On Efficient Resource Allocation for Cognitive and Cooperative Communications

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***Abstract*—Cooperative communication (CC) can offer high channel capacity and reliability in an efficient and low-cost way by forming a virtual antenna array among single-antenna nodes that cooperatively share their antennas. It has been well recognized that the selection of relay nodes plays a critical role in the performance of multiple source-destination pairs. Unfortunately, all prior work has made an unrealistic assumption that spectrum resources are unlimited and each source-destination pair can communicate over a dedicated channel with no mutual interference. In this paper, we study the problem of maximizing the minimum transmission rate among multiple source-destination pairs using CC in a cognitive radio network (CRN). We jointly consider the relay assignment and channel allocation under a finite set of available channels, where the interference must be considered. In order to improve the spectrum efficiency, we exploit the network coding opportunities existing in CC that can further increase the capacity. Such max-min rate problems for cognitive and cooperative communications are proved to be NP-hard and the corresponding MINLP (Mixed-Integer Nonlinear Programming) formulations are developed. Moreover, we apply the reformulation and linearization techniques to the original optimization problems with nonlinear and nonconvex objective functions such that our proposed algorithms can produce high competitive solutions in a timely manner. Extensive simulations are conducted to show that the proposed algorithms can achieve high spectrum efficiency in terms of providing a much improved max-min transmission rate under various network settings.**

***Index Terms*—cooperative communication, cognitive, resource allocation, spectrum efficiency.**

I. INTRODUCTION

By employing several single-antenna nodes to form a virtual antenna array, cooperative communication (CC) has been shown great advantages in offering high capacity and reliability in wireless networks [1], [2]. Typically, there are two cooperative communication modes, namely, amplify-and-forward (AF) and decode-and-forward (DF). For both AF and DF, it has been well recognized that the selection of relay nodes plays a critical role in the performance of CC. For a single source-destination pair, the full diversity order can be achieved by choosing the "best" relay node [3], [4]. Based on this approach, an optimal relay assignment (ORA) algorithm [5] is proposed to maximize the minimum data rate among

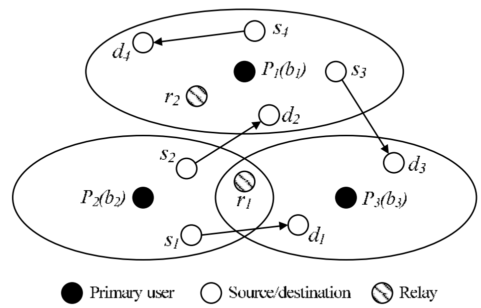

Fig. 1. Cooperative communication in a cognitive radio network

multiple source-destination pairs. Later, a more general model [6] that allows a relay node to be shared by multiple source nodes has been studied.

Although the optimal relay assignment problem has been solved under the models in [5], [6], the spectrum efficiency has never been addressed, under an assumption that each source-destination pair communicates over a dedicate channel without mutual interference. It is unrealistic in modern wireless networks with booming growth of various wireless applications, where the spectrum has become a scarce resource that should be efficiently utilized. Cognitive radio networks (CRNs) have been recently investigated extensively due to their potential to increase the spectrum utilization by allowing unlicensed (*i.e.*, secondary) users to opportunistically use the licensed channels as long as their transmissions do not interfere with licensed (*i.e.*, primary) users. At any time in a CRN, a set of channels that are unused by primary users can be provided for secondary users. As shown in Fig. 1, there are four source-destination pairs and two relay nodes in a CRN with three channels b_1, b_2 and b_3, which are assigned to primary users P_1, P_2 and P_3, respectively. The transmission range of each primary user is also illustrated in the figure. Each secondary user is constrained to access a set of channels due to the activities of primary users. For example, nodes s_1 and s_2 cannot use channel b_2 since they are in the transmission range of P_2 on this channel. Obviously, existing relay assignment algorithms fail to be applied in this scenario with channel constraints. For instance, although r_1 is the best relay for s_2, it cannot assist the transmissions since they are not allowed to work on the same channel.

