Spectrum Allocation of Multi-Priority Operators Based on Repeated Game for Future Mobile Communication

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***Abstract*—In the new generation of mobile communication systems, the rapidly growing wireless data services require more open spectrum resources and smarter spectrum allocation schemes. At the same time, different kinds of services may require different levels of spectrum resources. In order to solve the above problems, a multi-priority operators' model is proposed to solve the more complex spectrum allocation problem. By dividing the operators into multiple priority levels and price the spectrum, an infinitely repeated game model is built. Through simulation, the changes of press value over time when using different strategies for multiple operators are compared. The results show that the channel allocation strategy based on the multi-priority repeated game model performs better on system revenue than the non-cooperative full-spectrum sharing strategy after stabilization.**

***Index Terms*—Repeated game, spectrum allocation, multi-priority**

I. Introduction

In recent years, the amount of wireless communication data has ushered in an explosive growth. In order to alleviate the pressure on spectrum resources, a large amount of unlicensed spectrum has been opened up for use. Related spectrum allocation and sharing technologies are also emerging [1]-[3]. At present, different operators are encouraged to make the most of unlicensed spectrum, and there is no unified and effective cooperation plan, it is easy to cause the loss of efficiency due to interference from other services, which is also known as the tragedy of the commons [4].

There is a certain degree of competition among operators, which are inherently selfish. At the same time, the strategies that operators may adopt are also complicated. Regarding the issue of spectrum allocation among operators, it cannot be considered simply by means of overall planning and optimization. Considering the complexity of the dynamic spectrum allocation process, it is natural to introduce related concepts of game theory. There have been some researches on spectrum allocation schemes based on non-cooperative games. In 2007, R. Elkin et al.[5] first introduced game theory to study the problem of spectrum allocation. They use Shannon capacity as a utility function, and treat interference from other operators as noise, and each operator is bound by the total transmit power. At the same time, Raul et al.[6] proved that the segmented constant power distribution can achieve any Pareto efficiency vector in full cooperation. However, in the case of non-cooperation, formulating an appropriate punishment strategy will significantly reduce the debuffs in the game. In [7], considering the power and interference phenomena in cognitive radio, a mathematical model of game theory was established, but the problem of spectrum allocation was not involved. In [8], a proof analysis is given for the algorithm convergence of game theory in the spectrum allocation problem, which provides a theoretical basis for the feasibility of game theory in the spectrum allocation problem. In [9], Niyato et al. proposed a game for secondary users to compete for the amount of free spectrum, and used the Cournot model for analysis. Reference [10] introduced how to use the concept of game theory when designing spectrum sharing protocols, and looked forward to efficient, self-enhanced and distributed spectrum sharing solutions in future wireless networks. In [11], the author proposed a spectrum decision-making scheme based on game theory called EGSD(energy-efficient game-theory-based spectrum decision), which has a longer lifespan and lower overhead compared with traditional schemes. Reference [12] proposes a spectrum sharing scheme that optimizes resources in unlicensed frequency bands based on decision tree learning and repeated games, but the resource cost is huge. A heterogeneous network general model that jointly optimizes unlicensed and licensed frequency bands was proposed in [13] based on game theory, but it is not suitable for actual deployment. The author of [14] designed a pricing mechanism for multiple operators to negotiate power usage in unlicensed spectrum.

In this article, a multi-priority operators spectrum allocation method is proposed based on the repeated game mechanism. Operators are treated as completely rational agents. Without a penalty mechanism, all operators will maximize their own interests, that is, use non-cooperative strategies to occupy the entire spectrum as much as possible. However, this deviating behavior will be punished to a certain extent. The change of the expected income is charged by penalty tax in the case of betrayal to ensure the trust system. For operators of different levels, different penalties are used to restrict the channel occupation behavior of low-priority operators.

The rest of this paper is organized as follows. In Section II, the repeated game model based on penalty tax mechanism

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Fig. 1. The transformation of punishment and cooperation state.

is introduced. Section III focuses on the spectrum allocation strategy of multi-priority operators based on repeated games proposed in this paper, and gives the theoretical derivation and applicable conditions of the method. Numerical simulation and discussion are conducted in Section IV to provide comparisons between the proposed scheme and the non-cooperative full-spectrum sharing strategy. Finally, the paper is concluded in Section V.

