Economic-Robust Session based Spectrum Trading in Multi-hop Cognitive Radio Networks

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***Abstract*—Spectrum trading benefits primary users (PUs) by monetary gains and secondary users (SUs) by spectrum accessing opportunities in cognitive radio networks (CRNs). Unfortunately, most existing spectrum trading designs only focus on the guarantee of economic properties, but forget the wireless transmission nature, especially for multi-hop cognitive radio (CR) communications. In this paper, we propose an economic-robust session based spectrum trading, which has a joint consideration of economic properties such as incentive compatibility, individual rationality, and budget balance, and the end-to-end performance for multi-hop communications. Considering two bidding manners, i.e., bidding for the whole session and unit rate bidding, we formulate the spectrum trading optimization problems under multiple economic and multi-hop CR transmission constraints, design two pricing mechanisms to charge the winning spectrum bidders, and further mathematically prove the economic-robustness of the proposed spectrum trading schemes. Through extensive simulations, we show the proposed schemes are economic-robust and effective in improving spectrum utilization.**

I. INTRODUCTION

Nowadays, wireless service has played an indispensable role in our daily life. The corresponding ever-increasing wireless traffic calls for more and more radio spectrum, which is a scare and invaluable resource. On the other hand, current static spectrum allocation policy adopted by Federal Communications Commission (FCC) [1] still causes an appalling waste, where lots of licensed spectrum bands are not fully utilized, even idle most of the time in some geographical areas [2]. The dilemma between always increasing spectrum demands and the scarcity of spectrum resources has been pushing FCC to find new dynamic spectrum accessing technologies to effectively improve spectrum utilization.

Cognitive radio (CR) has emerged as one promising technology to solve the problem. CR technology enables unlicensed users, also called secondary users (SU), to dynamically access to the non-active bands belonging to licensed users, also known as primary users (PU). Considering the great economic values of spectrum resources, CR technology has initiated spectrum trading market in CR networks (CRNs), where PUs sell/lease their idle bands for monetary gains and SUs buy/rent the available bands for opportunistic accessing.

Since spectrum trading can noticeably improve spectrum efficiency and generate considerable economic gains, there have been active research efforts in spectrum trading designs. From the PUs' perspective, in [3], Niyato *et al.* have studied the competitive pricing problem in the spectrum trading market, where multiple PUs, aiming to maximize their own profit, compete with each other to sell spectrum accessing opportunities. From the SUs' perspective, Pan *et al.* have considered the risk for opportunistic spectrum accessing of SUs due to the unpredictable activities of PUs and proposed several effective measurements in [4] and [5] respectively. From the view of trading systems, many novel approaches based on game theory have been proposed by Duan *et al.* in [6], Wang *et al.* in [7] and Zhang *et al.* in [8]. Nevertheless, most works above target at the per-transmission pair or per-user based spectrum trading for single-hop communications.

Moreover, considering both frequency reuse and incentive compatibility (IC), which is a.k.a. truthfulness or strategy-proofness, in [9], Zhou *et al.* proposed a truthful spectrum auction to dynamically allocate spectrum resources. In [10], Jia *et al.* have investigated how to design the allocation and price to achieve the maximal revenue and enforce truthfulness as well. Although those smart trading designs consider the special feature of spectrum commodity, i.e., spatial reuse, they focus on how to make the CR users bid with their true evaluation values, and have very limited concerns on how the winning bidders use the won spectrum to conduct multi-hop CR transmissions. That is, who are the source/destination/relaying nodes, how to efficiently use the purchased spectrum bands in multi-hop CRNs w.r.t. interference avoidance, flow routing, etc., what kinds of end-to-end quality of services (QoS) can be guaranteed, and so on. Neglecting the fundamental wireless nature of multi-hop CR transmissions in spectrum trading design may critically lower the spectrum utilization, and significantly reduces the gains of spectrum trading.

