum price and β is the monetary coefficient which transforms the transmission capacity to uniform pricing unit.

For Spectrum I, its marginal cost can be given as $M_1 = C_1$. Then, to maximize the satellite system's profits, the optimal spectrum pricing for Spectrum I can be expressed as

$$p_1^* = argmaxN(p_1 - \beta C_1)\int_{\theta_1}^{\frac{\theta_1+\theta_2}{2}} g(\theta)d\theta \tag{5}$$

where C_1 can be obtained from (1). In similar, we can achieve the optimal spectrum pricing for Spectrum II, III and IV.

3 Operation of Blockchain

When a large number of nodes access to the satellite IoT system, malicious nodes have a huge threat to the security of spectrum trading, making the system chaotic. In this paper, blockchain, a distributed shared database with the characteristics of unforgetability and data transparency, is applied to the IoT system to build a secure architecture of spectrum sharing for satellite systems.

In Fig. 3, the blockchain-based satellite spectrum trading framework has been given includes the following major components.

- *Authorization center*: Authorization center is the standard and rule maker of blockchain, and initializes the spectrum trading system, public parameters and key, but does not participate in the specific transaction process.
- *Satellite*: Satellite systems are spectrum providers who rent their idle spectrum to terrestrial users.
- *Terrestrial users*: Terrestrial users are the spectrum demanders. They can obtain the corresponding spectrum use rights by paying virtual token to satellite systems.
- *Trustees*: The trustees are elected to be the maintainers of the whole blockchain, who are responsible for collecting the transaction information of the project, then signing and generating certain amount of virtual token as a reward for making contributions to the system.
- *Virtual token*: Virtual token is the transaction token of the IoT transaction system, which is stored in the edge node for virtual transaction.
- *Edge nodes*: The edge nodes are the terrestrial base stations, which are used to the computation of block generation, verify transaction users, conduct spectrum transactions and save transaction records.

The trustees number (T) of the blockchain proposed in this paper will be initiated by the authorization center. Each terrestrial user who holds the token can vote or participate in the election of the trustee. After each round of voting, the T terrestrial users with the highest voting rate will become the trustees of this round of the project. The T trustees are responsible for packing blocks, maintaining the operation of the system and receiving corresponding rewards in turn. If the trustee packs the block wrongly or overtime in his duty turn, a new round of voting will be conducted immediately and a new trustee will be elected to replace him. The blockchain has its own token system, and terrestrial users can obtain tokens by running as a trustee to generate blocks or charging. If terrestrial user wants to rent the spectrum of satellite and has enough tokens, a request will be sent to satellite. After the permission and the transaction is completed, the transaction information will be broadcast to the trustees, and the responsible trustee of the time interval will record the transaction in a new block. The routine for malicious trustee finding and replacing is shown in Algorithm 1 as below.

The choice of consensus algorithm is a core issue of blockchain. Considering the widely used consensus algorithm, Proof of Work (PoW) consensus algorithm has high security, but it wastes the resources seriously and has low network performance. Compared with PoW algorithm, Proof of Stake (PoS) consensus algorithm is more energy saving but the disadvantage is the defect of token circulation. Using the election system, DPoS consensus algorithm shortens the generation time and confirmation time of blocks, greatly improves the system efficiency. And at the same time, it still has the appropriate degree of decentralization. Due to the limitation of computing power of the IoT terminals, the complexity of consensus mechanism needs to be moderate. The

Algorithm 1 Malicious trustee finding and replacing

$slot \leftarrow glob\_time/interv; guar \leftarrow slot \mod T$
if $trustees(guar)$ exist in the node **then**
  while $trustees(guar)$ have not generate new block and it is not malicious **do**
    $slot \leftarrow glob\_time/interv; guar \leftarrow slot \mod T$
    if new $guar == guar + 1$ **then**
      $trustees(guar)$ is malicious
    end if
  end while
  if the record in the new bock generated by $trustees(guar)$ has a wrong transaction **then**
    $trustees(guar)$ is malicious
  end if
  if $trustees(guar)$ is malicious **then**
    for a **do**ll terrestrial users
      vote for a new trustee
    end for
    the user who gets the highest number of votes replace $trustee(guar)$
  end if
end if

consensus mechanism proposed in this paper is based on DPoS consensus algorithm. In DPoS system, with the authorization of the project sponsor, users who holds token can vote. This mechanism makes DPoS reach consensus faster than normal PoS. Generally, all nodes use polling method to generate one block at a tie. This prevents a node from issuing consecutive blocks to perform a double payment attack, and make the nodes do not need to have strong computing power to compete with each other for generating blocks. The algorithm can better match the spectrum allocation of satellite IoT systems.

