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# Session-Based Cooperation in Cognitive Radio Networks: A Network-Level Approach

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***Abstract*— Currently, the cooperation-based spectrum access in cognitive radio networks (CRNs) is implemented via cooperative communications based on link-level frame-based cooperative (LLC) approach, where individual secondary users (SUs) independently serve as relays for primary users (PUs) in order to gain spectrum access opportunities. Unfortunately, this LLC approach cannot fully exploit spectrum access opportunities to enhance the throughput of CRNs and fails to motivate PUs to join the spectrum sharing processes. To address these challenges, we propose a network-level session-based cooperative (NLC) approach, where SUs are grouped together to cooperate with PUs session by session, instead of frame by frame, for spectrum access opportunities of the corresponding group. To articulate our NLC approach, we further develop an NLC scheme under a cognitive capacity harvesting network architecture. We formulate the cooperative mechanism design as a cross-layer optimization problem with constraints on primary session selection, flow routing and link scheduling. Through extensive simulations, we demonstrate the effectiveness of the proposed NLC approach.**

***Index Terms*— Cognitive radio networks, dynamic spectrum sharing, cross-layer optimization, link scheduling, multi-hop multi-path routing.**

## I. Introduction

THE cooperation-based spectrum access, where secondary users (SUs) proactively help primary users' (PUs') transmissions in order to gain spectrum access opportunities as a reward, is an important spectrum access paradigm in cognitive radio networks (CRNs) [1]–[4]. In the current literature, the cooperation-based spectrum access is implemented through a link-level frame-based cooperative (LLC) approach which is built on cooperative communications. In the LLC approach, PUs employ SUs as relays to expedite data transmissions for each MAC frame so that the saved frame transmission time can be offered to SUs for spectrum access [4]–[10]. Although the LLC approach may maximize the achievable throughput of relaying SUs, it cannot efficiently exploit available spectrum access opportunities in cognitive radio networks (CRNs) to improve network-level throughput.

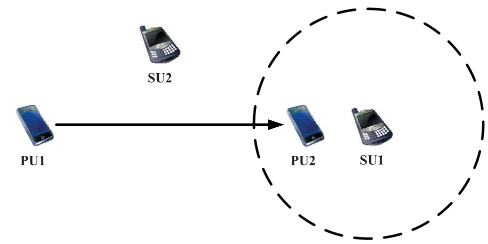

Fig. 1. The employed LLC scheme may lead to inefficient resource utilization. The dashed circle signifies the interference range of SU1.

An underlying assumption in the LLC approach is that individual SUs independently cooperate with PUs for their own spectrum access opportunities and the generated spectrum access opportunities are exclusively granted to relaying SUs such that other SUs cannot transmit during the cooperation-incurred periods [11], [12]. As a result, the LLC approach may miss a significant number of spectrum access opportunities to improve the throughput of CRNs. This is illustrated by the example shown in Fig. 1 where SU1 wants to access PUs' spectrum for data transmissions while PU1 is transmitting a file to PU2. SU2 does not have data to transmit. Because of unfavorable position, SU1 is unable to cooperate with PUs to gain spectrum access opportunities while SU2 is able to do so. In this case, if SU2 is willing to cooperate with PUs to acquire spectrum access opportunities and offer these opportunities to SU1, SU1 will be able to transmit its data and the throughput of the CRN as a whole is improved. Unfortunately, this is not supported by the LLC approach where SU1 and SU2 independently cooperates with PUs for their own spectrum access opportunities.

Motivated by this observation, in this paper, we propose a network-level session-based cooperative (NLC) approach for CRNs so that the spectrum access opportunities are utilized

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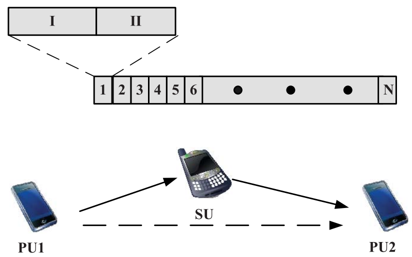


Fig. 2. SU intends to access the spectrum allocated to PU1 and PU2 while PU1 is delivering a file to PU2. The file is expected to be delivered in $N$ ($N \gg 1$) frames without the help of SU. Those digits in this figure represent different frames. The Roman numerals signify the division of each frame in the LLC approach.

more efficiently. Unlike the LLC approach where SUs cooperate with PUs for *their own spectrum access opportunities*, in our NLC approach, SUs are grouped together and cooperate with PUs for *the spectrum access opportunities of the corresponding group*. For the example in Fig. 1, if SU1 and SU2 are grouped together under our NLC approach, SU2 will help with PUs' transmissions and share the obtained spectrum access opportunities with SU1. In return, SU1 can also help SU2 get spectrum access opportunities whenever possible. In this way, both SU1 and SU2 can benefit from our NLC approach and the capacity of the considered CRN will be improved.

Another salient feature of our NLC approach, when compared with the LLC approach, is that our approach works session by session instead of frame by frame. To further elaborate on this difference between the LLC approach and our NLC approach, we consider the example shown in Fig. 2 where PU1 wants to transmit a file to PU2 in $N$ ($N \gg 1$) MAC frames. Following the LLC approach, each frame is divided into two parts which are indicated by the Roman numerals. SU helps with PU1's data transmission via, for example, decode-and-forward or amplify-and-forward relaying, so that PU1's scheduled data is delivered in the first part of a frame and obtains the second part of the frame as a reward, whereas our NLC approach requires SU to help PU1 deliver the whole file to PU2 in, for example, $\frac{2}{3}N$ frames and obtain the remaining $\frac{1}{3}N$ frames for its own data transmissions. As shown in Fig. 2, even if SU can help expedite PU1's file transferring process in each frame by following the LLC approach, PU1 still needs to wait until the last frame for the whole file to be delivered. As a result, PU1 might not actually benefit from SU's help and thus might not be interested in cooperating with SU [13]. In contrast, our NLC approach works session by session and requires SUs to help with PUs' end-to-end (E2E) data delivery in exchange for spectrum access opportunities. Hence, PUs will benefit from our NLC approach since the latency of their E2E service delivery will be significantly improved with the help of SUs and thus will be willing to yield spectrum access opportunities to SUs in exchange for enhanced quality of service.

As mentioned above, our NLC approach only provides a way for spectrum sharing and its nice features cannot be efficiently exploited without a suitable network architecture. To facilitate our NLC approach, necessary control messages, such as those for spectrum sharing, must be exchanged among SUs so that their actions are well coordinated. In the current literature, this is often achieved through the common control channels (CCCs) [14], [15]. Unfortunately, when SUs seek for opportunistic access to PUs' spectrum, they are likely already short of available spectrum resources for information exchange and do not have extra resources for CCC establishment, if a dedicated CCC is not provided [2], [14]. In view of this as well as the potential selfishness of SUs, it is difficult for SUs to enjoy the benefits promised by the NLC approach without a network-level solution. To fully exploit the benefits of our NLC approach, in this paper, we develop an NLC scheme for CRNs under a cognitive capacity harvesting network (CCHN) architecture where a secondary service provider (SSP) deploys base stations (BSs) and cognitive radio routers (CR routers) to provide secondary services to SUs [16]–[20]. In our NLC scheme, individual SUs only need to access the SSP's network, i.e., the CCHN, for services. It is the SSP and its deployed infrastructure that cooperate with PUs to gain spectrum access opportunities. This design frees SUs from the cooperating process and thus reduces user-side complexity. Under the supervision of the SSP, BSs and CR routers, as a group, cooperate with PUs to gain spectrum access opportunities for the CCHN. After that, the obtained spectrum access opportunities are efficiently allocated among those BSs and CR routers by the SSP to serve SUs. Under the CCHN, we demonstrate the feasibility of the NLC scheme as well as the impact of various network parameters through a throughput maximization problem. Our major contributions are summarized as follows:

- This is the first work to consider network-level session-based cooperation for CRNs. Unlike existing schemes, the proposed NLC scheme is a network-wide cooperative scheme where BSs and CR routers deployed by the SSP, as a group, cooperate with PUs for spectrum access opportunities of the CCHN.
- To characterize interfering relationships in the CCHN, we introduce a PU-related conflict graph which not only characterizes conflicting relationship between CR links,[1] but also captures conflicts among CR links, PU-related links,[2] and primary sessions.
- We formulate the cooperative mechanism design as a cross-layer optimization problem to maximize the throughput of the CCHN by jointly considering primary session selection, flow routing, and link scheduling constraints.

For the readers' convenience, the important notations used in this paper is summarized in Table I.

## II. Related Work

The LLC approach is originally introduced in [4] where Simeone *et al.* demonstrate the feasibility of their proposed scheme via analytical and numerical studies of the Stackelberg games. Later, based on this LLC approach, the cooperation-based spectrum access is studied via the optimal stopping

[1]CR links refer to the links between BSs, the links between CR routers, and the links between BSs and CR routers.

[2]PU-related links refer to the links from the sources of primary sessions to BSs or CR routers and the links from BSs or CR routers to the destinations of primary sessions.