To maximize the gains of spectrum trading, in this paper, we propose an economic-robust session based spectrum trading design for multi-hop CR communications. Here, economic-robustness means to guarantee the following three

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important economic properties: IC, individual rationality (IR), and budget balance (BB) [11], [12]. We employ the CRN architecture proposed in [13], where a secondary service provider (SSP) is employed to facilitate the access of SUs. We take the SSP as the spectrum trader with resources including its CR mesh routers and harvested available bands. All SUs have their own sessions with certain rate demands and source/destination nodes, and bid for the limited resources. According to the bids, the SSP allocates resources and charge the winners according to the proposed spectrum trading mechanism, which efficiently utilizes spectrum and effectively guarantees economic-robustness. Our major contributions are listed as follows.

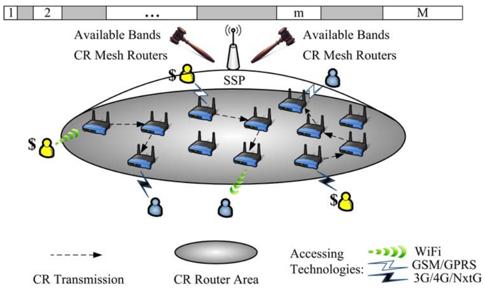
- Instead of per-user based spectrum trading, we propose a session based spectrum trading scheme in multi-hop CRNs by considering two bidding manners. One is bidding for the whole session and the other one is bidding for unit rate. For the two bidding manners, we formulate the resource allocation problem at the SSP, aiming to reach maximal revenue under multiple spectrum trading and multi-hop CR transmission constraints.
- Since the formulated optimization problems are mixed integer nonlinear programming (MINLP) problems, which are NP-hard to solve, we treat each nonlinear element as one variable, and convert them into mixed integer linear programming (MILP) problems. Then we achieve the solutions by using LP_SOLVE.
- For the winners after resource allocation conducted by the SSP, we design two pricing mechanisms corresponding to the two bidding manners, respectively, and provide proofs on their economic-robustness, i.e., the proposed pricing mechanisms can satisfy IC, IR and BB.
- Through extensive simulations, we can demonstrate the effectiveness of the proposed session based spectrum trading schemes in multi-hop CRNs. Furthermore, the satisfaction of economic properties can also be validated.

The rest of the paper is organized as follows. In Section II, the network model is presented, including system architecture, related models and some preliminaries. Then, we describe the interference and routing constraints mathematically and formulate the resource allocation problems in Section III. In Section IV we present the pricing mechanisms and prove their economic-robustness. Finally, simulation results are discussed in Section V and conclusion remarks are drawn in Section VI.

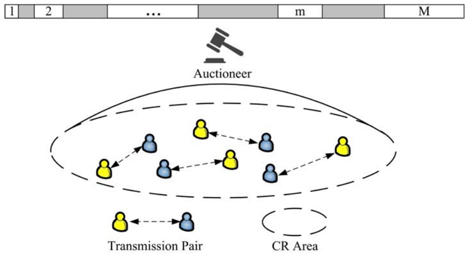
II. NETWORK MODEL

A. System Architecture for Spectrum Trading

The architecture of our spectrum trading market in multi-hop CRNs can be seen as Fig. 1(a). To realize the opportunistic spectrum accessing of SUs, a secondary service provider (SSP) is employed, which can be a base station or an access point with some basic bands and has CR capability to harvest unused licensed bands. Furthermore, a set of CR mesh routers with multiple CR radios are deployed and managed by it to undertake the service of SUs. In this market, SUs compete for the limited resources, CR mesh routers and available bands, from the trader SSP, and they can access the CR router area through the basic bands of SSP using any accessing approaches, e.g., Wi-Fi, GSM/GPRS, 3G/4G/NxtG, etc., without any specific requirements on their devices.



(a) Architecture of trading market in multi-hop CRNs.



(b) Architecture of trading market in single-hop CRNs.

