Towards A Game Theoretical Modeling of Rational Collaborative Spectrum Sensing in Cognitive Radio Networks

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***Abstract*—Collaborative spectrum sensing has been proposed recently to improve the sensing performance in Cognitive Radio networks. However, cooperative sensing will also introduce extra cost to the collaborator, such as the cooperative time and energy consumption. In reality, whether the rational secondary users have incentive to join the collaboration depends upon whether the benefit of the collaboration could outweigh the cost. In this paper, we model it as the Cooperative Spectrum Sensing Game (CSSG). In this game, every secondary user could choose to collaborate or not in each time slot, and the payoff is measured in terms of data throughput. Since the effectiveness of collaboration is proportional to the number of the collaborators, secondary users' decisions are based on how many users will choose to collaborate. Thus, CSSG could be modeled as the classic game: the Stag Hunt Game. In addition, to avoid the cooperation failure, we propose Cooperative Communication Incentive Scheme (CCIS) to enhance the collaborative sensing. At last, the numerical analysis about CSSG as well as the proposed scheme CCIS is given.**

Keywords – **Cognitive Radio, Collaborative Spectrum Sensing, Selfish Behavior, Incentive Issue in Collaboration**

I. Introduction

The ever increasing spectrum demand owing to the emerging wireless applications has inspired the conception of Cognitive Radio (CR) [1], which is proposed to improve the utilization of the precious resource, radio spectrum. Different from the traditional spectrum management paradigms in which most of the spectrum is allocated to fixed licensed users or primary users for exclusive use, a CR system allows unlicensed users or secondary users to utilize the idle spectrum as long as intolerable interference to primary users is not introduced.

To achieve such a dynamic spectrum access system, accurate spectrum sensing by secondary users is necessary. Existing methods for spectrum sensing could be classified as energy detection and feature detection based approach. In energy detection methods, a signal strength exceeding a certain threshold will be identified as the existence of primary user [2]. In feature detection methods, secondary user tries to discover primary users by their features, such as a pilot, a synchronization word, or a cyclostationarity [3]. However, the performance of these two methods could be degraded by shadowing as well as multipath fading. In addition, due to the high accuracy requirement of spectrum sensing in CR system, the cost of the detector is not ignorable. To deal with these problems, collaborative spectrum sensing is proposed, in which sensing results by divergent secondary users are collected and fused to make more accurate judgements towards the spectrum. According to [4]- [7], the collaboration between secondary users brings about better detection performance and lower implementation cost by diversity.

However, most of the existing collaborative sensing schemes assume all the secondary users are willing to collaborate. In reality, some rational (selfish) secondary users may refuse to provide the sensing results to save energy or transmission time, while still enjoying those from others. Such kind of free-riders may seriously disrupt the collaborative sensing. To enhance the collaboration, recently several researchers investigate this incentive problem from the perspective of Game Theory.

Existing works [8], [9] mainly focus on the incentive problems of the free-rider in collaborative sensing. However, even though free-riders are regarded as a serious threat of collaborative sensing, it is necessary to clearly distinguish the free-riders from rational secondary users who may not choose to collaborate with others in the case that the benefit in cooperation is less than the cost of performing collaborative sensing. We believe that a practical collaborative sensing system should allow each individual to have the full freedom to choose whether to collaborate or not. The existence of rational collaborative sensing may lead to the failure of cooperation in the two cases: Firstly, the secondary users may be reluctant to collaborate with others due to limited number of secondary users in the system, which cannot lead to an overall cooperation gain even with a collaborative sensing; In the second case, even though there exists a sufficient number of secondary users, they may still choose not to collaborate due to lack of the mutual trust or collaboration history. The former case justifies the situations that a rational secondary user has the right not to collaborate while the latter case is not expected due to the disruption of collaborative sensing. Therefore, it is desirable to establish a rational collaborative spectrum model to distinguish them and investigate the potential techniques to stimulate the rational nodes to collaborate in the second case.