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TABLE I
THE LIST OF IMPORTANT NOTATIONS AND DEFINITIONS

| Notation | Definition |
|---|---|
| $\mathcal{N}$ | The index set of CR routers |
| $\mathcal{L}$ | The index set of edge CR routers |
| $s(l)$ | The $l$th edge CR router |
| $\mathcal{L}_p$ | The index set of primary sessions |
| $s(l_p)$ | The source of the $l_p$th primary session |
| $d(l_p)$ | The destination of the $l_p$th primary session |
| $T_{l_p}$ | The length of the $l_p$th primary session |
| $D_{l_p}$ | The data volume of the $l_p$th primary session |
| $\theta_{l_p}$ | =1 if the SSP chooses to cooperate with the $l_p$th primary session and is 0 otherwise |
| $G=(V,E)$ | $G$ is the PU-related conflict graph, $V$ is the vertex set of $G$, and $E$ is the edge set of $G$ |
| $\mathcal{I}$ | The set of the maximal independent sets (MISs) of $G$ |
| $\mathcal{I}_{l_p}$ | The set of MISs containing the vertex corresponding to the $l_p$th primary session |
| $\overline{\mathcal{I}}_{l_p}$ | A set of MISs, satisfying $\mathcal{I}_{l_p} \cap \overline{\mathcal{I}}_{l_p} = \emptyset$ and $\mathcal{I}_{l_p} \cup \overline{\mathcal{I}}_{l_p} = \mathcal{I}$ |
| $T$ | Control Interval for the SSP |
| $f_{ij}(l)$ | The amount of the $l$th secondary flow allocated on the link between the $i$th and the $j$th CR routers |
| $f_{ij}^p(l_p)$ | The amount of the $l_p$th primary flow allocated on the link between the $i$th and the $j$th CR routers |
| $\Upsilon_l$ | The rate of the $l$th secondary flow |
| $\lambda_{mq}$ | The amount of time share allocated to the $q$th MIS |

theory, the contract theory, and the matching theory in [6]–[8], respectively. With growing concerns on energy consumption, energy-aware cooperative schemes and the multihop relay selection problem are investigated in [5] and [9]. Motivated by increasing concerns on information security, two types of cooperative schemes are proposed in [10] to improve PUs' secrecy rate. As aforementioned, an underlying assumption in the LLC approach is that individual SUs work independently for their own spectrum access opportunities and the generated spectrum access opportunities are exclusively granted to relaying SUs such that other SUs cannot transmit during the cooperation-incurred periods [11], [12]. Thus, the LLC approach will waste a significant number of spectrum access opportunities to improve the throughput of CRNs. In addition, in the LLC approach, PUs might not actually benefit from SUs' help and thus might not be interested in cooperating with SUs. These observations motivate us to introduce the NLC approach in order to enable the cooperation-based spectrum access and boost the capacities of CRNs.

Although the concept of session-based cooperation in cognitive radio networks (CRNs) has been discussed in a few works, such as [21] and [22], it is studied from a different perspective from our work. In [21] and [22], Yuan *et al.* primarily address how PUs interact with SUs so that both of them can gain from the cooperation, whereas our work focuses on the interactions between individual SUs. Unlike existing works where SUs independently cooperate with PUs for their own spectrum access opportunities, we advocate the cooperation among SUs based on the observation that SUs can benefit from the collaboration if they are grouped together and collectively cooperate with PUs for the spectrum access opportunities of the group instead of themselves. Different from [23] where non-selfish SUs opportunistically offer their spectrum access

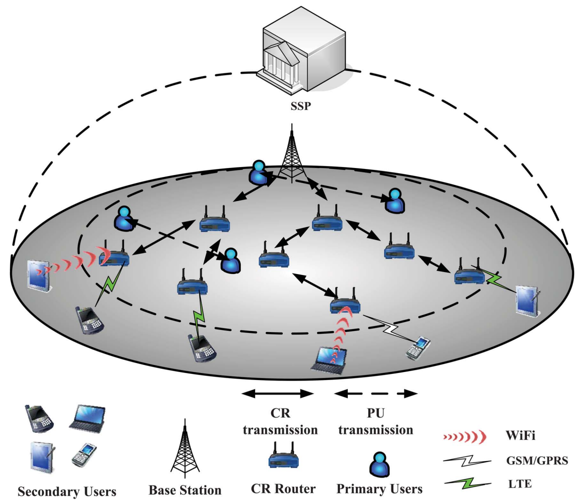


Fig. 3. The CCHN architecture.

opportunities to others with better channel conditions, our approach emphasizes mutual benefits between SUs. That is why we call it a network-level approach and articulate it via the CCHN architecture where CR routers collectively cooperate with PUs for the spectrum access opportunities of the CCHN.

The CCHN architecture is first introduced in [17]where the SSP is introduced to provide services for SUs by judiciously deploying CR routers. Although our previous works have demonstrated the CCHN can efficiently support the spectrum-sensing-based and the spectrum-auction-based spectrum access, how to support the cooperation-based spectrum access in the CCHN is still an open problem [17], [24], [25].

## III. CCHN AND NETWORK-LEVEL SESSION-BASED COOPERATION

### A. CCHN Architecture

Our CCHN consists of an SSP, BSs, CR routers, and SUs as shown in Fig. 3 [16], [17]. The SSP is an independent wireless service provider, such as a cellular operator that is willing to provide better or new types of services to cellular users, and has its own licensed spectrum bands, referred to as the SSP's basic bands. The SSP is in charge of spectrum coordination and service provisioning within its coverage area. To provide communication services to SUs, the SSP deploys or leases some BSs for fundamental service coverage as done in cellular systems and CR routers for efficient resource utilization. BSs are interconnected with wired connections via Internet or other high-speed data networks and work as gateways for CR routers, so that the CCHN can gain backbone network services. BSs also serve as an agent for the SSP to exchange control signaling with CR routers and SUs. CR routers are intelligent wireless routers with cognitive radio capability and operate under the supervision of the SSP. Both BSs and CR routers are equipped with multiple radio interfaces, such as cognitive radio interfaces, cellular interfaces, and WiFi interfaces, and can operate over the SSP's basic bands, unlicensed bands (e.g., ISM bands), and unoccupied licensed bands. CR routers form a cognitive radio mesh network to help the SSP deliver services to SUs in collaboration with BSs. SUs are wireless terminals or devices (e.g., smart phones and laptops) obtaining services via certain access technologies (e.g., GSM/GPRS, LTE and WiFi) and may or may not have the cognitive radio capability. SUs access the SSP's services by connecting to CR routers or BSs, and CR routers directly connecting to SUs are called edge CR routers. If SUs have the cognitive radio capability, they can communicate with edge CR routers via both their basic access technologies and cognitive radios.[3] If SUs' devices do not have cognitive radio interfaces, edge CR routers will tune to the interfaces which SUs normally use to deliver services. Each edge CR router constantly collects data requests in its coverage area and submits those collected data requests to the SSP for resource allocation. Based on the data requests and available resources, the SSP carries out network optimization, and the decisions will be delivered to CR routers via the SSP's basic bands.[4] Under the supervision of the SSP, BSs and CR routers collectively build up paths to deliver services to SUs via multi-hop transmissions through extensive use of the harvested spectrum as much as possible. As shown in [16], [17], and [25], the CCHN architecture is very flexible in supporting various types of spectrum-sharing paradigms, including the spectrum-sensing-based and the spectrum-auction-based spectrum sharing. In this paper, we consider the use of the CCHN to support another paradigm, i.e., the cooperation-based spectrum sharing.

### B. Proposed NLC Scheme

Under the proposed NLC scheme, when running out of available bands, the SSP will coordinate BSs and CR routers to cooperate with PUs to gain spectrum access opportunities. The SSP directly obtains lengths and data volumes of primary sessions from the primary service provider (PSP) and makes cooperating decisions on different primary sessions via network optimization. Once the SSP decides to cooperate with a primary session, it supervises its BSs and CR routers to build up high-speed paths for this primary session to expedite E2E primary service delivery. After a scheduled primary service is delivered, the remaining time of the primary session during the intended transmission period is granted to the SSP for spectrum access. Then, the SSP intelligently allocates cooperation-incurred spectrum access opportunities among its BSs and CR routers to efficiently serve SUs.

The NLC scheme has a number of appealing features when compared with existing LLC schemes. First, it is the SSP, not SUs, who involves with the cooperating process and the complexity of cooperation is shifted from SUs to the network. Second, under the supervision of the SSP, secondary network facilities, i.e., BSs and CR routers, form a group to cooperate with PUs for spectrum access opportunities of the CCHN, i.e., the SSP, and the SSP can optimally allocate the cooperation-incurred spectrum access opportunities among secondary network facilities so that the network capacity is significantly improved. Third, in our NLC scheme, PUs will enjoy better services since the latency of E2E service delivery is significantly improved with the help of the SSP and thus are more likely to join the cooperation-based spectrum access. How to design more viable schemes to stimulate both PUs and the SSP to have such kinds of cooperations is out of the scope of this paper and will be addressed elsewhere.

[3]By basic access technologies, we refer to the communication technologies which SUs normally use to get communication services. For example, for cellular users, their basic access technologies can be either GSM or LTE.

[4]The SSP will reserve a certain number of basic bands for the control message exchange among BSs and CR routers. Meanwhile, the SSP will allocate a certain number of basic bands to enable SUs to access the CCHN. Then, the remaining basic bands will be allocated to the cognitive radio mesh of CR routers for data delivery. In this work, we consider the case where these remaining bands are not enough to serve SUs' requests and the SSP needs extra spectrum resources.

## IV. Network Model

In this section, we introduce the basic network configuration as well as the related communication models. To examine the effectiveness of our NLC scheme, we do not consider the SSP's basic bands in the following analysis.