Fig. 1. Comparison of spectrum trading in multi-hop and single-hop CRNs

Different from traditional per-user based spectrum trading for single-hop communications as Fig. 1(b), where the bid of each SU is just its bidding value, we propose a session based one for the multi-hop network as Fig. 1(a), where the bid of each SU l is a bundle relevant to its session including its source and destination nodes, rate requirement and bidding value denoted as $s(l)$, $d(l)$, $r(l)$ and $b(l)$ respectively. To be specific, assume that $\mathcal{N} = \{1, 2, \cdots, N\}$ CR mesh routers are deployed in the market, and $\mathcal{L} = \{1, 2, \cdots, L\}$ competing SUs report their bidding bundle to the SSP through their nearby CR routers on certain basic bands. Then the SSP decides the winners and allocate $\mathcal{M} = \{1, 2, \cdots, M\}$ available bands, including the rest of basic bands and the harvested unused licensed bands with different bandwidths $\mathcal{W} = \{W_1, W_2, \cdots, W_M\}$, among the routers under multiple constraints of interference and routing to deliver the traffic of winners. Furthermore, the SSP also broadcasts the charging price for each winner which should guarantee some important economic properties. Considering the geographical limits, each CR router i may be able to access only a set of all available bands denoted as $\mathcal{M}_i \subseteq \mathcal{M}$. Moreover, different CR routers may have different available band sets, i.e., $\mathcal{M}_i \neq \mathcal{M}_j$, $i \neq j$, and the common band set between the two CR routers is denoted as $\mathcal{M}_{i \cap j} = \mathcal{M}_i \cap \mathcal{M}_j$.

B. Related Models in Multi-hop CRNs

Transmission Range and Interference Range: For the power propagation gain from CR router i to j, $i \neq j \in \mathcal{N}$, we adopt a widely used model [14] shown as $g_{ij} = \beta \cdot d_{ij}^{-\alpha}$, where β is an antenna related parameter, α is the path loss factor, and d_{ij} represents the distance between the two CR routers. Assume that the transmitted power at the ith CR router is P_i, and its data transmission is successful only when the received power can exceed a power threshold as P_{th}^T, i.e., $P_i \cdot g_{ij} \geq P_{th}^T$. Thus, we can obtain the transmission range of the ith CR router as $R_i^T = \left(\beta \cdot P_i / P_{th}^T\right)^{1/\alpha}$. Similarly, suppose that the received interference can be ignored only when its power is less than a threshold as P_{th}^I. Therefore, the interference range of the ith CR router can be denoted as $R_i^I = \left(\beta \cdot P_i / P_{th}^I\right)^{1/\alpha}$. Since $P_{th}^T > P_{th}^I$, for the ith CR router, it is obvious that $R_i^T < R_i^I$.

Link Capacity: Assume that the CR router j is in the transmission range of the CR router i and they have a common available band set, i.e., $\mathcal{M}_{i \cap j} \neq \emptyset$. Then, based on the Shannon-Hartley theorem, the link capacity from i to j with band $m \subseteq \mathcal{M}_{i \cap j}$ can be expressed as

$$c_{ij}^m = W^m \log_2 \left(1 + \frac{P_i \cdot g_{ij}}{\gamma}\right), \tag{1}$$

where γ is the Gaussian noise power at the CR router j. Interferences are not considered here since they can be handled following the scheduling of the SSP according to the interference range of each CR router. The link capacity is an important constraint for the design of flow routing since the aggregate flow rate on one link cannot exceed its capacity.

C. Preliminaries for Spectrum Trading

Before the design for session based spectrum trading, we introduce a set of notations and some important economic properties in this subsection.

Bidding Value: We consider two bidding manners. One is the bidding value for a whole session denoted as $b_s(l)$ for SU $l \in \mathcal{L}$. The other one is for unit rate expressed as $b_r(l)$.

True Value: For the bid, each SU $l \in \mathcal{L}$ has a true valuation, i.e., the true price they will to pay, which are denoted as $v_s(l)$ and $v_r(l)$ for the two manners respectively.

Clearing Price: According to the bidding bundle, the trader will decide winners and allocate its resources. Meanwhile, it will charge price for each winner t, denoted as $p_s(t)$ and $p_r(t)$, for one session and unit rate respectively corresponding to the two bidding manners.

Bidder Utility: For any SU $l \in \mathcal{L}$, the utility functions for the two manners are $u_{s/r}\left(l, b_{s/r}(l)\right) = v_{s/r}(l) - p_{s/r}(l)$ if it wins with bidding value $b_{s/r}(l)$, and 0 otherwise.

To maintain the stability of trading market, the trading scheme should be economic-robust, i.e., satisfy the following three important economic properties:

Incentive Compatibility (IC): A trading scheme is IC if no one can get higher utility by bidding untruthfully no matter how other bidders bid. Mathematically, for any bidder i, when others' bids are fixed, $u_{s/r}\left(i, v_{s/r}(i)\right) \geq u_{s/r}\left(i, b_{s/r}(i)\right)$ if $b_{s/r}(i) \neq v_{s/r}(i)$.