In this paper, we propose a Collaborative Spectrum Sensing Game (CSSG) to study this selfishness model. In this game, each secondary user could choose to collaborate or not, and only the collaborators could enjoy the benefit of the cooperation. Because the effectiveness of the cooperation depends on the number of the sensing secondary users, whether the benefit could outweigh the cost and whether secondary users have incentive to collaborate is based on how many secondary users will choose to collaborate. From this perspective, Collaborative Spectrum Sensing Game could be modeled as the classical game: the Stag Hunt Game [10]. Then we discuss the Nash equilibrium of the CSSG, and propose a Cooperative Communication Incentive Scheme (CCIS) to stimulate the rational secondary users even in the case of no mutual trust. The basic idea of CSSG is to introduce a periodically available trusted authority (TA) to compensate the secondary users who suffer losses in the collaborative sensing and this promise is expected to enhance the collaborative sensing when there are enough secondary users in the networks but no trust among them.

To the best of our knowledge, this is the first work towards modeling and investigating rational collaborative spectrum sensing issue. The remainder of this paper is organized as follows. The preliminary is given in section II. In section III, CSSG and its Nash equilibrium are discussed and CCIS is proposed. A numerical analysis is shown in section IV, and the conclusion is given in section V.

II. PRELIMINARY

In this section, we will introduce spectrum sensing, collaborative spectrum sensing as well as the Stag Hunt Game.

A. Spectrum Sensing

The objective of spectrum sensing is to detect whether a certain spectrum is occupied by the primary user. The basic method to sense the spectrum is to scan and analyze the signal $r(t)$ in this spectrum, which could be described as follows:

$$r(t) = \begin{cases} hs(t) + w(t) & if\ H_1 \\ w(t), & if\ H_0 \end{cases}$$

where $s(t)$ is the signal transmitted by the primary user, $w(t)$ is the additive white Gaussian noise(AWGN), and h is the amplitude gain of the channel. H_1 and H_0 denote the hypothesis that primary user is present and the hypothesis that the primary user is absent, respectively. Then to sense the spectrum is to decide between the two hypotheses.

Assume the energy detector is used to sense the spectrum, and the probability of detection and false positive is [5]:

$$P_f = \Pr\{Y > \lambda | P_j = -1\} = \frac{\Gamma(m, \lambda/2)}{\Gamma(m)}$$
$$P_d = e^{-\frac{\lambda}{2}} \sum_{k=0}^{m-2} \frac{1}{k!}\left(\frac{\lambda}{2}\right)^k + \left(\frac{1+\bar{\gamma}}{\bar{\gamma}}\right)^{m-1}$$
$$\times \left(e^{-\frac{\lambda}{2(1+\bar{\gamma})}} - e^{-\frac{\lambda}{2}} \sum_{k=0}^{m-2} \frac{1}{k!}\left(\frac{\lambda\bar{\gamma}}{2(1+\bar{\gamma})}\right)^k\right) \quad (1)$$

where $\Gamma(\cdot)$ and $\Gamma(\cdot,\cdot)$ are complete and incomplete gamma functions respectively, $\bar{\gamma}$ is the average SNR determined by path-loss and the transmitted power of the primary user, λ is the threshold, and $m = TW$ is the time-bandwidth product.

B. Collaborative Spectrum Sensing

We consider the centralized collaborative sensing [11], in which a fusion center (or a selected secondary user [12]) in the network will collect the sensing reports from the secondary users, and combine them to make final decision on spectrum availability. Since the fusion center may not take the task of spectrum allocation (in non-cooperative sharing scenario, etc.), the center is required to broadcast the final decision.

Similar with [8], collaborative sensing is required to be implemented synchronously, and the time slot could be $T = t_s + t_r + t_d$, which is illustrated in Fig. 1. t_s is the time that the spectrum sensing will take, t_r is the time for cooperation, and t_d is the time for data transmission. In this paper, we assume

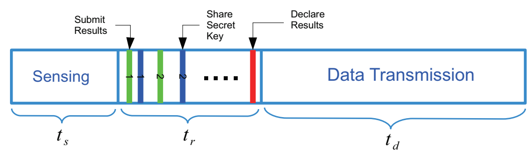

Fig. 1. The illustration for collaborative spectrum sensing

in each time slot any secondary user could choose to join the collaboration which will cost him t_r time, or to sense the spectrum by himself, having more time for data transmission. We also assume just the secondary users who contribute to the collaboration could receive the final decision from the center, and the other users couldn't access this information. This requirement could be realized by sharing a secret key between the center and the collaborators.