### A. Network Configuration

Consider a typical CCHN with a BS, denoted as $b$, and $N$ CR routers which are deployed by the SSP. Those CR routers are indexed as $\mathcal{N} = \{1, 2, \cdots, N\}$ and $L$ of them are edge CR routers denoted as $s(l)$, $l \in \mathcal{L}$, where $\mathcal{L} = \{1, \cdots, L\}$, and $s(l) \in \mathcal{N}$. The set of secondary network facilities is $\mathcal{N}_s = \mathcal{N} \cup \{b\}$. There are $L_p$ active primary sessions colocated with the CCHN.[5] $s_p(l_p)$ and $d_p(l_p)$ represent the source and the destination of the $l_p$th primary session, respectively, where $l_p \in \mathcal{L}_p = \{1, \cdots, L_p\}$. Unlike previous works, in this paper, the lengths and data volumes of different primary sessions are allowed to be different. The length and the data volume of the $l_p$th primary session is denoted as $T_{l_p}$ and $D_{l_p}$, respectively. Without loss of generality, the cooperation between PUs and the SSP is conducted on a single band, i.e., all the considered primary sessions operate in the same band. Each BS or CR router only has a single cognitive radio.[6] We assume that primary sessions do not interfere with each other due to the coordination of the PSP. BSs and CR routers can access the PUs' band only when their transmission activities do not cause harmful interference to ongoing primary sessions.

### B. Communication Models

*1) Transmission Range and Interference Range:* Our formulation proceeds with the widely adopted protocol model where a signal transmission in the physical layer is characterized by a transmission range and an interference range [26]. For example, CR router $j$ successfully receives signals from CR router $i$ if it falls in the transmission range of CR router $i$ and stays outside the interference range of any other transmitting secondary network facilities and PUs. For simplicity, we assume that network entities of the same type employ the same transmit power $P_t^{\mu}$, $\mu \in \{C, b, P\}$, where $C$ represents CR routers, $b$ represents the BS, $P$ represents PUs, and the

[5]In this work, each primary session is treated as a whole and can be implemented via either single-hop transmissions or multi-hop transmissions.

[6]Since the purpose of this paper is to investigate the feasibility of the NLC scheme, we consider the single-channel single-radio case for simplicity.

subscript $t$ indicates the power is for transmission. For a transmitter of type $\mu$, the received power at the receiver is

$$P_r = P_t^{\mu} \gamma d^{-n}, \quad (1)$$

where $\gamma$ is the antenna related constant, $n$ is the path loss exponent, and $d$ is the distance between the transmitter and the receiver. The received signal can be correctly decoded at the receiver only when $P_r$ is greater than a predetermined threshold $P_R^{\nu}$, where $\nu \in \{C, b, P\}$ signifies the type of the receiver. Then, the distance between the transmitter and the receiver should satisfy $P_t^{\mu} \gamma d^{-n} \geq P_R^{\nu}$, which implies the transmission range of a network entity of type $\mu$ to another network entity of type $\nu$ is $R_T^{\mu\nu} = (\gamma P_t^{\mu}/P_R^{\nu})^{1/n}$. Similar to [17] and [25], the received interference power is not negligible if it exceeds a threshold $P_I^{\nu}$, $\nu \in \{C, b, P\}$. Thus, the interference range of a network entity of type $\mu$ to another network entity of type $\nu$ is $R_I^{\mu\nu} = (\gamma P_t^{\mu}/P_I^{\nu})^{1/n}$.

*2) Achievable Data Rate:* If CR router $j$ is in the transmission range of CR router $i$, there exists a communication link, denoted as $(i, j)$, between these two routers. The achievable data rate of link $(i, j)$ is a given parameter denoted as $c_{ij}$. Generally, $c_{ij}$ is determined by the channel bandwidth and physical layer techniques, such as multi-antenna techniques, adaptive coding and modulation techniques. Once the physical layer techniques are given, $c_{ij}$ is determined accordingly and used as a constant in the subsequent development.

## V. Session-Based Cooperative Mechanism Design

In this section, we will explore the design of cooperative mechanism by jointly considering two tightly coupled problems, namely, primary session selection and efficient resource utilization, so that the aggregated throughput of the CCHN is maximized. To ease the problem formulation, we use $\theta_{l_p}$ to denote the cooperating decision of the SSP on the $l_p$th primary session, i.e.,

$$\theta_{l_p} = \begin{cases} 1, & \text{the } l_p\text{th primary session is selected} \\ 0, & \text{the } l_p\text{th primary session is not selected} \end{cases} \quad (2)$$

In this paper, we address the cooperative mechanism design through a maximal independent set (MIS) searching subproblem and a mixed integer linear programming (MILP) [27]. The MIS searching subproblem is a standard problem in wireless networking and tries to identify a set of MISs of the PU related conflict graph which characterizes the interfering relationships among CR links, PU-related links, and primary sessions [28], [29]. On the other hand, as shown below, the MILP considered in this paper can be directly solved with the result of the MIS searching subproblem. In this way, we can efficiently develop the cooperative mechanism to maximize the aggregated throughput of the CCHN.

### A. PU-Related Conflict Graph and MISs

Since flow routing and link scheduling decisions of the SSP are affected by primary session selection, unlike [17] and [25], our PU-related conflict graph $G = (V, E)$ characterizes the interfering relationship not only among different CR links but also among CR links, PU-related links, and primary sessions, where $V$ is the vertex set and $E$ is the edge set. Each vertex in the PU-related conflict graph corresponds to a CR link, a PU-related link or a primary session which is represented as an ordered pair. For example, $(i, j)$, $i, j \in \mathcal{N}$ represents the CR link from CR router $i$ to CR router $j$ and exists only when CR router $j$ is within CR router $i$'s transmission range. $(s_p(l_p), j)$, $l_p \in \mathcal{L}_p, j \in \mathcal{N}$, signifies the PU-related link from the source of the $l_p$th primary session to CR router $j$. $(s_p(l_p), d_p(l_p))$, $l_p \in \mathcal{L}_p$ represents the $l_p$th primary session.

Similar to [17], [25], and [28], two communication links are said to be conflicting if they meet one of the following three conditions:

1) Two links sharing the same transmitter or receiver.
2) The receiver of a link is the transmitter of another link.
3) Two links do not share a radio, but the transmission of a link will interfere with the reception of the other link.

The first conflicting relationship implies that a single radio cannot support multiple concurrent transmissions/receptions on the same band. The second one means that a single radio cannot use the same band for simultaneous transmission and reception. The last one is due to co-channel interference. Based on the conflicting conditions for communication links, a CR link or a PU-related link conflicts with a primary session once it conflicts with any primary link, i.e., links between PUs, used by this primary session. According to those defined conflicting relationships, we add an undirected edge between two vertices in $V$ if their corresponding links/sessions conflict with each other. An illustrative example for the construction of the PU-related conflict graph is provided in [27, Sec. V-A].

Given a set of vertices $I \subseteq V$, if any two vertices in $I$ do not share an edge, the corresponding links and primary sessions in $I$ can be scheduled simultaneously without interfering with each other. In this case, this set of vertices is called an independent set. If adding one more vertex into the independent set $I$ results in a non-independent set, the set $I$ is called the maximal independent set (MIS). By scheduling corresponding links of an MIS, we can accommodate as many communication links as possible, which improves frequency reuse. We collect all MISs of the PU-related conflict graph in a set $\mathcal{I} = \{I_1, \cdots, I_q, \cdots, I_Q\}$, where $I_q$ is the $q$th MIS, $Q$ is the total number of MISs and equals to the cardinality of $\mathcal{I}$, i.e., $|\mathcal{I}|$. Based on the $l_p$th primary session, we divide $\mathcal{I}$ into $\mathcal{I}_{l_p}$ and $\overline{\mathcal{I}}_{l_p}$ with $\mathcal{I}_{l_p} \cap \overline{\mathcal{I}}_{l_p} = \emptyset$ and $\mathcal{I}_{l_p} \cup \overline{\mathcal{I}}_{l_p} = \mathcal{I}$, where $\mathcal{I}_{l_p}$ is the set of MISs which include the vertex corresponding to the $l_p$th primary session. In the next subsection, we will formulate our throughput maximization problem based on MISs of the PU-related conflict graph.

### B. Flow Routing and Link Scheduling Constraints

To optimally utilize network resources, we should jointly consider flow routing and link scheduling which are tightly coupled problems. On the one hand, the scheduling at the data link layer should support the flows at the network layer. On the other hand, how much flow can be carried at the network layer is determined by the scheduling at the data link layer. To embrace possible cooperation between primary sessions

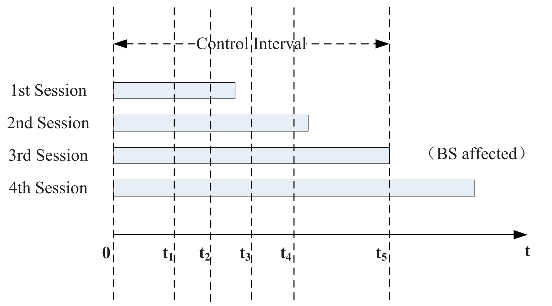


Fig. 4. The selection of the control interval. ($t_m$ represents the promised finishing time for the $m$th primary session if the SSP cooperates, defined later).

and the SSP, unlike existing works, we add extra constraints for PU-related links and incorporate primary session selection and variations in lengths of primary sessions into our formulation.