II. System Model

Assume that *N* operators share a certain frequency band of one or more unlicensed spectrum, and the operators can monitor each other's transmit power. Repeated game can be described as super-game formed by repeated games of the same structure. The repeated meta-games are also called stage games. The spectrum competition between users is modeled as a series of stage games on time slots. The network load strength of operator *i* in time slot *t* is defined as the traffic level during this time slot. Assuming that the operators' traffic load intensity varies randomly in each time slot, The traffic load intensity of each time slot and operator priorities are used as the basis for spectrum allocation. Each operator determines its transmission PSD(Power Spectral Density) at the beginning of each time slot based on a priori information, and keeps it on a single time slot.

In the repeated game, all parties should consider long-term benefits. Participants must consider the benefits of the game at this stage, and at the same time, consider that their strategy will not cause other participants to adopt retaliatory strategies in the future. During spectrum allocation, under unrestricted circumstances, operators will lie about their own network load strength and maximize the use of spectrum resources. Adopting a strategy of misrepresenting its own strength may result in a higher short-term profit for a single operator, but it will harm the overall profit. Therefore, it is necessary to punish this breach of contract that undermines cooperation between operators in order to maximize the overall benefits. Take the game process of two operators as an example, the transition between the cooperative state and the penalty state is shown in Fig. 1.

The entire repeated game process is shown in Fig. 2, where OP*X* refers to the *X*th operator that participates in the game on this frequency band. In the repeated game process, if the operator finds that the opponent has deceptive behavior, it will not choose to immediately and permanently suspend the cooperation, but will reduce the revenue of the deceptive behavior by imposing a penalty tax. For operators of different priorities, different penalty tax levels are set to achieve multi-priority resource allocation. As it can be seen from the picture, in time slot *T*, a certain operator OP1 committed a betrayal, falsely reported its own network load intensity, and was discovered by other operators. Then, the operator enters the penalty state, that is, pays the penalty tax according to its own priority in the press value of the time slot *T*, and then returns to the cooperative state.

If operators choose to cooperate, they will conduct spectrum transactions based on the traffic intensity reported at each stage, and operators with high traffic intensity will lease spectrum from operators with low traffic intensity. And in the transaction process, when the traffic intensity of multiple operators is high, the operator with the higher priority will conduct the transaction first. The specific algorithm of spectrum trading is as follows:

a. In the algorithm initialization stage, each operator divides the spectrum orthogonally and clears the balance value to zero. Assuming that the total bandwidth of the spectrum is W_0 and the number of operators is N, the initial bandwidth of each operator is $W_i = W_0/N$, the balance value is $B_i = 0$, and the maximum balance value is $B_0 = k\Delta$, where k is a constant, Δ is the smallest spectrum trading unit;
b. Each operator reports and learns the traffic levels L_i and L_{-i} of other participants. Where L_i is the traffic intensity of operator i, and L_{-i} represents the traffic intensity of all operators except operator i;
c. The operator whose traffic intensity is reported as high is defined as set A_0, and the operator whose traffic intensity is reported as low is defined as set A_1, let $s = min\ \{\mid A_1 \mid, \mid A_0 \mid\}$, for any $i \leq s$, the $i-th$ operator with the highest priority in A_0 leases ΔHz from the $i-th$ operator with the lowest priority in A_1 and updates the balance of both. If no transaction is required, the bandwidth and balance at this stage are kept unchanged for transmission.

III. Multi-priority Repeated Game Spectrum Allocation

The total return of the repeated game is the sum of the discounted returns of each stage of the game called present value. The discount factor can be understood as the probability or patience of the participants to continue participating in the next game. The normalized present value is used as the operator's benefit indicator in the game process as follows.

$$\bar{\pi_i} = (1-\delta)\sum_{t=1}^{\infty}\delta^{t-1}\pi_i^t(\lambda_t), \tag{1}$$

where δ represents the discount factor, u_i^t represents the utility function of time slot *t* for operator *i*. λ_t represents the network load strength of time slot *t* for operator *i*.