In this paper, we study the problem of joint relay assignment and channel allocation (RC) for cooperative communications in CRNs. Specifically, we aim at maximizing the minimum achievable transmission rate among multiple source-

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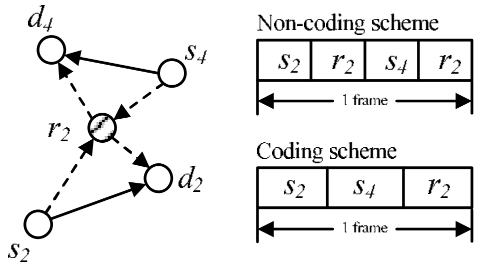

Fig. 2. Network coding for cooperation communication

destination pairs with the assistance of several dedicated relay nodes. Compared with previous works [5], [6] that focus on relay assignment, this research explores the spectrum efficiency by joint optimization of channel allocation and relay assignment. Further, network coding (NC) opportunities emerge when several source-destination pairs share a common relay node and thus can be applied to CC to achieve an increased spectrum efficiency. As shown in Fig. 1, relay r_2 can assist both s_2 and s_4 to forward signals on channel b_3. Without network coding, a frame is divided into four time slots and r_2 serves s_2 and s_4 individually. When network coding is applied, only three time slots are required as shown in Fig. 2, in which the transmissions by s_2 and s_4 in the first two slots can be overheard by all other nodes in the same channel and then r_2 broadcasts the combined signals received from both sources in the third time slot such that d_2 and d_4 can extract their desired signals.

The main contributions of this paper are summarized as follows. First, we consider a cooperative communication model in CRNs and formulate two problems RC and RCNC (RC with Network Coding) that jointly optimize relay assignment and channel allocation with the objective of maximizing the minimum transmission rate among a give set of source-destination pairs. Both problems are proved to be NP-hard. Second, we formulate the RC problem as an MINLP (Mixed-Integer Nonlinear Programming) problem and propose a low-complexity algorithm by exploiting the characteristic of the formulation. In particular, the SPCA (Sequential Parametric Convex Approximation) method [7] is applied to the relaxed problem and the results are used to find the final integer solution. Finally, extensive simulations are conducted to evaluate the proposed algorithms. The experimental results show that our proposals perform closely to the optimal solution and significantly improve the spectrum efficiency in terms of max-min transmission rate.

The rest of this paper are organized as follows. Section II reviews the related work. Section III presents the system model and problem formulation. The hardness of both problems is analyzed in Section IV. The solution for the RC and RCNC problems are elaborated in Section VI and VII, respectively. Performance evaluation is given in Section VIII. Finally, Section IX concludes this paper.

II. Related work

A. Cooperative communication

The basic idea of cooperative communication (CC) is proposed in the pioneering paper [1]. Later, Laneman *et al.* have studied the mutual information and outage probability between a pair of nodes using CC under both AF and DF mode in [2]. Based on their fundamental work, CC has been extensively studied from the perspectives of both physical layer and network layer. In [8], Bletsas *et al.* develop and analyze a distributed method to select the "best" relay based on local measurements of the instantaneous channel conditions. They show that the outage probability of the proposed method can achieve the same diversity-multiplexing tradeoff with the protocols that require coordination and distributed space-time coding for multiple relays. In [3], Zhao *et al.* show that it is sufficient to choose one "best" relay node instead of multiple ones for a single unicast session under AF mode. Moreover, they propose an optimal power allocation algorithm based on the best relay selection to minimize the outage probability. For multiple unicast sessions, Sharma *et al.* [5] consider the relay node assignment with the goal of maximizing the minimum data rate among all concurrent sessions. With the restriction that any relay node can be assigned to at most one source-destination pair, an optimal algorithm call ORA is developed. By relaxing this constraint to allow multiple source-destination pairs to share one relay node, Yang *et al.* [6] prove that the total capacity maximization problem can be also solved with an optimal solution within polynomial time. The benefit of CC in multi-hop wireless networks is exploited in [9], where the joint optimization problem of relay assignment and flow routing for concurrent sessions is formulated as a mixed-integer linear programming and an efficient solution procedure based on branch-and-cut framework is proposed. With the objective of minimizing the long-term average cost while satisfying the QoS requirement, a dynamic relay selection scheme taking user mobility into consideration is proposed in [10]. Network coding has been shown great advantages in improving throughput gain and robustness in wireless networks. The problem of how NC can affect the performance of CC has been investigated in [11]–[13].

B. Spectrum efficiency

The spectrum efficiency has been extensively investigated in multi-channel multi-radio wireless networks [14]–[17]. For example, Wu *et al.* [16] study the problem of adaptive-width channel allocation from a game-theoretic point of view, in which the nodes are rational and always pursue their own objectives. For CRNs, Zhang *et al.* [18] provide an overview of the state-of-art results on resource allocation over space, time and frequency. The energy efficient resource allocation problem in heterogeneous cognitive radio networks is studied in [19]. Although the existing work provides significant contributions, they do not exploit the potential of CC on resource allocation in networks with channel constraints. On the other hand, the resource allocation problems in cooperative networks are investigated in [20], [21], which only focus on optimizing the resource of energy or relay nodes and do not take the spectrum efficiency into consideration. A joint optimization problem of channel pairing, channel-user assignment and power allocation in a dual-hop relaying network with multiple channels is studied in [22]. It deals with a simple scenario that a source communicates with multiple users via a fixed relay, which is different from our model. A cooperative cognitive radio framework is studied in [23] and [24], with the idea that primary users select some of secondary users to be the cooperative relays and in turn lease portion of the channel access time to them for their own data transmission. They focus on the interaction between the secondary and primary users.