*1) Control Interval:* Usually, the SSP makes link scheduling and routing decisions during a certain time period which is called the control interval. In the CCHN, SUs' data are delivered to the BS where the connections to data networks are provided. As a result, to exploit the cooperation-incurred spectrum access opportunities for service delivery, the SSP must cooperate with the primary sessions whose activities will conflict with that of the BS so that SUs' data can be delivered to the BS during the cooperation-incurred periods. Suppose multiple primary sessions exist in the vicinity of the BS and let $T_{min}$ denote the lengths of the shortest primary sessions conflicting with the activity of the BS. Considering the uncertainty in PUs' activities, it makes no sense for the SSP to make scheduling for a period longer than $T_{min}$ as it may not be able to access data networks afterwards. Thus, it is reasonable to set the length of the control interval as $T = T_{min}$. For clarity, let us consider an example shown in Fig. 4, where $4$ primary sessions exist and the activity of the BS happens to be affected by the 3rd primary session. In this case, we set the length of the control interval as the length of the 3rd primary session. In the following formulation, we will regard $T$ as a given parameter.

*2) Flow Routing Constraints:* To study how much the SSP can gain from cooperating with primary sessions, we consider multi-path routing in this paper. According to our NLC scheme, the SSP should first help PUs finish their transmissions earlier in order to utilize the cooperation-incurred periods to serve SUs. When reflected at the network layer, there are two kinds of data flows to be carried over the CCHN. The flows originated from the edge CR routers are referred to as secondary flows, and the flows generated by the primary sessions are called primary flows. For secondary flows, the achievable rate depends on what the network can provide since secondary data traffic is transmitted during cooperation-incurred periods. To encourage PUs to join the cooperating process, the SSP must ensure PUs' data is delivered before a certain time, which implies that certain flow rates should be assured for primary flows. Given different rate requirements, the flow routing constraints for secondary and primary flows are introduced separately.

Let $\Upsilon_l$ be the rate of the $l$th secondary flow originated from the $l$th edge CR router $s(l)$. We have the following flow conservation constraints at the source $s(l)$ as

$$\sum_{j\in\mathcal{T}_{s(l)}} f_{s(l)j}\left(l\right) = \Upsilon_l, \tag{3}$$

$$\sum_{j\in\mathcal{R}_{s(l)}} f_{js(l)}\left(l\right) = 0, \tag{4}$$

where $f_{ij}\left(l\right)$ is the rate of the $l$th secondary flow over link $(i,j)$ $(l \in \mathcal{L},\ i,j \in \mathcal{N}_s)$. (3) implies that the rate of the flow originated from $s(l)$ is limited by what the network can support. (4) guarantees no flow comes back to the source. $\mathcal{T}_{s(l)}$ is the set of secondary network facilities within $s(l)$'s transmission range. $\mathcal{R}_{s(l)}$ is the set of secondary network facilities with $s(l)$ in their transmission ranges, i.e., $\mathcal{R}_{s(l)} = \{j \in \mathcal{N}_s\,|s(l) \in \mathcal{T}_j\}$.

If CR router $i$ is an intermediate relay of the $l$th secondary flow, i.e., $i \in \mathcal{N}_s$, $i \neq s(l)$ and $i \neq b$, the flow into $i$ must be equal to the flow out of $i$. That is,

$$\sum_{j\in\mathcal{T}_i} f_{ij}\left(l\right) = \sum_{j\in\mathcal{R}_i} f_{ji}\left(l\right). \tag{5}$$

In the CCHN, all secondary flows go through the BS for Internet services, which implies that the BS $b$ is the common destination for secondary flows. For the $l$th secondary flow, the constraints at $b$ can be formulated as

$$\sum_{j\in\mathcal{R}_b} f_{jb}\left(l\right) = \Upsilon_l \tag{6}$$

$$\sum_{j\in\mathcal{T}_b} f_{bj}\left(l\right) = 0. \tag{7}$$

By adding (5) for all intermediate relays, we notice that, if (3), (4) and (7) are given, (6) must be satisfied. Therefore, it is sufficient to adopt (3), (4) and (7) in the flow routing constraints for secondary flows.

Unlike traditional network flow problems, PU-related links will not carry any secondary flows. Thus, the $l$th $(l \in \mathcal{L})$ secondary flow over PU-related links must be 0, i.e., $f_{s_p(l_p)j}\left(l\right) = f_{id_p(l_p)}\left(l\right) = 0,\ j \in \mathcal{T}_{s_p(l_p)}, i\ \in \mathcal{R}_{d_p(l_p)}, l_p \in \mathcal{L}_p$.

Besides above constraints, the NLC scheme requires the SSP help PUs finish their transmissions before utilizing the band for its own data transmissions, which implies that certain flow rate should be guaranteed for primary flows. Consequently, for the $l_p$th primary flow, which is generated by the $l_p$th primary session, the constraint at the source $s_p\left(l_p\right)$ can be written as

$$\sum_{j\in\mathcal{T}_{s_p(l_p)}} f^p_{s_p(l_p)j}\left(l_p\right) \geq \frac{\theta_{l_p} D_{l_p}}{T}, \tag{8}$$

where $f^p_{s_p(l_p)j}\left(l_p\right)$ is the rate of the $l_p$th primary flow allocated over the link from the source of the $l_p$th primary session to CR router $j$ $(j \in \mathcal{N}_s)$, $\mathcal{T}_{s_p(l_p)}$ is the set of secondary network facilities within the transmission range of $s_p\left(l_p\right)$, $\theta_{l_p}$ is a $0-1$ parameter representing the SSP's decision on whether to cooperate with the $l_p$th primary session. $D_{l_p}$ is the data volume of the $l_p$th primary session. $T$ is the length of the control interval. Since we have already precluded the links from secondary network facilities to $s_p(l_p)$ during the construction of the conflict graph, it is not necessary to include the constraint similar to (4) for primary flows.

Similar to (5), if CR router $i$ is an intermediate relay of the $l_p$th primary flow, then,

$$\sum_{j \in \mathcal{T}_i \cup \omega_{i,T}} f_{ij}^p(l_p) = \sum_{j \in \mathcal{R}_i \cup \omega_{i,R}} f_{ji}^p(l_p), \quad (9)$$

where $\omega_{i,T} = \emptyset$ if $d_p(l_p)$ is outside the transmission range of CR router $i$ and $\omega_{i,T} = \{d_p(l_p)\}$, otherwise. Likewise, $\omega_{i,R} = \emptyset$ if CR router $i$ is out of the transmission range of $s_p(l_p)$ and $\omega_{i,R} = \{s_p(l_p)\}$, otherwise. $f_{ij}^p(l_p)$ is the rate of the $l_p$th primary flow over CR link $(i,j)$ ($l_p \in \mathcal{L}_p$, $i,j \in \mathcal{N}_s$), and $f_{id_p(l_p)}^p(l_p)$ represents the flow rate of the $l_p$th primary session over the link from CR router $i$ ($i \in \mathcal{N}_s$) to the destination of the $l_p$th primary session.

Like the secondary flow case, the constraint at the destination $d_p(l_p)$ will be automatically satisfied once (8) and (9) hold. As a result, this constraint is not listed.

Noticing that PU-related links $(s_p(l_p), j)$'s and $(i, d_p(l_p))$'s, $j \in \mathcal{T}_{s_p(l_p)}, i \in \mathcal{R}_{d_p(l_p)}, l_p \in \mathcal{L}_p$ will not relay traffic for other primary flows, we require $f_{s_p(l_p)j}^p(l_p') = f_{id_p(l_p)}^p(l_p') = 0$ when $l_p \neq l_p'$ and $l_p, l_p' \in \mathcal{L}_p$.

*3) Link Scheduling Constraints:* In this paper, we consider time based link scheduling where different links are allocated with certain periods of time to build up flows between end systems. Consequently, the flow rates which the network layer can provide depend on the data rate of each link as well as the time share allocated to these links. To provide PUs with incentives to cooperate, the SSP must guarantee PUs' data is delivered to the destination earlier than what would have been scheduled without the SSP's help. We introduce an incentive parameter $\alpha$ to capture this point and assume the SSP will consider cooperating with the $l_p$th primary session only if it can at least deliver the data of the $l_p$th primary session to the destination during a period of $T_{l_p}/\alpha$. In practice, $\alpha$ can either be determined by the PSP who proactively looks for cooperation or be set by the SSP who wishes to cooperate with PUs for spectrum access opportunities. As mentioned above, if the SSP decides to cooperate with the $l_p$th primary session, the CCHN has to support a network flow with rate $D_{l_p}/T$. In this case, the incentive mechanism demands a link scheduling which is able to build up a flow with rate $D_{l_p}/T$ for the $l_p$th primary session during a period of $T_{l_p}/\alpha$.

Without loss of generality, in the following development, we assume primary sessions are sorted by session times and the $l_p$th primary session has the $l_p$th shortest duration, i.e., $T_1 \leq T_2 \leq \cdots \leq T_{L_p}$. Our formulation needs another set of parameters defined as[7]

$$t_m = \begin{cases} 0 & m = 0 \\ \min\{T_m/\alpha, T\} & 1 \leq m \leq L_p \\ T & m = L_p + 1 \end{cases}, \quad (10)$$

[7]We assume all primary sessions start at 0 for simplicity. In practice, the start time can be determined by the SSP.

where $t_m$ ($m = 1, \cdots, L_p$) corresponds to the finishing time of the $m$th primary session promised by the SSP. If $T_m/\alpha \geq T$, the incentives for PUs will be automatically satisfied when the SSP delivers their data during the control interval of length $T$. In view of that, it is enough to set $t_m$ as $\min\{T_m/\alpha, T\}$ for $m = 1, \cdots, L_p$. To facilitate the mathematical formulation of the incentive-related constraints, we divide the control interval based on $t_m$'s defined in (10). For example, in Fig. 4, the control interval is divided by $\{t_1, t_2, t_3, t_4, t_5\}$, where $t_1$, $t_2$, $t_3$, $t_4$ are the promised finishing time of the four primary sessions and $t_5 = T$ is the end of the control interval. Since the data of the $m$th primary session must be delivered before $t_m$, different set of flows are carried by the CCHN during the intervals $(t_{m-1}, t_m)$, $m = 1, \cdots, L_p + 1$. In this view, we establish separate link scheduling constraints for these intervals.