Individual Rationality (IR): A trading scheme is IR if the clearing price of any bidder i is not higher than its bidding value, i.e., $p_{s/r}(i) \leq b_{s/r}(i)$.

Budget Balanced (BB): A trading scheme is BB if the generated revenue of the trader is non-negative.

In this paper, we do not consider the cost at the trader, SSP, during the trading and thus the revenue is the total clearing price charging for the winners, which is always non-negative. Therefore, BB can be always satisfied in our scheme and we will focus on the other two properties.

III. OPTIMAL RESOURCE ALLOCATION FOR SESSION BASED SPECTRUM TRADING IN MULTI-HOP CRNS

In this section, we formulate the resource allocation of the session based spectrum trading into an optimization problem to maximize the expected revenue of the SSP under interference constraints and flow routing in the CR router network.

A. Interference Constraints

In the CR router network, the allocation of available bands should avoid interference among different links. We exploit a binary value to describe the condition of the link from router i to j, $i \neq j \in \mathcal{N}$, on band $m \in \mathcal{M}_{i \cap j}$ as

$$x_{ij}^m = \begin{cases} 1, & \text{if } i \text{ can transmit data to } j \text{ with band } m, \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Furthermore, we denote the set of CR routers, which are in the transmission range of CR router $i \in \mathcal{N}$ and can use band $m \in \mathcal{M}_i$, as

$$\mathcal{T}_i^m = \left\{ j | d_{ij} \leq R_i^T, j \neq i, m \in \mathcal{M}_{i \cap j} \right\}. \tag{3}$$

Similarly, the CR routers which can interfere with CR router i on band m are expressed as

$$\mathcal{I}_i^m = \left\{ k | d_{ki} \leq R_k^I, k \neq i, m \in M_{i \cap k}, \mathcal{T}_k^m \neq \emptyset \right\}. \tag{4}$$

Based on the aforementioned notations, we present the interference constraints. For any CR router $i \in \mathcal{N}$, it cannot transmit to or receive from different routers on the same band and we achieve the constraint I1 as

$$\text{I1: } \sum_{j \in \mathcal{T}_i^m} x_{ij}^m \leq 1 \quad \text{and} \quad \sum_{\{i | j \in \mathcal{T}_i^m\}} x_{ij}^m \leq 1. \tag{5}$$

Besides, one CR router cannot transmit and receive on the same band simultaneously considering the "self-interference" at physical layer, which brings the constraint I2 as

$$\text{I2: } x_{ij}^m + \sum_{q \in \mathcal{T}_j^m} x_{jq}^m \leq 1. \tag{6}$$

Moreover, interference among different CR routers should be noticed as well. According to (4), we note that when CR router $i \in \mathcal{N}$ is transmitting data on band $m \in \mathcal{M}_i$, any other routers who can interfere with router i cannot use this band. Thus we can obtain the constraint I3 as

$$\text{I3:}\ \ x_{ij}^{m}+\sum_{q\in\mathcal{T}_{k}^{m}}x_{kq}^{m}\leq 1,k\in\mathcal{I}_{j}^{m},k\neq i. \tag{7}$$

B. Flow Routing

Besides interference management, how to deliver the traffic for winning sessions from their sources to destinations is also an important issue. In this subsection, we will present the constraints considered for the flow routing design.

Similarly, we employ a binary variable to denote whether the SU $l\in\mathcal{L}$ wins or not as

$$w\left(l\right)=\begin{cases}1, & \text{if session } l \text{ wins the bid,}\\ 0, & \text{otherwise.}\end{cases} \tag{8}$$

Let $f_{ij}^{m}\left(l\right)$ represent the flow attributed to SU $l\in\mathcal{L}$ on link i to j, $i\neq j\in\mathcal{N}$, using band $m\in\mathcal{M}_{i\cap j}$.