III. System Model and Problem Formulation

A. System model

In this work, we study the data dissemination of secondary users in a CRN. Specifically, we consider a number of unicast sessions over source-destination pairs (s_i, d_i), $s_i \in S = \{s_1, s_2, ..., s_n\}$ and $d_i \in D = \{d_1, d_2, ..., d_n\}$, under the support of a set of m dedicated relay nodes $R = \{r_1, r_2, ..., r_m\}$. In the following, we also use s_i to represent the unicast pair (s_i, d_i). All the nodes are equipped with a single antenna and work in a half-duplex mode that they cannot transmit and receive simultaneously.

Without loss of generality, we consider the AF mode and our results can be applied to the DF mode. Suppose each transmission between (s_i, d_i) under the assistance of a relay r_j uses time division on a frame-by-frame basis and each frame is partitioned into two time slots. In the first time slot, source s_i transmits the signal to destination d_i with power P_{s_i}. The SNR (signal-to-noise ratio) $\gamma_{s_i d_i}$ at d_i can be calculated as:

$$\gamma_{s_i d_i} = \frac{P_{s_i} |h_{s_i d_i}|^2}{\sigma_{d_i}^2}, \tag{1}$$

where $\sigma_{d_i}^2$ denotes the variance of background noise at d_i and $h_{s_i d_i}$ represents the effect of path-loss, shadowing and fading between s_i and d_i. Due to the broadcast nature of wireless communication, this transmission is also overheard by relay r_j. In the second time slot, relay r_j amplifies the received signal and forwards it to destination d_i. Following the analysis in [2], the mutual information I_{ij} between s_i and $d_i (1 \leq i \leq n)$ under the assistance of relay $r_j (1 \leq j \leq m)$ can be calculated by:

$$I_{ij} = \frac{1}{2} \log_2 \big(1 + \gamma_{s_i d_i} + \frac{\gamma_{s_i r_j} \gamma_{r_j d_i}}{\gamma_{s_i r_j} + \gamma_{r_j d_i} + 1}\big). \tag{2}$$

Under the direct transmission, source s_i transmits data to its destination in both time slots and the corresponding mutual information, denoted by I_{i0}, is:

$$I_{i0} = \log_2 (1 + \gamma_{s_i d_i}). \tag{3}$$

Different from most existing models, *e.g.*, in [5], [6], where the channel resource is always sufficient, we consider a more realistic one with a finite number of available channels denoted by $B = \{b_1, b_2, ..., b_l\}$ and each channel b_k has bandwidth W_k that may be different from each other. In a CRN, each node employs some spectrum sensing techniques [25] to identify a set of available channels that are not used by primary users for its communication. Due to geographical differences, the set of accessible channels at each node, denoted by $\mathcal{B}(a), a \in S \cup D \cup R$, may be different. We suppose that there is at least one common channel between s_i and d_i, *i.e.*, $\mathcal{B}(s_i) \cap \mathcal{B}(d_i) \neq \emptyset$. Because of the channel constraint, multiple source-destination pairs may work over the same channel, which shall be shared equally according to time division for the purpose of fairness [6], [12].

B. Formulation of the basic RC problem

We define a binary variable $u_{ij} (1 \leq i \leq n, 0 \leq j \leq m)$ for relay assignment as follows:

$$u_{ij} = \begin{cases} 1, & \text{if relay } r_j \text{ is assigned to pair } (s_i, d_i), \\ 0, & \text{otherwise.} \end{cases}$$

Following the discussion in [3], [8], each source-destination pair is assigned at most one relay node, leading to the following constraint:

$$\sum_{j=0}^{m} u_{ij} = 1, \forall i, 1 \leq i \leq n. \tag{4}$$

Note that u_{i0} denotes direct transmission between s_i and d_i. To model the channel allocation, we define the following binary variables for sources and relays:

$$v_{ik} = \begin{cases} 1, & \text{if channel } b_k \text{ is allocated to pair } (s_i, d_i), \\ 0, & \text{otherwise,} \end{cases}$$

$$w_{jk} = \begin{cases} 1, & \text{if channel } b_k \text{ is allocated to relay } r_j, \\ 0, & \text{otherwise,} \end{cases}$$

where $1 \leq i \leq n$, $1 \leq j \leq m$ and $1 \leq k \leq l$. Due to the channel constraint at each node, *i.e.*, the channels occupied by primary users are not accessible, we have:

$$v_{ik} = 0, \forall b_k \in B - \mathcal{B}(s_i) \cap \mathcal{B}(d_i), \forall i, 1 \leq i \leq n, \tag{5}$$

$$w_{jk} = 0, \forall b_k \in B - \mathcal{B}(r_j), \forall j, 1 \leq j \leq m. \tag{6}$$