As mentioned before, at any time, at most one MIS in $\mathcal{I}$ can be scheduled to transmit. To proceed, define $0 \leq \lambda_{mq} \leq 1$ as the time share allocated to the $q$th MIS $I_q$ in the interval $(t_{m-1}, t_m)$, $m = 1, \cdots, L_p + 1$. Then, we have our first set of link scheduling constraints

$$\sum_{q=1}^{Q} \lambda_{mq} \leq \frac{t_m - t_{m-1}}{T}, \quad m = 1, \cdots, L_p + 1. \quad (11)$$

To protect primary sessions, the links conflicting with the $l_p$th primary session can be scheduled only when the SSP chooses to cooperate with the $l_p$th primary session. That is, the SSP can schedule the MISs in $\overline{\mathcal{I}}_{l_p}$ if it decides to cooperate with the $l_p$th primary session. Otherwise, only the MISs in $\mathcal{I}_{l_p}$ can be scheduled. Consequently, we have the following constraint related to the $l_p$th ($l_p \in \mathcal{L}_p$) primary session in interval $(t_{m-1}, t_m)$, $m = 1, \cdots, L_p + 1$

$$\sum_{q=1}^{Q} \lambda_{mq} 1\left(I_q \in \overline{\mathcal{I}}_{l_p}\right) \leq 1\left(T_{l_p} \geq t_{m-1}\right) \theta_{l_p} \times \frac{\min\left\{T_{l_p} - t_{m-1}, t_m - t_{m-1}\right\}}{T}, \quad (12)$$

where $1\left(I_q \in \overline{\mathcal{I}}_{l_p}\right) = 1$ if $I_q$ belongs to $\overline{\mathcal{I}}_{l_p}$, otherwise, $1\left(I_q \in \overline{\mathcal{I}}_{l_p}\right) = 0$. $1\left(T_{l_p} \geq t_{m-1}\right)$ is an indicator function which signifies the MISs in $\overline{\mathcal{I}}_{l_p}$ cannot be scheduled after $T_{l_p}$, the duration of the intended transmission periods of the $l_p$th session. When the SSP decides to cooperate with the $l_p$th primary session, $\theta_{l_p} = 1$, and at most $\frac{\min\left\{T_{l_p} - t_{m-1}, t_m - t_{m-1}\right\}}{T}$ can be assigned to the MISs in $\overline{\mathcal{I}}_{l_p}$. The min operation in (12) is used to cover the case where $t_{m-1} < T_{l_p} < t_m$ (e.g., $t_2 < T_1 < t_3$ in Fig. 4). If the SSP chooses not to cooperate with the $l_p$th primary session, $\theta_{l_p} = 0$. Since $\lambda_{mq} \geq 0$, (12) forces $\lambda_{mq} = 0, \forall I_q \in \overline{\mathcal{I}}_{l_p}$, i.e., MISs in $\overline{\mathcal{I}}_{l_p}$ cannot be scheduled if the SSP does not cooperate with the $l_p$th primary session.

Since a flow is feasible only when there exists a schedule of the links to support it, we need a few more constraints to relate flow rate to link scheduling. To mathematically formulate these constraints, we denote the data rate for CR link $(i, j)$,

$i, j \in \mathcal{N}_s$, when $I_q$ is scheduled as $r_{ij}(I_q)$ which is defined as

$$r_{ij}(I_q) = \begin{cases} c_{ij} & (i,j) \in I_q \\ 0 & (i,j) \notin I_q. \end{cases} \tag{13}$$

$c_{ij}$ is the achievable data rate for CR link $(i, j)$. If $I_q$ is assigned $\lambda_{mq}$ of the whole control interval during $(t_{m-1}, t_m)$, the flow rate contributed by scheduling $I_q$ over $(t_{m-1}, t_m)$ is $\lambda_{mq} r_{ij}(I_q)$. Following (13), we can define similar parameters for PU-related links.

As mentioned above, the data of the $l_p$th primary session must be delivered before $t_{l_p}$, $l_p \in \mathcal{L}_p$, which implies the SSP must be able to build up the $l_p$th primary flow in the CCHN merely based on the link scheduling in $\left(0, t_{l_p}\right)$. Together with the fact that the data of the $k$th ($1 \le k \le l_p$) primary session has already been delivered at the time $t_{l_p}$, we have the following set of constraints for CR link $(i, j)$, $i, j \in \mathcal{N}_s$

$$\sum_{k=1}^{l_p} f_{ij}^p(k) \le \sum_{m=1}^{l_p} \sum_{q=1}^{Q} \lambda_{mq} r_{ij}(I_q), \quad l_p \in \mathcal{L}_p. \tag{14}$$

For example, when $l_p = 1$, (14) reduces to $f_{ij}^p(1) \le \sum_{q=1}^{Q} \lambda_{1q} r_{ij}(I_q)$ which means the data of the 1st primary session has been delivered by $t_1$.

Unlike primary flows, secondary flows are carried by the leftover network resources. Thus, their rates depend on both the rates of primary flows and the amount of network resources which can be provided by the CCHN during the whole control interval. This provides us with the following constraints for CR link $(i, j)$, $i, j \in \mathcal{N}_s$

$$\sum_{l_p=1}^{L_p} f_{ij}^p(l_p) + \sum_{l=1}^{L} f_{ij}(l) \le \sum_{m=1}^{L_p+1} \sum_{q=1}^{Q} \lambda_{mq} r_{ij}(I_q), \tag{15}$$

where the left side is the sum of flow rates supported by the network and the right-hand side represents what the link scheduling can provide.

Since each PU-related link will not relay traffic for either the SSP or other primary sessions, we have following constraints for PU-related links as ($l_p \in \mathcal{L}_p$)

$$f_{s_p(l_p)j}^p(l_p) \le \sum_{m=1}^{l_p} \sum_{q=1}^{Q} \lambda_{mq} r_{s_p(l_p)j}(I_q) \tag{16}$$

$$f_{id_p(l_p)}^p(l_p) \le \sum_{m=1}^{l_p} \sum_{q=1}^{Q} \lambda_{mq} r_{id_p(l_p)}(I_q). \tag{17}$$

### *C. Cooperative Mechanism Design Under Multiple Constraints*

In our NLC scheme, to fully exploit the cooperation-incurred benefits to serve SUs, the SSP seeks optimal strategies to select appropriate primary sessions to cooperate with, choose secondary network facilities to relay PUs' data, assign cooperation-incurred periods to BSs and CR routers for data transmissions, and route secondary flows such that the total throughput of the CCHN is maximized. With the flow routing and link scheduling constraints introduced in Section V.B, the cooperative mechanism design can be cast into the following throughput maximization problem under multiple constraints as

$$\text{maximize} \sum_{l \in \mathcal{L}} \Upsilon_l$$

$$\begin{aligned}
\text{s.t.: } & (3) \sim (5), (7), (8), (9) \\
& (11), (12), (14) \sim (17) \\
& f_{ij}(l) \ge 0 \quad (l \in \mathcal{L}, i \in \mathcal{N}_s, j \in \mathcal{T}_i) && (18)\\
& f_{ij}^p(l_p) \ge 0 \quad (l_p \in \mathcal{L}_p, i \in \mathcal{N}_s, j \in \mathcal{T}_i) && (19)\\
& f_{s_p(l_p)j}^p(l_p) \ge 0 \quad \left(l_p \in \mathcal{L}_p, j \in \mathcal{T}_{s_p(l_p)}\right) && (20)\\
& f_{id_p(l_p)}^p(l_p) \ge 0 \quad \left(l_p \in \mathcal{L}_p, i \in \mathcal{R}_{d_p(l_p)}\right) && (21)\\
& f_{s_p(l_p)j}(l) = f_{id_p(l_p)}(l) = 0 \\
& \left(l \in \mathcal{L}, j \in \mathcal{T}_{s_p(l_p)}, i \in \mathcal{R}_{d_p(l_p)}, l_p \in \mathcal{L}_p\right) && (22)\\
& f_{s_p(l_p)j}^p\left(l_p'\right) = f_{id_p(l_p)}^p\left(l_p'\right) = 0 \\
& \left(j \in \mathcal{T}_{s_p(l_p)}, i \in \mathcal{R}_{d_p(l_p)}, l_p \ne l_p', l_p, l_p' \in \mathcal{L}_p\right) && (23)\\
& \theta_{l_p} \in \{0,1\} \quad (l_p \in \mathcal{L}_p) \quad \Upsilon_l \ge 0 \quad (l \in \mathcal{L}) && (24)
\end{aligned}$$

where $\theta_{l_p}$, $f_{ij}(l)$, $f_{ij}^p(l_p)$, $f_{s_p(l_p)j}^p(l_p)$, $f_{id_p(l_p)}^p(l_p)$, $f_{s_p(l_p)j}(l)$, $f_{id_p(l_p)}(l)$, $f_{s_p(l_p)j}^p\left(l_p'\right)$, $f_{id_p(l_p)}^p\left(l_p'\right)$, $\lambda_{mq}$ and $\Upsilon_l$ are decision variables. Although set membership functions and indicator functions have been employed in this problem (e.g., constraints (12)), they become constants given the MISs of the PU-related conflict graph and the lengths of primary sessions. Clearly, after reformulating this problem based on the MISs of the PU-related conflict graph and the lengths of primary sessions, both the objective function and constraints of the reformulated optimization problem are linear. The only integer decision variables involved are those 0-1 variables $\theta_{l_p}$ which signifies the cooperating decision of the SSP on the $l_p$th primary session. Thus, given the MISs of the PU-related conflict graph and the lengths of primary sessions, the above optimization problem is a mixed integer linear programming (MILP). In this MILP, the 0-1 integer variables are resulted from the selection of primary sessions instead of interference constraints. Noticing that the number of active primary sessions in the considered areas is limited due to potentially mutual interference between them [6], [10], the number of integer variables in the MILP part of our formulation is limited and thus the considered MILP can be solved by optimization softwares, such as CPLEX and lp_solve, employing, for example, the classical branch-and-bound approach. Thus, the most difficult part of the optimization problem is to search for MISs in $G = (V, E)$, which will be introduced next.