First, consider the source router of the winner l, i.e., $i=s\left(l\right)$. The incoming data should be zero and the sum rate of outgoing transmission to different routers using different bands should meet the rate requirement $r\left(l\right)$. Therefore, we have the following constraints as

$$\text{F1:}\ \ \sum_{m\in\mathcal{M}_{i\cap j}}\sum_{j\in\mathcal{T}_{i}^{m}}f_{ji}^{m}\left(l\right)w\left(l\right)=0,i=s\left(l\right), \tag{9}$$

$$\sum_{m\in M_{i\cap j}}\sum_{j\in T_{i}^{m}}f_{ij}^{m}\left(l\right)w\left(l\right)=r\left(l\right)w\left(l\right),i=s\left(l\right). \tag{10}$$

Next, consider the intermediate routers, i.e., $i\neq s\left(l\right)$, $i\neq d\left(l\right)$. The total outgoing data rate should be equal to its total incoming data rate to keep the flow balance, which leads to the following constraint as

$$\text{F2:}\sum_{m\in\mathcal{M}_{p\cap i}}\sum_{i\in\mathcal{T}_{p}^{m}}^{p\neq d(l)}f_{pi}^{m}\left(l\right)w\left(l\right)=\sum_{m\in\mathcal{M}_{i\cap j}}\sum_{j\in\mathcal{T}_{i}^{m}}^{j\neq s(l)}f_{ij}^{m}\left(l\right)w\left(l\right).$$
$$,i\neq s\left(l\right),i\neq d\left(l\right). \tag{11}$$

For the destination router of the winner l, i.e., $i=d\left(l\right)$, in contrast to F1, there is no outgoing data and the total incoming data rate should be the rate requirement $r\left(l\right)$. Then we have

$$\text{F3:}\ \ \sum_{m\in M_{i\cap j}}\sum_{j\in T_{i}^{m}}f_{ij}^{m}\left(l\right)w\left(l\right)=0,i=d\left(l\right), \tag{12}$$

$$\sum_{m\in M_{i\cap j}}\sum_{j\in T_{i}^{m}}f_{ji}^{m}\left(l\right)w\left(l\right)=r\left(l\right)w\left(l\right),i=d\left(l\right). \tag{13}$$

Furthermore, considering the link from router i to j, $i\neq j\in\mathcal{N}$, if it is active under the interference constraints, i.e., $\exists x_{ij}^{m}=1$, $m\in\mathcal{M}_{i\cap j}$, the sum flow of all winners on this link should not be higher than its capacity, i.e.,

$$\text{F4:}\ \ \sum_{m\in\mathcal{M}_{i\cap j}}\sum_{l\in L}^{i\neq d(l),j\neq s(l)}f_{ij}^{m}\left(l\right)w\left(l\right)\leq\sum_{m\in\mathcal{M}_{i\cap j}}c_{ij}^{m}x_{ij}^{m},j\in\mathcal{T}_{i}^{m}, \tag{14}$$

where c_{ij}^{m} is the capacity of link i to j on band m and can be calculated as (1).

C. Problem Formulation

In the spectrum trading market, the objective of the trader (SSP) is to maximize its expected revenue. Two bidding manners are considered. One is that each SU $l\in\mathcal{L}$ bids for its whole session, $b_{s}\left(l\right)$, and the optimal resource allocation can be formulated as follows.

$$\begin{aligned}\text{R1:}\ \ &\text{Maximize}\ \sum_{l\in\mathcal{L}}b_{s}\left(l\right)w\left(l\right)\\ &\text{s.t.}\quad (6)\sim(8),\quad (10)\sim(15)\end{aligned}$$

$$x_{ij}^{m},w\left(l\right)\in\left\{0,1\right\}\left(i\in\mathcal{N},j\in\mathcal{T}_{j}^{m},m\in\mathcal{M}_{i\cap j},l\in\mathcal{L}\right) \tag{15}$$

$$f_{ij}^{m}\left(l\right)\geq 0$$
$$\left(l\in\mathcal{L},i\in\mathcal{N},i\neq d\left(l\right),j\in\mathcal{T}_{j}^{m},j\neq s\left(l\right),m\in\mathcal{M}_{i\cap j}\right), \tag{16}$$

where $b_{s}\left(l\right)$, $r\left(l\right)$, and c_{ij}^{m} are given constants, and $w\left(l\right)$, x_{ij}^{m}, and $f_{ij}^{m}\left(l\right)$ are optimization variables.