If CC is adopted, each source-destination pair (s_i, d_i) and its associated relay r_j must be allocated a channel. Otherwise, the channel allocation at the relay node may be not necessary for direct transmission. These lead to the following constraints:

$$\sum_{k=1}^{l} v_{ik} = 1, \forall i, 1 \leq i \leq n, \tag{7}$$

$$\sum_{k=1}^{l} w_{jk} \leq 1, \forall j, 1 \leq j \leq m. \tag{8}$$

Moreover, a common channel should be assigned to the nodes in the same unicast session using either CC or direct transmission. Such a network configuration for CC has been widely adopted in the literature [26] and can be represented by:

$$u_{ij} + v_{ik} - 1 \leq w_{jk} \leq v_{ik} - u_{ij} + 1, \quad \forall i, j, k, 1 \leq i \leq n, 1 \leq j \leq m, 1 \leq k \leq l. \tag{9}$$

When relay assignment is made, *i.e.*, $u_{ij} = 1$, constraint (9) becomes $w_{jk} = v_{ik} (1 \leq k \leq l)$, implying that the same channel is used for s_i and r_j. Otherwise (*i.e.*, $u_{ij} = 0$), it becomes $v_{ik} - 1 \leq w_{jk} \leq v_{ik} + 1$, which is always redundant.

The transmission rate of a source-destination pair (s_i, d_i) on channel b_k with the help of relay r_j can be calculated by:

$$C(s_i, b_k, r_j) \leq \frac{W_k \cdot I_{ij}}{|\mathcal{S}(b_k)|}. \quad (10)$$

where $\mathcal{S}(b_k)$ denotes the set of pairs allocated with the same channel b_k. Using our defined binary variables, we can express the transmission rate of (s_i, d_i) as:

$$C_i \leq \frac{\sum_{k=1}^{l}(v_{ik}W_k)\sum_{j=0}^{m}(u_{ij}I_{ij})}{\sum_{k=1}^{l}(v_{ik}\sum_{j=1}^{n}v_{jk})}. \quad (11)$$

Note that the denominator represents the number of pairs sharing a channel with (s_i, d_i). The objective of our RC problem is to find the optimal relay assignment and channel allocation that maximize the minimum capacity among all source-destination pairs, i.e.,

$$\begin{aligned} \textbf{RC:} \quad & \max \mathcal{C}, \quad \text{s.t.} \\ & \mathcal{C} \leq C_i, \forall i, 1 \leq i \leq n, \\ & (4), (5), (6), (7), (8), (9), (11), \\ & u_{ij}, v_{ik}, w_{jk} \in \{0, 1\}. \end{aligned} \quad (12)$$

Compared with existing works, the RC problem here is more challenging since the relay assignment and channel allocation should be jointly considered.

C. Formulation of the RCNC problem

As in the motivation example shown in Fig. 2, when serving multiple source-destination pairs, the relay can encode the received signals together and broadcast it to destinations by one transmission instead of forwarding the signals individually. Using network coding, the achievable transmission rate of s_i with the help of relay r_j on channel b_k can be calculated by:

$$C^{NC}(s_i, r_j, b_k) \leq \frac{W_k I_{ij}^{NC}|\mathcal{S}(r_j)|}{|\mathcal{S}(b_k)|(|\mathcal{S}(r_j)| + 1)}, \quad (13)$$

where $\mathcal{S}(r_j)$ denotes the set of pairs assigned a common relay node r_j. As derived in [11], the mutual information I_{ij}^{NC} when NC is applied can be calculated by:

$$I_{ij}^{NC} = \log_2\left(1 + \gamma_{s_i d_i} + \frac{\gamma_{s_i r_j}\gamma_{r_j d_i}}{\frac{\delta_{d_i}^2}{\sigma_{d_i}^2}\sum_{k=1}^{n}u_{kj} + \gamma_{r_j d_i} + \frac{\delta_{d_i}^2}{\sigma_d^2}\sum_{k=1}^{n}(u_{kj}\gamma_{s_k r_j})}\right), \quad (14)$$

where

$$\delta_{d_i}^2 = \sigma_{d_i}^2 + (\sum_{k=1}^{n}u_{kj} + 1)(\alpha_{r_j}h_{r_j d_i})^2\sigma_{r_j}^2 + \sum_{k\in[1,n]}^{k\neq i}\Big[u_{kj}\sigma_{d_i}^2\big(\frac{\alpha_{r_j}h_{s_k r_j}h_{r_j d_i}}{h_{s_k d_i}}\big)^2\Big], \quad (15)$$

and α_{r_j} is the amplification factor at relay node r_j [11].