### *D. Augmented SIO-Based Algorithm for MIS Search*

Generally, finding all MISs of a conflict graph $G = (V, E)$ is NP-complete and is often encountered in multi-hop wireless networks [25], [28]. When the size of $G = (V, E)$ is small, all MISs can be found via brute-force search. When the size of $G = (V, E)$ becomes large, the complexity of brute-force search is prohibitive so that it is impractical to find all MISs [28]. Recently, the computation of MISs in multi-hop wireless networks has been systematically studied in [28], where Li *et al.* point out that only a small set of MISs, i.e., the critical MISs, are needed and scheduled by the optimal solution although $G = (V, E)$ has exponentially many MISs. Noticing that the critical MISs are closely related to the locations of the sources and destinations of the involved network flows, they developed an scheduling index ordering based (SIO-based) method to intelligently compute a set of MISs such that critical MISs are covered as many as possible. As shown in [28], the SIO-based method returns a set of MISs in polynomial time and outperforms the widely adopted random algorithms.

To find the critical MISs for the considered throughput maximization problem, the SSP needs to know the locations of the sources and destinations of primary sessions. We assume such information can be obtained from primary users (PUs) or their service providers. This assumption is made based on the following considerations. First, this work addresses problems in cooperative cognitive radio networks (CRNs) where a certain level of cooperation and information exchange exist between primary networks and secondary networks. Second, as a service provider, the SSP will have more credibility than individual SUs, which will facilitate such information sharing with PUs. With such information, the SSP can construct the PU-related conflict graph based on which the critical MISs can be found. Once the SSP knows which primary sessions to cooperate with, it can employ the SIO-based method to identify a set of MISs where critical MIS are covered as many as possible. Unfortunately, the sources and destinations of the considered throughput maximization problem are not known in advance since the SSP needs to intelligently select primary sessions to cooperate with in order to maximize cooperation-incurred benefits. Clearly, different primary sessions will lead to different sources and destinations and thus different critical MISs. To address this challenge, we develop an heuristic algorithm, called the augmented SIO-based algorithm, on the basis of the SIO-based method so that critical MISs can be covered as many as possible. Once the SSP obtains the PU-related conflict graph based on the information shared by PUs, it can employ the augmented SIO-based algorithm as well as the information on the CCHN and primary sessions to find a set of MISs where critical MISs are covered as many as possible.

The augmented SIO-based algorithm, as shown in Algorithm 1, is developed based on the observation that the uncertainty of sources and destinations comes from the selection of primary sessions. The basic idea of the proposed algorithm is to compute a set of MISs for every possible combination of primary sessions and collect all these computed MISs to augment the set of MISs computed by the original SIO-based method. Specifically, for each choice of primary sessions, we will first eliminate the unselected primary sessions and the links which conflict with these primary sessions from the PU-related conflict graph and, then, run the SIO-based algorithm on the resulting graph to obtain a set of MISs of this graph. After that, the unselected primary sessions are added back to each of these MISs to obtain a set of MISs of the original PU-related conflict graph. Once such a set of MISs is obtained, it is combined with the previously computed sets of MISs. Following this procedure, we can obtain the augmented set of MISs after going through all possible choices of primary sessions. Finally, this augmented set of MISs is combined with that computed by the original SIO-based method into a new set of MISs which will be used in the considered optimization problem for solution finding. Given $L_p$ primary sessions, line $5 - 8$ will be iterated for $2^{L_p} - 1$ times. As proved in [28], the running time of line 6 is $\mathrm{O}\left(V^4\right)$ and dominates the running time of each iteration, where $V$ inside the parentheses represents the number of vertices in the corresponding conflict graph [30]. Noticing line 1 takes $\mathrm{O}\left(V^4\right)$ time, the complexity of the proposed algorithm is $\mathrm{O}\left(2^{L_p} V^4\right)$. Due to mutual conflict/interference, the number of primary sessions $L_p$ in a certain area is limited and is bounded by a constant. Then, the complexity of the proposed algorithm becomes $\mathrm{O}\left(V^4\right)$, which implies that the proposed algorithm will terminate in polynomial time.

**Algorithm 1** Augmented SIO-Based Algorithm

**Input:** The topology of the CCHN, sources and destinations of primary sessions, and the PU-related conflict graph $G = (V, E)$,

**Output:** A set of MISs $\mathcal{I}_a$

1: Compute a set of MISs $\mathcal{I}_a$ of $G$ based on the SIO-based method
2: **for** $j$=0 to $L_p - 1$ **do**
3:   Compute all subsets of $\mathcal{L}_p$ with cardinality $j$ and collect these subsets in a set $\mathcal{P}_j$;
4:   **for** all $p \in \mathcal{P}_j$ **do**
5:     Construct another graph $G_p$ from the PU-related conflict graph $G$ by removing the primary sessions in $\mathcal{L}_p - p$ as well as the vertices/links conflicting with these primary sessions
6:     Compute a set of MISs of $G_p$, $\mathcal{M}_p$, with $\{s(l), l \in \mathcal{L}\} \cup \{s(l_p), l_p \in p\}$ as the source and $\{b\} \cup \{d_p(l_p), l_p \in p\}$ as the destinations based on the SIO-based method
7:     add the primary sessions in $\mathcal{L}_p - p$ to each element of $\mathcal{M}_p$ to obtain a set, $\mathcal{I}_p$, of MISs in $G$
8:     $\mathcal{I}_a$=$\mathcal{I}_a \cup \mathcal{I}_p$
9:   **end for**
10: **end for**

## VI. Performance Evaluation

In this section, we evaluate the feasibility and effectiveness of the proposed NLC scheme via extensive simulations.

### *A. Simulation Setup*

We consider a CCHN with a BS and $\mathcal{N} = 24$ CR routers. According to [24], the placement of CR routers should be carefully planned to improve the spectrum efficiency and system capacity. As a result, we assume the BS and CR routers are regularly deployed based on a grid topology where the BS is located at the center and each pair of secondary network facilities is $200m$ away [27]. Among those CR router, CR1, i.e., the one at the upper left corner, and CR24, i.e., the one at the lower left corner, are edge CR routers. There are $5$ primary

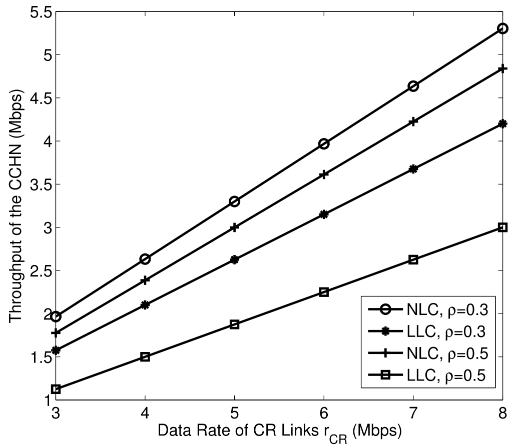


Fig. 5. The throughput performance of the NLC approach and the LLC approach.

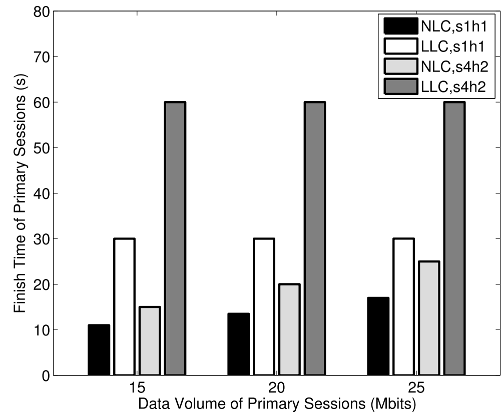


Fig. 6. The completion time of primary transmissions under the NLC approach and the LLC approach.

sessions colocated with the CCHN and the source of each session is $200m$ far away from its destination. The sources and destinations of primary sessions are $100\sqrt{2}m$ away from the nearest secondary network facilities [27]. The BS, CR routers and the source of each primary session all employ 2 $W$ for transmission, i.e., $P_t^{\mu} = 2W$, $\forall \mu \in \{C, b, P\}$. The thresholds for successful reception and the interference thresholds are set as $P_R^{\nu} = 10^{-6}W$ and $P_I^{\nu} = 1.34 \times 10^{-7}W$, $\forall \nu \in \{C, b, P\}$, respectively. The path loss exponent is $n = 3$ and the antenna related constant $\gamma = 4.63$. Based on Section IV.B, $R_T^{\mu\nu} = 210\ m$ and $R_I^{\mu\nu} = 410\ m$, $\forall \mu, \nu \in \{C, b, P\}$, i.e., CR routers, the BS, and PUs share the same transmission range and interference range.