The other bidding manner is that each bidder $l\in\mathcal{L}$ bids for unit rate denoted as $b_{r}\left(l\right)$. Considering the rate requirement $r\left(l\right)$, the total bidding value actually is $r\left(l\right)\cdot b_{r}\left(l\right)$. Thus, the optimal resource allocation is turned to be R2 as follows.

$$\begin{aligned}\text{R2:}\ \ &\text{Maximize}\ \sum_{l\in\mathcal{L}}r\left(l\right)b_{r}\left(l\right)w\left(l\right)\\ &\text{s.t.}\quad (6)\sim(8),\quad (10)\sim(17)\end{aligned}$$

We can find that the formulated problems, R1 and R2, are MINLP problems, which are hardly to solve. Thus, we substitute $f_{ij}^{m}\left(l\right)\cdot w\left(l\right)$ by $F_{ij}^{m}\left(l\right)$, and the problems will turn to be MILP ones, which can be solved by LP_SOLVE.

IV. ECONOMIC-ROBUST PRICING MECHANISM FOR SESSION BASED SPECTRUM TRADING

After the resource allocation, the SSP will broadcast the price charging for the winners, which should guarantee IC and IR. In this section, we first present the pricing mechanisms corresponding to two bidding manners respectively, and then give the proofs on their economic-robustness.

A. Pricing Mechanism

Consider the first bidding manner corresponding to R1. Denote the set of all winners after solving R1 as $\mathcal{L}_{1}^{*}$, i.e., $w\left(l\right)=1,\forall l\in\mathcal{L}_{1}^{*}$ and $w\left(l\right)=0,\forall l\notin\mathcal{L}_{1}^{*}$. Then the clearing price for one session of each winner $t\in\mathcal{L}_{1}^{*}$, expressed as $p_{s}\left(t\right)$, is defined as follows.

Pricing for One Session: Denote $S_{s}\left(\mathcal{L}_{1}^{*}\right)$ and $S_{s}^{t}\left(\mathcal{L}_{1}^{*}\right)$ as the total bidding value of all winners and that except the winner t, respectively, i.e.,

$$S_{s}\left(\mathcal{L}_{1}^{*}\right)=\sum_{l\in\mathcal{L}_{1}^{*}}b_{s}\left(l\right)\ \ \text{and}\ \ S_{s}^{t}\left(\mathcal{L}_{1}^{*}\right)=\sum_{l\in\mathcal{L}_{1}^{*},l\neq t}b_{s}\left(l\right). \tag{17}$$

Then assume that the SU t quits the bid, i.e., let $b_{s}\left(t\right)=0$, and the set of updated winners through solving R1 is expressed as $\widetilde{\mathcal{L}_{1}^{*}}$. Denote the total bidding value of all new winners as $S_{s}\left(\widetilde{\mathcal{L}_{1}^{*}}\right)$. Then we give the clearing price for one session charging for the winner $t\in\mathcal{L}_{1}^{*}$ as

$$\text{P1:}\ \ p_{s}\left(t\right)=S_{s}\left(\widetilde{\mathcal{L}_{1}^{*}}\right)-S_{s}^{t}\left(\mathcal{L}_{1}^{*}\right). \tag{18}$$

Next, we consider the other bidding manner corresponding to R2. Similarly, the set of all winners by solving R2 is denoted as $\mathcal{L}_2^*$ and the clearing price for unit rate of each winner $t \in \mathcal{L}_2^*$, denoted as $p_r(t)$, is defined as follows.

Pricing for Unit Rate: Similar to (17), the total bids of all winners after solving R2 can be expressed as

$$S_r(\mathcal{L}_2^*) = \sum_{l \in \mathcal{L}_2^*} r(l)\, b_r(l), \tag{19}$$

and that without winner t is

$$S_r^t(\mathcal{L}_2^*) = \sum_{l \in \mathcal{L}_2^*, l \neq t} r(l)\, b_r(l). \tag{20}$$

Then let $b_r(t) = 0$, and the set of updated winners by solving R2 can be described as $\widetilde{\mathcal{L}_2^*}$, and the updated total winners' bids can be denoted as $S_r\left(\widetilde{\mathcal{L}_2^*}\right)$. Then the clearing price for unit rate of winner $t \in \mathcal{L}_2^*$ is set as

$$\text{P2:} \;\; p_r(t) = \frac{S_r\left(\widetilde{\mathcal{L}_2^*}\right) - S_r^t(\mathcal{L}_2^*)}{r(t)}. \tag{21}$$

B. Proof of Economic-robustness

In this subsection, we will prove that our trading scheme with two bidding manners is IR and IC.