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TABLE I
MULTI-PRIORITY SPECTRUM ALLOCATION PARAMETERS

Parameter Name	Parameter Value
Total Bandwidth	100MHz
Channels	10
Operators	2(3,4)
Priority	{1,2,3}
Maximum Transmit Power	20dBm
Minimum Rental Unit	10MHz
Maximum Balance	3

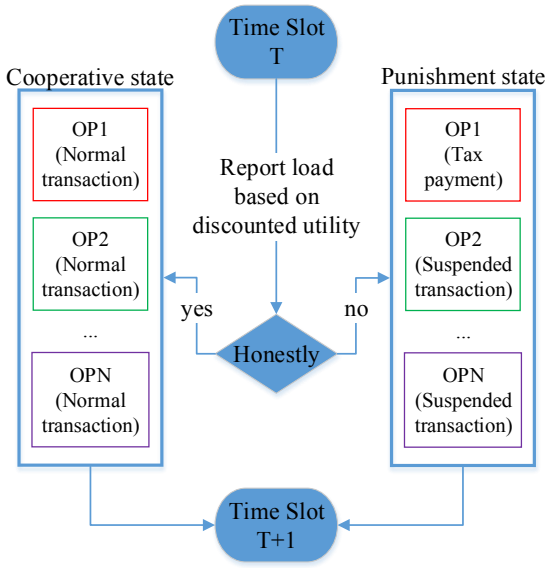


Fig. 2. The specific process of the transformation of the cooperative state and the punishment state in the process of repeated games.

The benefit function is determined by the system capacity and spectrum utilization together. According to Shannon's formula, that is

$$\pi_i^t = \lambda_t^i W_i^t \log_2\left(1 + \frac{p_i^t}{n_0 + \sum_{j \neq i} p_j^t}\right), \tag{2}$$

where W_i^t represents the spectrum bandwidth allocated by the operator for the time slot, p_i^t represents the power spectral density.

In the process of repeated game, if the operator finds that the opponent has deceptive behavior, it will not permanently suspend the cooperation. However, the opponent will enter a state of punishment for a period of time. This process is implemented by imposing penalty tax to reduce the benefit of deception. For operators of different priorities, different levels of penalty tax are set to reduce the interference caused by low priority.

Assuming that operator *i* adopts a deception strategy in time slot *T*, its benefit is

$$\bar{\Pi}_i = (1-\delta)\left(\sum_{t=1}^{T-1} \delta^{t-1}\pi_i^t + (1-\beta)\gamma^i \varpi_i^T + \sum_{t=T+1}^{\infty} \delta^{t-1}\pi_i^t\right), \tag{3}$$

where β represents the penalty tax factor, γ^i stands for the priority function of operator *i*, v_i^T represents the benefit at this stage when the deception strategy is adopted.

It can be seen that when the condition of $\bar{\pi}_i > \bar{\Pi}_i$ is met, operators will continue to adopt cooperative strategies to ensure the maximization of overall benefits, which is

$$\beta > \frac{\gamma^i \varpi_i^T - \pi_i^T}{\gamma^i \varpi_i^T}, \tag{4}$$

The priority function of the operator is determined by the predetermined priority and the average load intensity, namely

$$\gamma^i = \left(\bar{\lambda} e^{n_i}\right)^{-1}, \tag{5}$$

where $\bar{\lambda}$ refers to the average historical load intensity, and n_i refers to the integer priority set in advance due to the type of service and spectrum requirements.

IV. SIMULATION RESULTS

This section will simulate the multi-priority spectrum allocation algorithm based on repeated games proposed above, and then analyze the simulation results. Consider the situation where operators of different priorities compete with each other. The total bandwidth of the system is 100MHz, including 10 channels. The maximum transmit power is 20dBm, the network load intensity changes randomly with time. The parameters involved in the simulation process are detailed in the table below.

When the number of operators is two, the comparison of the utility functions of these methods is shown in Fig. 3. At the beginning of the simulation, due to the orthogonal equal distribution, the bandwidth of the operators is the same. As time and traffic intensity change, operators continue to lease spectrum and finally stabilize. The multi-priority repeated game method quickly reached stability, the final utility was higher than the orthogonal spectrum sharing strategy, and much higher than the full spectrum sharing strategy.

When the number of operators increases, for example to four, the operators' utility function is shown in Fig. 4. At this time, the spectrum trading scheme adopted by operators has changed: high-priority operators are more likely to obtain the released spectrum when their own traffic intensity is reported as high, while low-priority operators have to wait. It can be seen that in the initial stage, the strategy of full-spectrum can achieve greater short-term benefit. This is because the spectrum width allocated by the operator at this time is much lower than the spectrum width when full spectrum sharing is adopted. However, when the system quickly stabilizes, the balance achieved by repeated games can achieve higher system benefit. Operators have adopted mutual cooperation strategies