4 Numerical Results

In this section, we evaluate the performances of the proposed solution from the perspectives of convergence speed of blockchain, spectrum pricing and system profits. At first, in the comparison simulation tests, we assume that all terrestrial users have limited and uniformed computing power. The difficulty value of PoW consensus algorithm is set as D. The difficulty value of PoS varies from $D-4$ to $D+4$ according to the token held, and the difficulty value of DPoS consensus algorithm is $D-4$. In Fig. 4, we give the block generation speed of three consensus algorithms with the increase of difficulty value D. The generating time of PoW consensus algorithm increases greatly. However, although PoS consensus algorithm's speed is low due to the low token age at the beginning, the reduction of speed is very slow. It can be obtained that the DPoS consensus is most efficient of the three.

In Fig. 5, we simulate an IoT scenario with 30 nodes. Due to the influence of token age and the mechanism of clearing out the token age, the time of block generation in PoS consensus algorithm in this network fluctuates. As

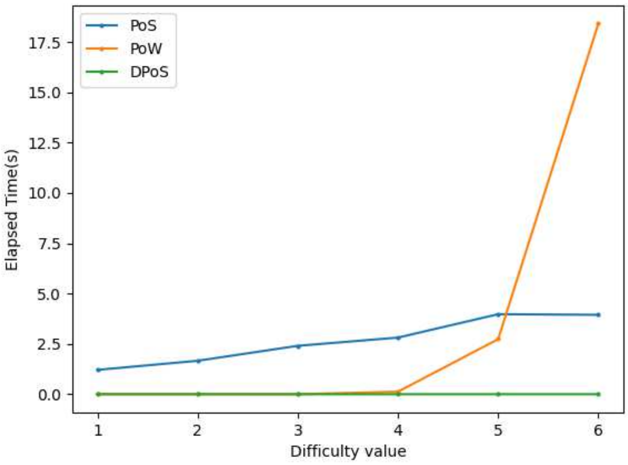

Fig. 4 Block generation time with difficulty value increasing

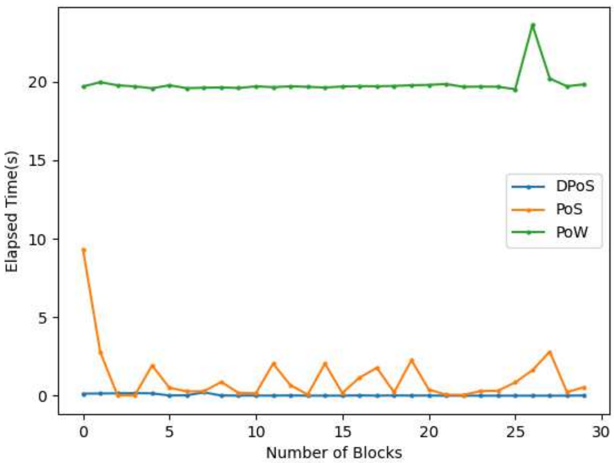

Fig. 5 Block generation time in the system with 30 nodes

shown from Fig. 5, the efficiency of PoW consensus algorithm is the lowest among the three methods while DPoS is the highest.