### B. Results and Analysis

The performance of our NLC approach is first compared with that of the LLC approach in Fig. 5 where the LLC approach is implemented based on decode-and-forward relaying with a frame length of $10ms$ [5]. The PU-related links have the same data rate $3Mbps$, the CR links have the same data rate $r_{CR}$. To make our comparison more comprehensive, we introduce $\rho$, the probability that PUs are active, to signify PUs' activity and obtain final results by averaging the corresponding throughput of the CCHN when PUs are active and inactive. In the case where PUs are active, the data volume of primary sessions is set as $D_1 = \cdots = D_{L_p} = 20Mbits$, and the lengths of the 5 primary sessions are $30s, 30s, 30s, 60s, 60s$, which implies that the length of the control interval is $T = 30s$ since the activity of the BS conflicts with the third primary session. For the LLC approach, we assume PUs equally allocate their scheduled data into different frames. For our NLC approach, we set the incentive parameter $\alpha$ as 1. As shown in Fig. 5, our NLC approach can achieve much higher throughput than that of the LLC approach, which demonstrates the effectiveness of our approach in throughput enhancement. With a higher $r_{CR}$, the CCHN can deliver more data during a fixed time period, and thus it is not surprising that the throughput of the CCHN grows with $r_{CR}$ increasing. Another observation from Fig. 5 is that the throughput of the CCHN decreases when $\rho$ increases from 0.3 to 0.5. Intuitively, the increase in PUs' activities will limit the number of network resources available to the CCHN, which will in turn lead to the reduction in the throughput of the CCHN.

In Fig. 6, we further compare the completion time of primary transmissions under our NLC approach with that under the LLC approach. To facilitate the comparison, we focus on the data transmission of the first primary session, i.e., the data transmission from Ps1 to Pd1, and assume that it is active with probability 1. Ps1 and Pd1 are the source and the destination of the first primary session, respectively. The LLC approach is implemented based on decode-and-forward relaying [5]. Other parameters are the same as those in Fig. 5. The results are shown in Fig. 6 with the label "s1h1" which means the first primary session implemented via one hop transmissions. As shown in Fig. 6, when compared with the LLC approach, our NLC approach can greatly shorten the completion time of the primary session and thus are more likely to motivate PUs to join the cooperation-based spectrum access processes. From Fig. 6, with the data volume of the primary session growing, the completion time of the primary transmission increases when our NLC approach is adopted and almost remains the same when the LLC approach is employed. Clearly, given the network topology of the CCHN and the amount of available spectrum, the completion time of the primary transmission will increase when the data volume of the primary session increases, which explains the results under our NLC approach. As aforementioned, under the LLC approach, no matter how fast PUs' data could be delivered in each frame, PUs still need to wait until the last frame for their data transmissions to be finished. Due to small frame length, under the LLC approach, the completion time of the primary transmission is almost the same when the volume of primary session varies. To further evaluate the performance of our NLC approach in dealing with multi-hop primary sessions, we consider the case where the fourth primary session is implemented via multi-hop transmissions as shown in Fig. 13 in [27]. In this case, the LLC approach is implemented in each hop over a subframe of length $5ms$. The results are shown in Fig. 6 with the label "s4h2", meaning the fourth primary session implemented via two hop

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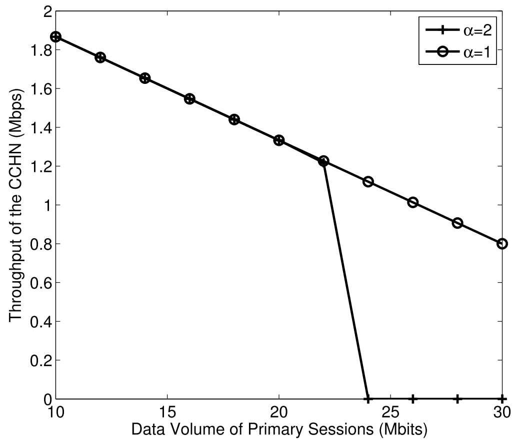


Fig. 7. The throughput of the CCHN v.s. the data volume of primary sessions.

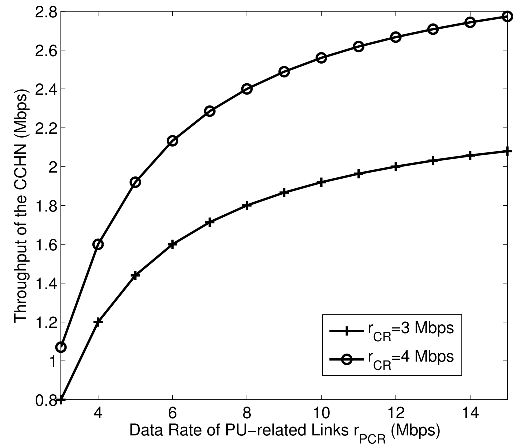


Fig. 8. The throughput of the CCHN v.s. the data rate of PU-related links.

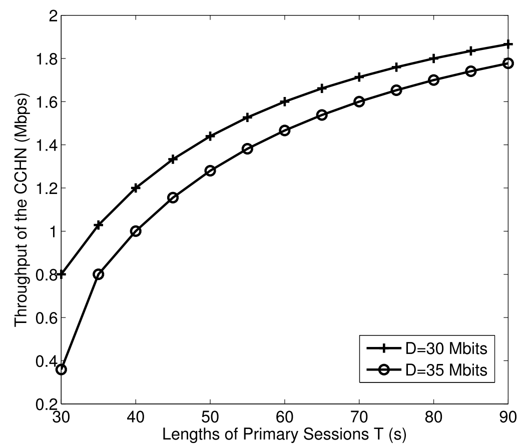


Fig. 9. The throughput of the CCHN v.s. the lengths of primary sessions.

transmissions, which further demonstrates the effectiveness of our NLC approach.

In Fig. 7, we study the relationship between the throughput of the CCHN and the data volumes of primary sessions $D_{l_p}$'s. To clearly reflect the impact of $D_{l_p}$'s, we set $D_1 = \cdots = D_{L_p} = D$, $\rho = 1$, and assume both CR links and PU-related links have the same data rate $3Mbps$. The lengths of primary sessions are the same as those in Fig. 5. Fig. 7 shows the throughput of the CCHN decreases as $D$ increases. During a control interval, the number of available network resources in the CCHN is fixed once the SSP determines which primary sessions to cooperate with. When $D$ gets larger, the SSP will allocate more resources to relay PUs' traffic and less resources will be used to deliver secondary data, which leads to a reduction in the amount of delivered secondary data during the control interval. Consequently, the growth of $D$ results in a decrease of the throughput of the CCHN. Additionally, the impact of the incentive parameter $\alpha$ shown in Fig. 7 is very interesting. When the data volume $D$ of the primary sessions is small, the CCHN can obtain the same throughput under $\alpha = 1$ and $\alpha = 2$. However, after $D$ reaches a certain value, the throughput of the CCHN under $\alpha = 2$ becomes $0$. In the considered network, when $D$ is small, delivering PUs' data will not cost too much and the SSP will choose to cooperate with those primary sessions no matter $\alpha = 1$ or $\alpha = 2$. Generally, the amount of available network resources is fixed once the SSP decides which primary sessions to cooperate with. Given the same amount of primary data traffic, the amount of network resources left for secondary flows is the same for $\alpha = 1$ and $\alpha = 2$ cases, which results in the same throughput of the CCHN under $\alpha = 1$ and $\alpha = 2$. When $D$ is large enough, things become different since PUs' data must be delivered in a shorter period of time when $\alpha = 2$. In this case, the requirements of primary sessions are too high to be satisfied and thus the SSP chooses not to cooperate, which leads to a $0$ throughput.

How the data rates of different links affect the throughput of the CCHN is shown in Fig. 8. In general, the SSP is able to schedule two kinds of links, PU-related links and CR links. To study the impacts of these links, we assume all PU-related links have the same data rate $r_{PCR}$ (i.e., $r_{s_p(l_p)j} = r_{id_p(l_p)} = r_{PCR}, i, j \in \mathcal{N}_s, l_p \in \mathcal{L}_p$) and all CR links have the same data rate $r_{CR}$ (i.e., $r_{ij} = r_{CR},\ i, j \in \mathcal{N}_s$). The other parameters are the same as in Fig. 7, except $\alpha = 1$ and $D = 30Mbits$. It is observed that the throughput of the CCHN grows at a decreasing growth rate with $r_{PCR}$ increasing. When $r_{PCR}$ is higher, the CCHN can help PUs finish their transmission more quickly and obtain longer cooperation-incurred periods to deliver more secondary data. As a result, the CCHN obtains higher throughput with $r_{PCR}$ increasing. When $r_{PCR}$ is high enough, further increases in $r_{PCR}$ will not extend cooperation-incurred periods too much and thus the growth rate decreases. Since the secondary flows are carried by CR links, high-speed CR links will result in improvement in the throughput of the CCHN as shown in Fig. 8. Particularly, when cooperation-incurred periods are extended due to high $r_{PCR}$, much more secondary data can be delivered with higher $r_{CR}$, which explains the gap between the two curves in Fig. 8.

In Fig. 9, we study the relationship between the throughput of the CCHN and the lengths of primary sessions. To make it more clear, we assume all primary sessions have the same length, i.e., $T_1 = \cdots = T_{L_p}$, and thus the length of control interval is $T = T_1 = \cdots = T_{L_p}$. The values of other

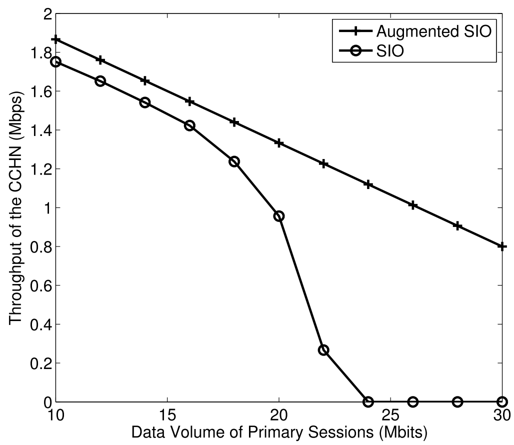


Fig. 10. Comparison between the augmented SIO-based algorithm and the original SIO-based method.