In addition, we suppose there are M spectrums in the environment, and these spectrums are owned by M primary users, respectively. We use the set $\{T_1, T_2, \ldots, T_M\}$ to denote these spectrums. Similarly with [9], we suppose a certain spectrum will be divided into K sub-bands, and each secondary user could operate exclusively in one of them. In this paper, we assume K is equal or greater than the number of secondary users, and the secondary users could just access a single spectrum at once. Let C_k^0 denote the data rate that a secondary user will have when the busy spectrum T_k is utilized, and C_k denote the data rate when the idle spectrum T_k is used. Here, we assume $C_1 > C_2 > \cdots > C_M$.

C. the Stag Hunt Game

Stag Hunt game, also known as trust dilemma, is a classical game model in Game Theory. In this game, the two hunters could choose to hunt a stag or to hunt a hare (which is less valuable than the stag), and If a hunter chooses to hunt stag, he should have the cooperation of the other, or he will fail. On the contrary, hunting a hare could be achieved by himself. further, when each hunter makes his decision, one has no idea about the choice of the other. Should the hunter hunt the stag at the risk of being not trusted and end up with failure, or safely hunt a hare? That depends upon the other hunter's decision.

III. Collaborative Spectrum Sensing: A Stag Hunt Game

In this section, we will first introduce the collaborative spectrum sensing game, then we will analyze the payoff functions and the equilibrium of this game.

A. Collaborative Spectrum Sensing Game

In Cognitive Radio network, the secondary users could form the cooperation group to improve their sensing performance. Typically, they should first submit their sensing reports to a fusion center (or selected secondary user), where the reports are aggregated and declared. By such way, the sensing performance could be improved, and these users can discover better radio spectrum resources to transmit their data. However, cooperation also incurs system overhead, such as the lose of transmission time. When the benefit of cooperation is less than its cost, secondary users will choose to quit, and the collaborative sensing will fail. Notice that the benefit of the cooperation is proportional to the collaborator number, therefore whether the cooperation fails depends on the users' number in the network and their decisions about whether to cooperate. In the following, we propose the collaborative spectrum sensing game to further analyze this problem:

Definition 1: *The Collaborative Spectrum Sensing Game is the Game*

$$G =< N, \{a_i\}, \{U_i\} >$$

- $N = \{s_1, s_2, \ldots, s_N\}$ is the set of the players.
- a_i is the strategy of the user s_i. Let $a_i = 1$ denote s_i decides to collaborate, and $a_i = 0$ denote the reverse.
- U_i is the payoff of the secondary user s_i, and it is measured from the aspect of data throughput.

Further, we will discuss the payoff function and the Nash equilibrium of this game.

B. The Payoff Function of The CSSG

First of all, we investigate the payoff of a secondary user who doesn't participate in collaboration. In this paper, the payoff of the user is defined as its throughput expectation. We assume P_D is the targeted primary user detection probability which is required by the CR system. According to the equation (2), a certain secondary user $s_i, i \in N$ will have the corresponding set of false positive rate $\mathcal{P}_{Fi} = \{P_{Fi}^1, P_{Fi}^2, \cdots, P_{Fi}^M\}$ towards the M spectrum. In the meantime, his throughput of utilizing the spectrum that gets the data rate C is:

$$\overline{C} = \frac{t_r + t_d}{t_s + t_r + t_d} C \tag{2}$$

Then we could get the following conclusion:

Lemma1: *Given the targeted detection probability P_D and false positive set $\mathcal{P}_{Fi}$, the payoff of the secondary user s_i who doesn't participate in the cooperation is:*

$$E(U_i) \approx \sum_{k=1}^{M} [\overline{C}_k (p_0^k - p_0^k p_{Fi}^k) \prod_{j=1}^{k-1} (1 - p_0^j - p_{Fi}^j p_0^j)] \tag{3}$$

Where p_0^k is the rate that T_k is idle, and $p_1^k = 1 - p_0^k$.