Considering the bidding manner for one session, in which the resource allocation and pricing mechanism correspond to R1 and P1, respectively. We first prove the satisfaction of IR.

Theorem 1: The proposed trading scheme with bidding for one session is IR.

Proof. Since $\mathcal{L}_1^*$ is the winner set of R1, the value of the objective function corresponding to $\mathcal{L}_1^*$, i.e., the total bids of all winners, should be maximum. Thus, we have $S_s(\mathcal{L}_1^*) \geq S_s\left(\widetilde{\mathcal{L}_1^*}\right)$. Then, for each winner $t \in \mathcal{L}_1^*$, we can get

$$b_s(t) = S_s(L_1^*) - S_s^t(L_1^*) \geq S_s\left(\widetilde{L_1^*}\right) - S_s^t(L_1^*) = p_s(t), \tag{22}$$

which means that the IR property can be satisfied. □

Before giving the proof of IC, we first present some definitions and lemmas.

Definition 1: **Monotonic Allocation:** For any bidder l, when the bids of other bidders are fixed, if it can win the resources with bidding value $b(l)$, then it can always win by bidding $\overline{b(l)} \geq b(l)$. On the contrary, if it loses with $b(l)$, it will always lose by bidding $\overline{b(l)} \leq b(l)$.

Definition 2: **Critical Value:** Critical value is a boundary value. For any bidder l, if it bids higher than its critical value, it will win, and if it bids lower than that, it will lose.

Lemma 1: The resource allocation with bidding for one session of our trading scheme as R1 is a monotonic allocation.

Lemma 2: The clearing price $p_s(t)$ for each winner $t \in \mathcal{L}_1^*$ is a critical value.

Then based on the two lemmas, we can prove the satisfaction of IC and have the following theorem.

Theorem 2: The proposed trading scheme with bidding for one session is IC.

For the proof in details, please refer to the technical report at http://cs.tsu.edu/pan/TR-ERST-Xuanheng.pdf. Besides, the similar proofs on economic-robustness of the other bidding manner for unit rate can also be found.

V. SIMULATION RESULTS

A. Simulation Setup

We consider a SSP based multi-hop CRN with multiple CR mesh routers deployed randomly in a 400×400 m^2 area. Suppose that the path loss factor $\alpha = 4$, the antenna related parameter $\beta = 4$, and the noise power at each router $\gamma = 10^{-9}$ W. The transmitted power at each router is assumed to be equal as 10 W, i.e., $P_i = 10$ W, $\forall i \in \mathcal{N}$, and the transmission/interference range of each router are assumed to be 100 m and 150 m, respectively. Furthermore, we assume that all available bands in the network have identical bandwidth as $W_m = 10$ MHz, $\forall m \in \mathcal{M}$, and the available band set of each router is set randomly as a subset of all available bands. Each SU has one session with a random rate demand within $[30, 90]$ Mbps and the source/destination nodes are chose randomly among the routers.

B. Results and Analysis

For the two bidding manners, in Fig. 2 and Fig. 3, we show the expected revenue of SSP, i.e., the total bids of winners, versus the number of SUs with different amounts of CR mesh routers ($|\mathcal{N}| = 15, 20$) and total available bands ($|\mathcal{M}| = 3, 5$) in the CRN. The bidding value of each SU is randomly set within $[100, 150]$ for its whole session in Fig. 2 and within $[3, 10]$ for unit rate in Fig. 3. We employ 100 data sets and take the average as the results. From the figures, we can find that with the increase of the number of competing SUs, the revenue of SSP in both manners will be enhanced as well. The reason is that for SSP, it always tries to serve more SUs to get more revenue, and the growth of revenue can just verify the effectiveness of the resource allocation. However, it is subject to the resources owned by SSP. Comparing the revenue under different network settings in Fig. 2 and Fig. 3, we can observe that when SSP has more resources, i.e., CR mesh routers and available bands, more revenue can be reached.