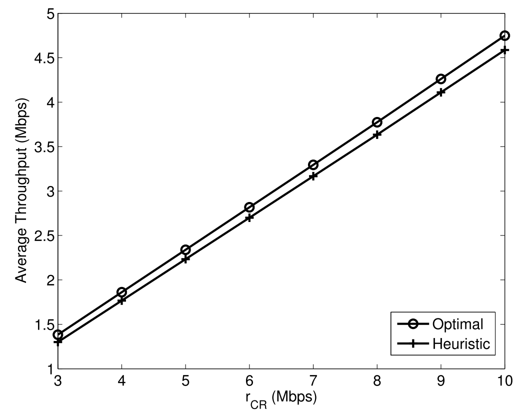


Fig. 11. The optimal throughput (labeled as "Optimal") v.s. the maximum throughput achieved by our heuristic solution (labeled as "Heuristic").

parameters are the same as in Fig. 7. The results show the throughput of the CCHN is an increasing function of $T$ with decreasing growth rate. Let $\tau_m$ be the maximum achievable throughput of the CCHN when all network resources are dedicated to secondary data transmissions, $\tau_T$ and $\tau_{T+\Delta T}$ be the achievable throughput of the CCHN via cooperating with primary sessions over control intervals with lengths of $T$ and $T+\Delta T$, respectively. Intuitively, $\tau_m \geq \tau_T$. For illustration, we assume the CCHN can deliver PUs' data in $T$ and the SSP's cooperating decision on each primary session remains unchanged when $T$ is extended to $T+\Delta T$. As a result, during the period $\Delta T$, all network resources will be used for secondary transmissions. Then, we have $\tau_{T+\Delta T}=\frac{\tau_T T+\tau_m \Delta T}{T+\Delta T} \geq \frac{\tau_T T+\tau_T \Delta T}{T+\Delta T} = \tau_T$, which explains why the throughput of the CCHN increases when $T$ is extended to $T+\Delta T$. Additionally, the growth rate of the throughput can be derived as $\frac{\tau_{T+\Delta T}-\tau_T}{\Delta T} = \frac{(\tau_m-\tau_T)}{T+\Delta T}$. Since $\tau_T$ increases with respect to $T$, the growth rate of $\tau_T$, i.e., $\frac{\tau_{T+\Delta T}-\tau_T}{\Delta T}$, decreases when $T$ gets larger.

To examine the performance of the augmented SIO-based algorithm, we compare the maximum throughput of the CCHN based on the augmented SIO-based algorithm with that based on the original SIO-based method in Fig. 10. The parameter settings are the same as Fig. 7 except the incentive parameter $\alpha = 1$. The results demonstrate the superiority of the augmented SIO-based algorithm, particularly when primary sessions have a large amount of data to transmit. According to Fig. 10, the original SIO-based method can achieve comparable performance with that of the augmented SIO-based method when $D$ is small. Intuitively, a small $D$ means PUs' data can be easily delivered and the maximum throughput of the CCHN mainly depends on the scheduling of secondary flows. In the CCHN, the sources and the destinations of secondary flows are known to be the edge CR-routers and the BS, which implies that the SIO-based method can cover almost the same set of MISs as the augmented SIO-based algorithm for secondary flows. Consequently, when $D$ is small, based on the SIO-based method, the achievable throughput is close to that based on the augmented SIO-based algorithm. When $D$ gets larger, the SSP will allocate more resources to relay PUs' traffic to acquire the spectrum access opportunities. In this case, the achievable throughput of the CCHN will not only be determined by the scheduling of secondary flows but also be affected by how the primary traffic is delivered. Since the SIO-based method is not efficient in computing the critical MISs for PUs' data delivery, the CCHN will get lower throughput by scheduling the set of MISs computed from the original SIO-based method.

### C. Effectiveness of Our Solution Approach

To evaluate the effectiveness of our solution approach, we consider a CCHN with 15 nodes. These nodes are randomly deployed in a $800m \times 800m$ area. There are two primary sessions coexisting with the considered network. Each primary session intends to transmit $30Mbits$ data in $30s$. The transmission range and the interference range of each node are 240 $m$ and 320 $m$, respectively. The data rate of PU-related link is 3 $Mbps$. To evaluate effectiveness of our heuristic solution, we randomly generate 10 network topologies. For each network topology, there are two edge CR routers and a BS, which are randomly chosen from the network. For each of the 10 network topologies, we obtain the optimal throughput by directly solving the MIS searching subproblem and the MILP and obtain the average optimal throughput by averaging over these 10 network topologies. Meanwhile, we also apply our proposed approach to obtain the maximum achievable throughput for each network topology and obtain the average maximum achievable throughput by averaging over these 10 network topologies. The results are shown in Fig. 11 where the average optimal throughput is labeled as "Optimal" and the average maximum throughput achieved by our heuristic solution is labeled as "Heuristic". As shown in Fig. 11, the maximum throughput achieved by our heuristic solution is close to the optimal throughput, which demonstrates the effectiveness of our approach.

To show how the complexity of our solution approach varies with the size of the considered network, we express the computational complexity in terms of the number of vertices in the corresponding conflict graph. In our heuristic solution approach, we employ heuristic algorithms to solve an MIS searching subproblem and directly solve an MILP.

As shown in Section V.D, our heuristic algorithm is able to solve the MIS searching subproblem in $O\left(V^4\right)$ time, where $V$ inside the parentheses is the number of vertices in the corresponding conflict graph [30]. On the other hand, given the limited number of primary sessions, we can directly solve the MILP by solving a few linear programming (LP) problems with $O\left(V^2\right)$ constraints and $O\left(V^2\right)$ variables. Following from [31], the MILP in our formulation can be solved in $O\left(V^{10}\right)$ time. These results imply that, through our approach, both the MIS searching subproblem and the MILP can be efficiently solved and a solution can be returned in polynomial time.

## VII. Throughput Analysis

In this section, we will analyze what our CCHN based NLC scheme can offer to individual SUs. Specifically, we consider a network where $n$ SUs are distributed in a square with side length $n^{\frac{1}{2}}$. There are totally $n^b$ BSs and CR routers regularly placed in the considered square among which there are $n^d$ BSs, where $0 < d \leq b < 1$. It is not difficult to show mathematically that the achievable throughput of individual SUs is [27]

$$\xi = \begin{cases} \Omega\left(n^{b-1}\right) & 0 < d = b < 1 \\ \Omega\left(\min\left\{n^{b-1}, W n^{\frac{b}{2}-1}\right\}\right) & 0 < \frac{b}{2} < d < b < 1 \\ \Omega\left(\min\left\{n^{b-1}, W n^{d-1}\right\}\right) & 0 < d \leq \frac{b}{2} < 1, \end{cases} \quad (25)$$

where $W$ is the bandwidth which can be exploited by BSs and CR routers for data transmissions and is obtained by, for example, helping with PUs transmissions. $0 < b = d < 1$ corresponds to the case where all nodes deployed by the SSP are BSs.

From (25), we can gain a couple of insights on the behaviour of the CCHN when the number of SUs is high. Clearly from (25), the achievable throughput of each SU decreases when more SUs are served by the CCHN. This is not surprising since there will be more SUs contending for resources. Fortunately, as shown in (25), depending on specific situations, the SSP can improve its service provisioning via either identifying more spectrum resources or deploying more BSs/CR routers. For example, given $0 < \frac{b}{2} < d < b < 1$ and the number of BSs (i.e., $d$), the achievable throughput of individual SUs is determined by $b$ and $W$ which represents the number of CR routers and the number of harvested spectrum resources available to BSs/CR routers. In this case, the SSP can offer higher achievable throughput by deploying more CR routers and acquiring more harvested bands. Once enough CR routers are deployed, i.e., $0 < d \leq \frac{b}{2} < 1$, the achievable throughput of SUs is limited by the number of BSs due to contention at BSs. In this case, the SSP should deploy more BSs in order to resolve contention. Deploying extra BSs and CR routers will not only result in an increase in both the OPEX and CAPEX of the SSP but also increase the complexity of network management. Thus, the deployment of BSs and CR routers in the CCHN should be carefully studied. This is the reason why we study the placement of BSs and CR routers in [24].

## VIII. Conclusion

In this paper, we propose a network-level session-based cooperative (NLC) approach to enable the cooperation-based spectrum access in CRNs. Our NLC approach advocates that a group of SUs, instead of individual SUs, cooperate with primary sessions for spectrum access opportunities. To elaborate on our NLC approach, we further develop an NLC scheme under our cognitive capacity harvesting network (CCHN) architecture. By leveraging the PU-related conflict graph, we mathematically formulate the cooperative mechanism design as a throughput maximization problem with constraints on primary session selection, flow routing, and link scheduling. To facilitate the cross-layer optimization, we develop an augmented algorithm based on scheduling index ordering (SIO) to search for MISs. The impacts of various network parameters on the throughput of the CCHN are carefully studied via extensive simulations, and the results demonstrate the superiority of the proposed CCHN based NLC scheme which provides a promising solution for future cooperative CRNs.

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