We observe that the NC noise could be ignored when the background noise level is low or the relay node is shared by a small number of source-destination pairs. To reduce computation complexity of (14), we take an approximation approach in the remaining problem formulation, in which the NC noise is ignored, leading to $I_{ij}^{NC} = 2I_{ij}$ since the content in the $\log$ operation is the same [11]. Therefore, the transmission rate of (s_i, d_i) using NC can be expressed in the optimization variables as:

$$C_i^{NC} \leq \frac{\big(\sum_{k=1}^{l}(v_{ik}W_k)\big)\big(\sum_{j=0}^{m}(u_{ij}I_{ij}^{NC})\big)|\mathcal{S}(r_j)|}{\big(\sum_{k=1}^{l}(v_{ik}\sum_{j=1}^{n}v_{jk})\big)(|\mathcal{S}(r_j)| + 1)}, \quad (16)$$

where $|\mathcal{S}(r_j)| = \sum_{j=1}^{m}(u_{ij}\sum_{k=1}^{n}u_{kj}) + u_{i0}$ represents the number of pairs sharing the same relay node with (s_i, d_i). Eventually, the resulting formulation is:

$$\begin{aligned} \textbf{RCNC:} \quad & \max \mathcal{C}^{NC}, \quad \text{s.t.} \\ & \mathcal{C}^{NC} \leq C_i^{NC}, \forall i, 1 \leq i \leq n, \\ & (4), (5), (6), (7), (8), (9), (16), \\ & u_{ij}, v_{ik}, w_{jk} \in \{0, 1\}. \end{aligned} \quad (17)$$

The results under the DF mode can be obtained by replacing the expression of mutual information with the following formula:

$$I_{ij}^{DF} = \frac{1}{2}\min\Big\{\log_2(1 + \gamma_{s_i r_j}), \log_2(1 + \gamma_{s_i d_i} + \gamma_{r_j d_i})\Big\}.$$

That is because the proposed algorithms take the general mutual information of each source-destination pair as input for both cases.

IV. Hardness analysis

In this section, we show the NP-hardness of the formulated problems by reducing the well known NP-complete 3-dimensional matching (3DM) problem to the RC problem, which is first presented in this paper.

Theorem 1: The RC problem is NP-hard.

Proof: In order to prove an optimization problem to be NP-hard, we need to show the NP-completeness of its decision form, which is formalized as follows.

The RC_D problem

INSTANCE: Given a set of source nodes S, a set of destination nodes D and a set of relay nodes R in a wireless network with channel set B, a constant $C \in R^+$

QUESTION: Is there a relay assignment as well as a channel allocation such that the minimum transmission rate is no less than C?

It is easy to see that the RC_D problem is in NP class as the objective function associated with a given resource allocation scheme can be evaluated in a polynomial time. The remaining proof is done by reducing the well-known 3DM problem to the RC_D problem.

The 3DM problem

INSTANCE: Given three disjoint sets X, Y and Z, where $|X| = |Y| = |Z| = \lambda$. Set $T \subseteq X \times Y \times Z$ consists of a set of 3-tuples (x_i, y_i, z_i), $x_i \in X$, $y_i \in Y$ and $z_i \in Z$.

QUESTION: Is there a subset $M \subseteq T$ such that any two 3-tuples in M are disjoint and $|M| \geq \lambda$?

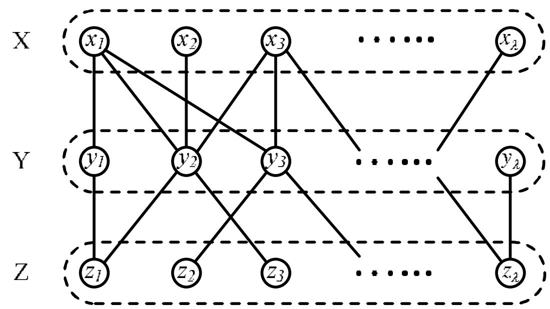

Fig. 3. An instance of 3-dimensional matching.