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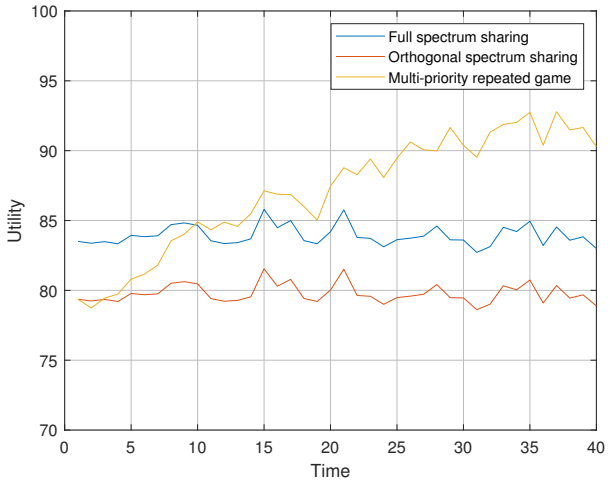


Fig. 5. Changes in the utility functions when the number of channels changes.

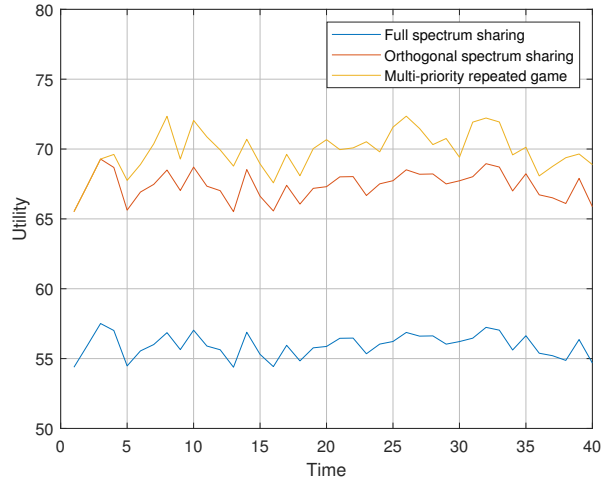


Fig. 3. Changes in the utility function between two operators.

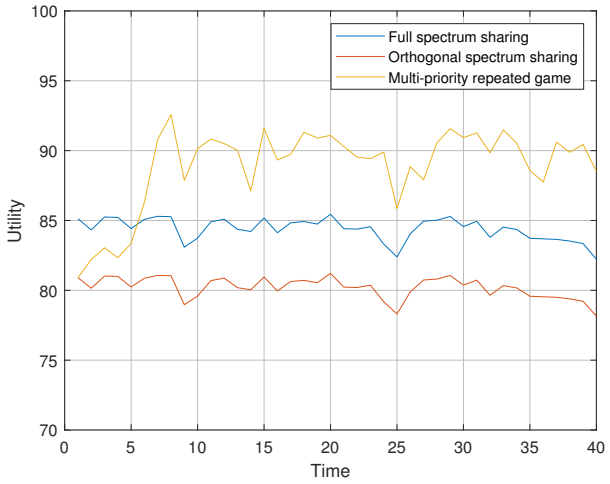


Fig. 4. Changes in the utility function between more operators.

and continuously leased spectrum to realize resource allocation according to changes in traffic intensity, so they have achieved higher returns than non-cooperative strategies, and eventually stabilized. This shows that if appropriate penalties are taken, operators of different priorities will be in a cooperative state for a long time to share spectrum resources. This can achieve better results than general methods.

When keeping the number of operators unchanged, and increasing the number of channels, the result is shown in Fig. 5.

In the simulation, the number of channels increased from 10 to 40. The results shows that the speed of iteration in the transaction process slows down. In other words, the granularity of the transaction process is increased. On the one hand, the convergence time based on the repeated game method will increase slightly. On the other hand, it avoids the phenomenon that the bandwidth allocated by the operator will be quickly reduced to zero due to the low priority, and it becomes difficult to increase it later.

V. Conclusion

In this article, a spectrum allocation strategy for multi-priority operators based on repeated games is proposed, and the competition for spectrum resources between operators is modeled as an infinitely repeated game with complete information. Operators with low load intensity will transfer spectrum to operators with higher load intensity, and use the penalty tax mechanism to avoid operators' behavior of falsely reporting their own load intensity. The amount of the penalty tax is related to the operator's priority, making low-priority operators more inclined to adopt a cooperative attitude, thereby reducing interference to high-priority operators. Finally, through simulation, it is proved that compared with the general method, when the traffic intensity changes in real time and the operators' services have different spectrum requirements, the use of the spectrum allocation strategy of multi-priority operators based on repeated games can achieve higher system revenue.

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