The optimal spectrum pricing obtained from our solution has been given in Fig. 6. Wherein, better spectrum corresponds to higher spectrum price. As given in (5), the optimal spectrum pricing is affected by various parameters such as N, β, θ. When terrestrial users' spectrum preferences incline to

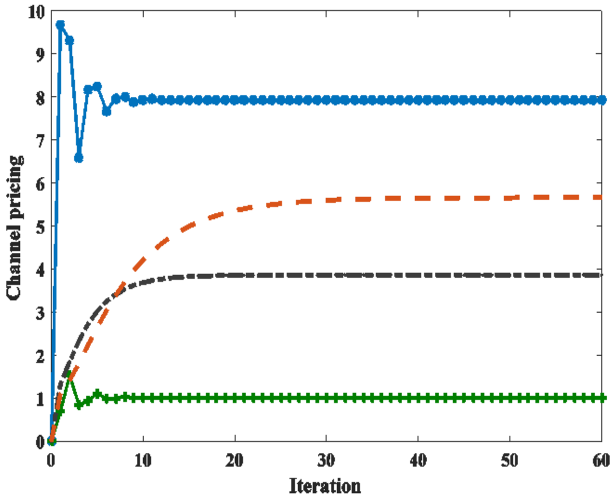

Fig. 6 Channel pricing

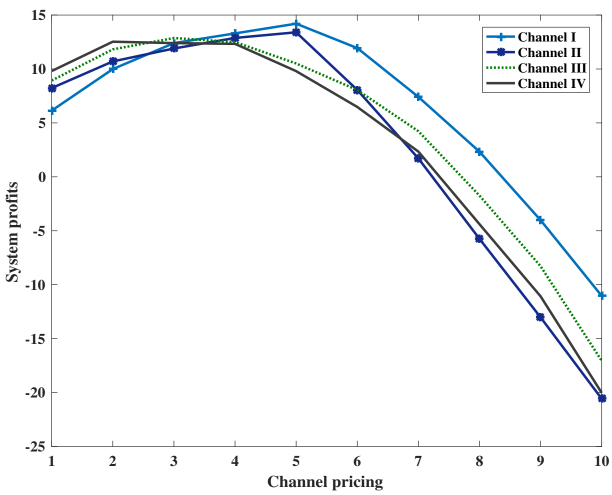

Fig. 7 System profits

high-quality spectrum, the channel pricing of high-quality spectrum will rise. Besides, when parameter N increases which means the terrestrial user's number rises, the channel pricing becomes higher as the spectrum demand goes up.

In addition, in Fig. 7, the system profits are presented with changing spectrum pricing. As shown from Fig. 7, the satellite system's profits will not always benefit from the increase of the spectrum pricing. Too high spectrum pricing will inevitably lead to the decreasing spectrum demand from the terrestrial users which takes effect on the system profits in results. Proper spectrum pricing is a key point to optimize the satellite system's profits and the channel utilization rate.

5 Conclusions

In this paper, a blockchain-based satellite spectrum sharing scheme was proposed in satellite IoT to improve and secure the spectrum utilization. The main contribution of this paper lies in that we introduced the blockchain technology to satellite spectrum optimization for enhancing the security of spectrum sharing in satellite IoT. In 5G+ generation, when massive IoT terminals dynamically access the satellite channels, how to secure the data security and user privacy is a critical issue. In our proposal, we proposed a differential spectrum pricing method by designing a spectrum pool structure to sell four different quality spectrum so as to solve the heterogeneity of LEO satellite spectrum. In addition, we introduce blockchain technology to ensure the security of spectrum trading. To solve the problem of low computing power of satellite IoT terminals, the blockchain is based on DPoS consensus algorithm where the edge nodes are devised to undertake the mining tasks and form the blockchain. Numerical results were further provided to evaluate the convergence speed of blockchain generation and the effects of optimal spectrum pricing on satellite system profits..

Declarations

-Ethical Approval: All listed authors have approved the manuscript before submission, including the names and order of authors.

-Consent to Participate: All listed authors agreed with the content and that all gave explicit consent to submit and that they obtained consent from the responsible authorities at the institute/organization where the work has been carried out, before the work is submitted.

-Consent to Publish: All listed authors approved the version to be published.

-Authors Contributions: Dr. Li Wang proposed the framework of this work, Dr. Feng Li formulated the algorithm, Yuhang Zheng and Yu Zhang performed the simulation tests.

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-Competing Interests: No competing Interests.

-Availability of data and materials: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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