Next, we validate the economic-robustness of the proposed spectrum trading scheme in Fig. 4 and Fig. 5 corresponding to the two bidding manners respectively. Assume that $|\mathcal{N}| = 15$ CR mesh routers and $|\mathcal{M}| = 3$ available bands are in the network, and $|\mathcal{L}| = 7$ SUs participate in the trading. We employ 500 data sets corresponding to 500 different network topologies. On each data set, we choose one SU randomly and show its utility considering it bids truthfully and untruthfully, respectively. For the truthful bidding value, it is equal to the true valuation as a random value within $[100, 150]$ in Fig. 4 and $[3, 10]$ in Fig. 5. For the untruthful bidding value, it is additional added a random value within $[-100, 100]$ in Fig. 4 and $[-3, 3]$ in Fig. 5. From both figures,

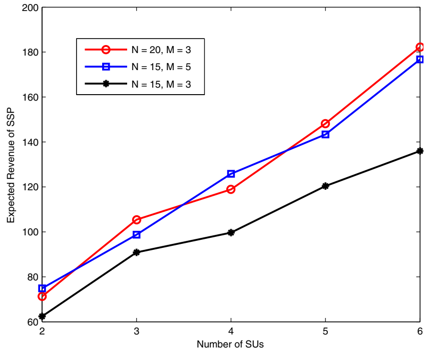


Fig. 2. Expected revenue of SSP versus the number of SUs with bidding for whole session.

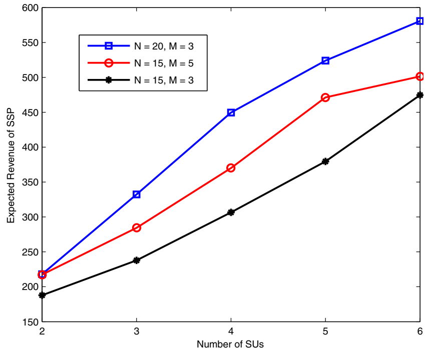


Fig. 3. Expected revenue of SSP versus the number of SUs with bidding for unit rate.

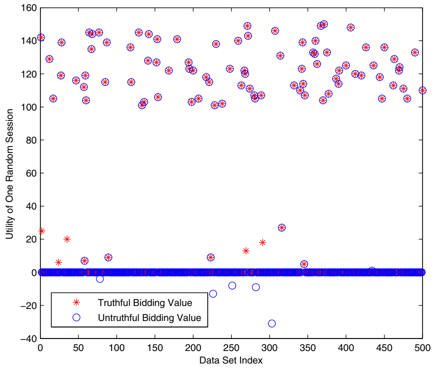


Fig. 4. 500 data sets of utility of one random session with truthful and untruthful bidding value for whole session.

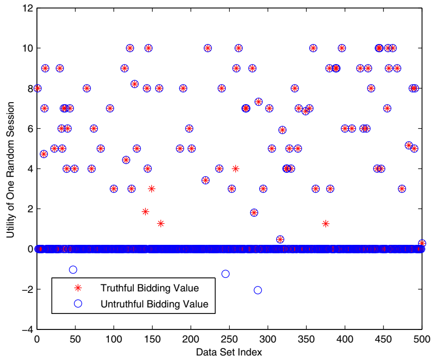


Fig. 5. 500 data sets of utility of one random session with truthful and untruthful bidding value for unit rate.

we can find that when SUs bid truthfully, their utilities are non negative, which indicates that the trading is IR. Furthermore, when they bid untruthfully, their utilities cannot be improved, which means that the trading is IC and all SUs will bid according to their own true valuations.

VI. CONCLUSIONS

In this paper, we have designed an economic-robust session based spectrum trading scheme in multi-hop CRNs. Specifically, we consider two bidding manners, for one session and for unit rate, respectively, and formulate the resource allocation under multiple spectrum trading and multi-hop CR transmission constraints into MINLP problems, which are further converted into MILP problems. For the two manners, we propose two pricing mechanisms, and prove the satisfaction of economic properties. By carrying out extensive simulations, we have shown the effectiveness and economic-robustness of the proposed trading scheme.

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