For clarity, we illustrate the 3DM problem in Fig. 3, where nodes x_i, y_i, and z_i $(1 \leq i \leq \lambda)$ represent the items in set X, Y and Z, respectively. We connect x_i and y_k as well as y_k and z_j together if $(x_i, y_j, z_k) \in T$. We now describe the reduction from 3DM to an instance of the RC_D problem. For each node $x_i \in X$, we create a source-destination pair (s_i, d_i), i.e., $S = X$ and $D = X$. Each node in Y corresponds to a channel in B, i.e., $B = Y$, and all channels have the same bandwidth. The relay node set is created by letting $R = Z$. Each 3-tuple (x_i, y_j, z_k) in T specifies a configuration including a source-destination pair x_i, a channel y_j, and a relay node z_k with the same transmission rate C. We also set the rate of each source-destination pair under the direct transmission to be less than C. In the following, we only need to show that the 3DM problem has a solution if and only if the resulting instance of RC_D problem has a resource allocation scheme that satisfies the minimum rate requirement.

For the only-if case, we suppose that there exists a subset $M \subseteq T$ such that any two 3-tuples are disjoint and $|M| \geq \lambda$. It is a straightforward exercise to verify that the solution of the RC_D problem according to the configurations specified by M is exactly to assign each channel and relay only one source-destination pair such that the capacity C of each pair can be achieved. In other words, the minimum transmission rate is no less than C.

For the if case, we suppose that the RC_D problem has a solution no less than C. In our constructed instance, the maximum rate C of each source-destination pair can be achieved only when it is assigned a relay and a channel exclusively since using direct transmission and sharing channel or relay node will produce a lower transmission rate. In order to achieve the required minimum rate C, all λ source-destination pairs should have the maximum rate C, which forms a solution of the 3DM problem including λ disjoint 3-tuples.

Based on the preceding analysis, we conclude that the RC_D problem is NP-complete. Thus, its optimization form RC problem is NP-hard. ■

For the RCNC problem, we construct an instance by setting the NC noise at a proper level such that the transmission rate under network coding is alwasy less than C. Then, the NP-hardness of RCNC problem can be proved following the similar process.

V. Solution of the RC problem

Recall that the RC problem is formulated in an MINLP model. Since existing mathematical tools, such as CPLEX, do not provide a general solver for MINLP problems, we shall explore the intrinsic properties of our formulation in low-complexity algorithm design in this section. The basic idea is to relax the integer variables into continuous ones such that the global optimum solution of the resulting NLP (Nonlinear Programming) problem can be obtained. After carefully examining the formulation, we eventually convert the NLP problem into LP (Linear Programming) problem, which can be solved fast, by applying the SPCA technique [7]. If the solution of relaxed variables are integers, they are the optimal solution of the original problem as well. Otherwise, we propose a heuristic algorithm that uses the result of the relaxed problem to obtain the feasible integer solution.

A. Solving the relaxed problem

We observe that the formulation is in the linear form except constraint (11) with multiplication and division operations. Due to the fact that the logarithm function can transfer these operations into linear forms, we replace the objective function by:

$$\bar{C}_i \leq \ln\Big(\sum_{k=1}^{l}(v_{ik}W_k)\Big) + \ln\Big(\sum_{j=0}^{m}(u_{ij}I_{ij})\Big) - \ln\Big(\sum_{k=1}^{l}(v_{ik}\sum_{j=1}^{n}v_{jk})\Big), \forall i, 1 \leq i \leq n, \quad (18)$$

such that the objective function and constraint (12) should be changed to $\max \bar{\mathcal{C}}$ and $\bar{\mathcal{C}} \leq \bar{C}_i, 1 \leq i \leq n$, respectively. Note that the problem equivalency is maintained because of the monotonicity property of the logarithm function.

In the following, we consider to transfer the three nonlinear terms in (18) into linear forms. First of all, constraints (4) and (7) under binary variables u_{ij} and v_{ik} guarantee that the first two terms in (18) can be equivalently written in linear forms as:

$$\ln\Big(\sum_{k=1}^{l}(v_{ik}W_k)\Big) = \sum_{k=1}^{l}(v_{ik}\ln W_k), \quad (19)$$

$$\ln\Big(\sum_{j=0}^{m}(u_{ij}I_{ij})\Big) = \sum_{j=0}^{m}(u_{ij}\ln I_{ij}). \quad (20)$$

To linearize the multiplication operation in the third term in (18), we define a new variable θ_{ik}:

$$\theta_{ik} = v_{ik}\sum_{j=1}^{n}v_{jk}, \forall i, k, 1 \leq i \leq n, 1 \leq k \leq l. \quad (21)$$

which represents the number of source-destination pairs sharing channel b_k with s_i. Equation (21) can be equivalently replaced by the following linear constraints:

$$nv_{ik} - n + \sum_{j=1}^{n}v_{jk} \leq \theta_{ik} \leq \sum_{j=1}^{n}v_{jk}, \quad \forall i, k, 1 \leq i \leq n, 1 \leq k \leq l, \quad (22)$$

$$0 \leq \theta_{ik} \leq nv_{ik}, \forall i, k, 1 \leq i \leq n, 1 \leq k \leq l. \quad (23)$$

This is because when $v_{ik} = 1$, new constraint (22) becomes (21), and (23) is redundant. Similarly when $v_{ik} = 0$, new constraint (23) becomes (21), and (22) is redundant.