Proof: Let $T_k = u$ denote that the spectrum T_k is utilized by the secondary user, and $T_k = N$ denote the reverse case. Thus, the expectation of the secondary user s_i's payoff is:

$$E(U_i) = \sum_{k=1}^{M} E(U_i(k)) \tag{4}$$

where $U_i(k)$ is the payoff of the secondary user s_i when the spectrum T_k is utilized. Since the spectrum who gets the higher data rate will have the higher priority to be chosen, in our defined model the spectrum T_1 has the highest priority. Thus, the secondary user s_i's payoff expectation of utilizing T_1 is:

$$\begin{aligned} E(U_i(1)) &= \mathbb{P}(T_1 = u | H_0^1) \overline{C}_1 + \mathbb{P}(T_1 = u | H_1^1) \overline{C_1^0} \\ &= p_0^1 (1 - p_{Fi}^1) \overline{C}_1 + p_1^1 (1 - p_D) \overline{C_1^0} \end{aligned} \tag{5}$$

Because in the CR system, the targeted detection probability is closely equal to 1, and $\overline{C_1^0}$ is very low due to the interference from the primary user, then equation (5) can be written as:

$$E(U_i(1)) \approx p_0^1 (1 - p_{Fi}^1) \overline{C}_1 \tag{6}$$

The payoff expectation of utilizing the spectrum T_k is:

$$\begin{aligned} E(U_i(k)) &= \mathbb{P}(T_k = u | H_0^k, T_1, T_2, \ldots, T_{k-1} = N) \overline{C}_k \\ &+ \mathbb{P}(T_k = u | H_1^k, T_1, T_2, \ldots, T_{k-1} = N) \overline{C_k^0} \\ &\approx \overline{C}_k (p_0^k - p_0^k p_{Fi}^k) \prod_{j=1}^{k-1} (1 - p_0^j - p_{Fi}^j p_0^j) \end{aligned} \tag{7}$$

Then we could rewrite the equation (4):

$$E(U_i) \approx \sum_{k=1}^{M} [\overline{C}_k (p_0^k - p_0^k p_{Fi}^k) \prod_{j=1}^{k-1} (1 - p_0^j - p_{Fi}^j p_0^j)] \qquad \blacksquare$$

Secondly, consider the secondary user who has participated in the collaboration. We assume n secondary users choose to collaborate, and they belong to the set $Q = \{s_{q1}, s_{q2}, \ldots, s_{qn}\}$. Then a single collaborator's throughput of utilizing the spectrum that gets the data rate C is:

$$\widetilde{C} = \frac{t_d}{t_s + t_r + t_d} C \tag{8}$$

We could find when a certain spectrum is used, the throughput of the cooperative secondary user decreases, because it takes the user t_r time to cooperate. However, the improved detection performance enables the secondary user discover better spectrum resources to transmit the data. Whether the cooperation could increase the secondary user's throughput depends upon how much the performance has been improved. In the following, we will discuss it.

In this paper, we assume the fusion center uses the Majority rule to combine the sensing results, which means that a spectrum will be determined available when the majority of the users detect the spectrum available. The fusion process is as follows: firstly the collaborators share their observed energy with the fusion center; then based on the number of the collaborators the fusion center determines the proper threshold each collaborator should have; at last the center gets the collaborators' decision and combines them. We assume each collaborator has the same detection rate P_d^k towards the spectrum T_k individually, then we could have:

$$P_D = \sum_{g=\lfloor \frac{n}{2} \rfloor+1}^{n} \binom{n}{g} (P_d^k)^g (1-P_d^k)^{n-g} \quad (9)$$

By numerical calculation, we could obtain the value of P_d^k and therefore P_{Fqi}^k according to the equation (2). After the collaboration, each collaborator will have the false positive probability P_f^k towards the spectrum T_k:

$$P_f^k = \sum_{g=\lfloor \frac{n}{2} \rfloor+1}^{n} \sum_{A \in F_g} \prod_{i \in A} P_{Fqi}^k \prod_{j \in A^c} (1-P_{Fqj}^k) \quad (10)$$

where F_g is the set of all subsets of g integers that can be selected from $\{q1, q2, \cdots, qn\}$, A^c is the complement of A. Then, we could have the following conclusion:

Lemma2: *Given the targeted detection probability P_D, the set of cooperative secondary users Q and their false positive rate, the payoff of the secondary user $s_{qi}, i \leq n$ is:*

$$E(\overline{U}_{qi}(n)) \approx \sum_{k=1}^{M} [\widetilde{C}_k (p_0^k - p_0^k P_f^k) \prod_{j=1}^{k-1} (1 - p_0^j - P_f^j p_0^j)] \quad (11)$$