Finally, we introduce a new variable η'_i to replace the third term in (18) and its associated constraints can be written as follows:

$$\eta'_i \leq -\ln \eta_i, \forall i, 1 \leq i \leq n, \tag{24}$$

$$\eta_i = \sum_{k=1}^{l} \theta_{ik}, \forall i, 1 \leq i \leq n. \tag{25}$$

After the above efforts on linearization, we obtain a new formulation, in which both the objective function and the constraints are expressed in linear forms except (24). Fortunately, after relaxing all integer variables to real number variables, the resulting problem, denoted as RRC, can be solved by an LP solvers using the SPCA method [7], in which (24) is replaced by linear constraints. This conclusion is guaranteed by the property of the formulation that we developed and will be proved at the end of this subsection.

The basic idea of SPCA [7] is to iteratively solve a new LP problem by replacing the nonlinear constraints with linear ones until a converged solution (*i.e.*, the improvement is less than a given accuracy ϵ) is achieved. At each iteration, a new linear constraint is constructed such that the corresponding line is tangent to the curve defined by the nonlinear constraint at the point, which is a solution obtained in the previous iteration. The algorithm to solve the RRC problem is given in Algorithm 1.

Algorithm 1 Solve the RRC problem

$\mathcal{C} = -\infty$, $\mathcal{C}^{(0)} = 0$ and $q = 0$.
while $|\mathcal{C}^{(q)} - \mathcal{C}| > \epsilon$ **do**
  $\mathcal{C} = \mathcal{C}^{(q)}$
  $q = q + 1$
  obtain $\mathcal{C}^{(q)}$ as well as $\eta_i^{(q)} (1 \leq i \leq n)$ by solving the following problem with relaxed variables:

LP_RRC: $\max \bar{\mathcal{C}}$, s.t.

$$\bar{\mathcal{C}} \leq \bar{C}_i, \forall 1 \leq i \leq n, \tag{26}$$

$$\bar{C}_i \leq \Big(\sum_{k=1}^{l} (v_{ik} \ln W_k) \Big) + \Big(\sum_{j=0}^{m} (u_{ij} \ln I_{ij}) \Big) + \eta'_i \tag{27}$$

$$\text{s.t.} \quad (4)-(9), (22), (23), (25), (29)$$

end while

In the proposed algorithm, the nonlinear constraint (24) is initially replaced by:

$$\eta'_i \leq \frac{-\ln n}{n-1} (\eta_i - 1), \forall i, 1 \leq i \leq n, \tag{28}$$

as shown by the line corssing poting $(1, 0)$ and $(n, -\ln n)$ in Fig. 4. The corresponding solution will serve as an upper-bound because the constraints are relaxed. Such setting guarantees to find an initial feasible solution of the RRC problem. Let $x^{(q)}$ denote the optimal solution of variable x by solving the corresponding LP problem formulated as LP_RRC at the

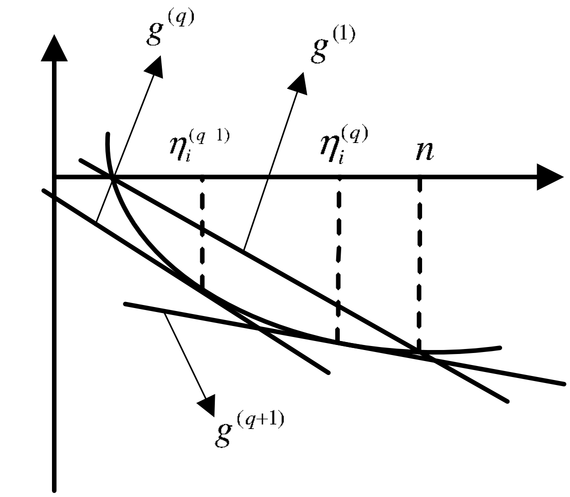

Fig. 4. Sequential parametric convex approximation for $-\ln x$ function

q-th iteration of Algorithm 1. Therefore, the linear constraint at the q-th iteration can be expressed as:

$$\eta'_i \leq g^{(q)}(\eta_i, \eta_i^{(q-1)}), \forall i, 1 \leq i \leq n, \tag{29}$$

where function $g^{(q)}$ is given by:

$$g^{(q)}(x, x_0) = \begin{cases} \frac{-\ln n}{n-1}(x-1), & q = 1, \\ \frac{-1}{x_0}(x - x_0) - \ln x_0, & q \geq 2. \end{cases}$$

Function $g^{(q)} (q \geq 2)$ is defined by the tangent line to $-\ln x$ at point $(\eta_i^{(q-1)}, -\ln \eta_i^{(q-1)})$ as shown in Fig. 4.