Proof: similarly, we could obtain:

$$E(\overline{U}_{qi}(n,k)) \approx \widetilde{C}_k (p_0^k - p_0^k P_f^k) \prod_{j=1}^{k-1} (1 - p_0^j - P_f^j p_0^j) \quad (12)$$

Then, we could get the result. ■

C. The Nash Equilibrium of CSSG

In this section, we will discuss the Nash equilibrium in CSSG. A Nash Equilibrium is defined as a set of strategies, in which no player has incentive to deviate unilaterally. According to this definition, we have following conclusions:

Theorem 1: *In CSSG, the strategy that all players choose to collaborate is a Nash Equilibrium if $E(\overline{U}_{qi}(n)) > E(U_{qi})$*

Proof: Let $a^* = \{a_1^*, a_2^*, \ldots, a_n^*\}$ denote the strategy profile that all secondary users choose to collaborate. If the user s_i deviates the strategy a_i^*, then

$$u_i(a_i, a_{-i}^*) = E(U_i) < E(\overline{U}_i(n)) = u_i(a^*) \quad (13)$$

Thus, when $E(\overline{U}_i(n)) > E(U_i)$, a user will gain less by unilaterally deviating a^*, and all players choose to cooperate is an Nash equilibrium. ■

Theorem 2: *In CSSG, the strategy that all players choose not to collaborate is a Nash Equilibrium.*

Proof: Similarly, let $a^* = \{a_1^*, a_2^*, \ldots, a_n^*\}$ denote the strategy profile that all secondary users choose not to collaborate. if the user s_i deviates the strategy a_i^*, then

$$u_i(a_i, a_{-i}^*) = E(\overline{U}_i(1)) = \frac{t_d}{t_r + t_d} E(U_i) \quad (14)$$

We could obtain:

$$u_i(a_i, a_{-i}^*) < E(U_i) = u_i(a^*) \quad (15)$$

Thus, the strategy that all players choose not to collaborate is a Nash Equilibrium in this game. ■

Since this game will be played sequentially, in each time slot secondary users could learn from the previous time slot and makes their own decision. As the result of learning or evolution in this game, the game will finally approximate the Nash equilibrium. Thus, when $E(\overline{U}_{qi}(n)) < E(U_{qi})$, the game will end up with no collaborators. On the contrary, when $E(\overline{U}_{qi}(n)) > E(U_{qi})$, the results of the game may be that every secondary user joins the collaboration, or that no one joins. Which Nash equilibrium will appear depends on the startup phase as well as the development of the game.

D. The Avoidance of Cooperation Failure

Collaborative sensing will fail in the case that there are not enough secondary users to satisfy $E(\overline{U}_{qi}(n)) > E(U_{qi})$ or in the case that although users are sufficient, they don't believe other ones are willing to participate in the collaboration. To address this problem, we propose our Cooperative Communication Incentive Scheme(CCIS) to enhance the collaboration. The basic idea of CCIS is to change the payoff matrix of the game, giving the secondary users concrete benefit to inspire them to collaborate. In CCIS, a periodically available trusted authority (TA) is introduced, and when the secondary users suffer losses during the cooperation, they could turn to the TA for compensation (e.g., using the relay to help transmit their data during transmission time). To prevent collusion attack in which a certain amount of nodes collude to cheat for more data transmission, TA should contact both of fusion center and secondary users for cross-checking. If the failed collaborative spectrum sensing with sufficient sensing nodes are confirmed by both of fusion center and secondary users, the compensation will be triggered. In this scheme, the amplify and forward method [13] is adopted, and we assume the helper node could help a secondary user increase the data rate from p to $(1+h)p$. We also assume in a certain slot just the users $\{s_{p1}, s_{p2}, \ldots, s_{pb}\}$ join the collaboration, and each user s_{pi} suffers the loss $E(U_{pi}) - E(\overline{U}_{pi}(b))$. Then the time T_h^i during which fusion center will help the user s_{pi} is:

$$T_h^i \geq \frac{t_d(E(U_{pi}) - E(\overline{U}_{pi}(b)))}{hE(\overline{U}_{pi}(b))} \quad (16)$$

By this way, secondary users are motivated to cooperate with each other, and the overhead on the fusion center is not much.

IV. Numerical Analysis

In this section, we will give the numerical analysis about the CSSG and our proposed scheme CCIS. We assume that there are 3 spectrums $\{T_1, T_2, T_3\}$, and each of them is owned by a single primary user. Meanwhile, we set $C_1 = 100$ kbps, $C_2 = 60$ kbps, $C_3 = 20$ kpbs, $p_1^1 = 0.4$, $p_1^2 = 0.2$ and $p_1^3 = 0.1$. The time-bandwidth product is $m = 5$. We consider the Rayleigh Fading environment, and the average SNR $\bar{\gamma}$ is $10dB$. We also assume the time $t_s = 10ms$, $t_r = 20ms$, and the time t_d for data transmission is $40ms$. We also set the targeted primary user detection probability to be 0.85.

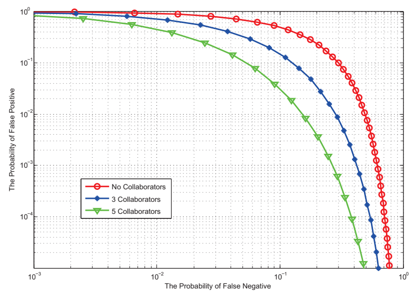

Fig. 2. Complementary ROC for different No. of collaborators ($\bar{\gamma} = 10dB$)

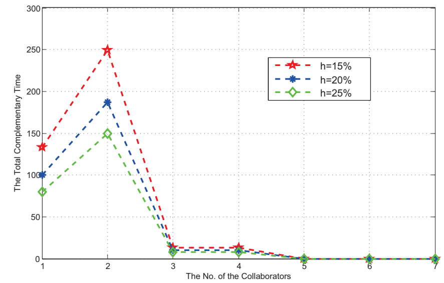

Fig. 4. Total complementary time of the fusion center

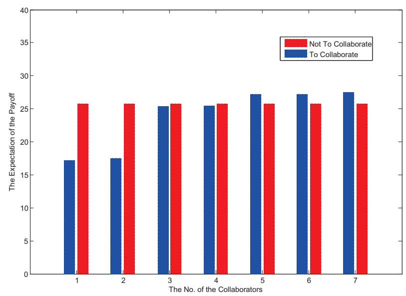

Fig. 3. Payoff comparison ($\bar{\gamma} = 10dB$)

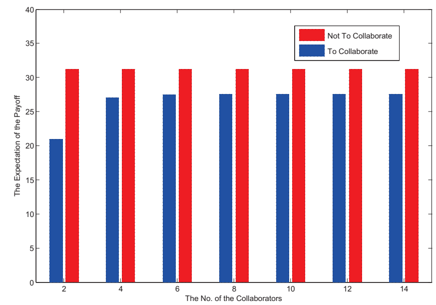

Fig. 5. Payoff comparison ($\bar{\gamma} = 15dB$)

In Fig. 2, the complementary Receiver Operating Characteristics (ROC) (plot of false positive rate vs. false negative rate) is shown for different number of collaborators. From the figure, we could conclude that given a targeted primary user detection probability, the cooperation having more collaborators will bring lower false positive probability. In Fig. 3, the expectation of the user who chooses not to collaborate and that of the collaborator are compared when different number of collaborators is given. We could see that the payoff of each collaborator is related to how many secondary users choose to collaborate, and that to collaborate is preferable when there are more than 4 users choose to do so. In Fig. 4, the complementary time of the fusion center is shown for different number of collaborators when $h = 0.15, 0.2, 0.25$. From the figure, we could see the overhead on the fusion center is acceptable. In Fig. 5, a extreme example of CSSG is given. We set the average SNR $\bar{\gamma}$ to be $15dB$, and we could see that to collaborate is a dominated strategy no matter how many users get involved. Under this situation, there is only one Nash equilibrium: not to collaborate.

V. CONCLUSION

In this paper, Collaborative Spectrum Sensing Game is proposed to study the incentive issue in the collaboration. In this game, every user can choose to collaborate or not in each time slot. And whether the users are willing to collaborate depends upon whether the benefit of the collaboration is worth the cost. Meanwhile, we discuss the Nash equilibrium of this game, and propose the scheme CCIS to enhance the collaboration. Our future work is to take the cost of the energy consumption into consideration in CSSG.

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