Theorem 2: The solution of RRC problem obtained by Algorithm 1 satisfies the Karush-Kuhn-Tucker (KKT) conditions.

Proof: For any feasible point $(\eta_i^{(q-1)}, -\ln \eta_i^{(q-1)})$, we update the linear constraint $\eta'_i \leq g^{(q)}(\eta_i, \eta_i^{(q-1)})$ for the LP_RRC formulation in the Algorithm 1. As guaranteed by the analysis in [7], the conclusion is achieved when the nonlinear function $-\ln \eta_i$ and its replaced linear function $g^{(q)}(\eta_i, \eta_i^{(q-1)}) (q \geq 2)$ have the same values at $\eta_i = \eta_i^{(q-1)}$ for both original and their first-order differential functions. These can be verified by:

$$g^{(q)}(\eta_i^{(q-1)}, \eta_i^{(q-1)}) = -\ln \eta_i^{(q-1)}, \tag{30}$$

$$\nabla g^{(q)}(\eta_i^{(q-1)}, \eta_i^{(q-1)}) = \nabla(-\ln \eta_i^{(q-1)}) = \frac{-1}{\eta_i^{(q-1)}}. \tag{31}$$

■

Note the KKT conditions are satisfied only for the relaxed problem, referred to as RRC in our paper, not for the MILP problem. Although Algorithm 1 returns a solution satisfying the KKT conditions, we find out that it is always the global optimal solution empirically through extensive numerical experiments.

B. Finding the feasible integer solution

If the results of variables u_{ij}, v_{ik} and w_{jk} in the solution of the RRC problem are integers, they are also the optimal solution of the original RC problem. Otherwise, they will serve as the guidance in finding the feasible integer solution. In this section, we propose a heuristic algorithm that can quickly find feasible integer solution by rounding the results returned by Algorithm 1.

Algorithm 2 Find feasible integer solution

1: **for** $i = 1$ to n **do**
2: find $v_{ik'}$ with the largest value among $v_{ik}(1 \leq k \leq l)$
3: set $v_{ik'} = 1$, $v_{ik} = 0(1 \leq k \leq l, k \neq k')$ and $\rho(i) = k'$
4: **end for**
5: **for** $i = 1$ to n **do**
6: find the $u_{ij}(1 \leq j \leq m)$ with values greater than zero and store them in set J according to ascending order
7: **for** $k = 1$ to $|J|$ **do**
8: get the $u_{ij'}$ in the k-th position in J
9: **if** relay $r_{j'}$ can work on channel $b_{\rho(i)}$ without any conflict and improve the direct transmission rate of (s_i, d_i) **then**
10: set $u_{ij'} = 1$, $u_{ij} = 0(1 \leq j \leq m, j \neq j')$ and $w_{j'\rho(i)} = 1$
11: break;
12: **else**
13: set $u_{ij'} = 0$
14: **end if**
15: **end for**
16: **end for**

The basic idea is to first make channel allocation for all unicast pairs under direct transmission, and then to assign relay node for each pair if a common channel for this CC session is available and an improved performance can be obtained. The pseudo code of the heuristic algorithm is given in Algorithm 2. In the channel allocation for each pair (s_i, d_i), we find $v_{ik'}$ with the largest value and set $v_{ik'} = 1$, $v_{ik} = 0(1 \leq k \leq l, k \neq k')$. Such setting is expected to achieve comparable performance to the optimal one because the real value v_{ik} would represent the probability of the corresponding channel allocation. At the same time, we save index k' of allocated channel $b_{k'}$ in $\rho(i)$. Suppose all pairs initially working under the direct transmission after channel allocation. Then, we assign relays by determining the value of each u_{ij} from line 5 to 16. For each pair (s_i, d_i), we still find the $u_{ij'}$ with the largest value among $u_{ij}(1 \leq j \leq m)$. If $r_{j'}$ can work on channel $b_{\rho(i)}$ without introducing any conflict and improve the direct transmission rate, we set $u_{ij'} = 1$, $u_{ij} = 0(1 \leq j \leq m, j \neq j')$ and $w_{j'b(i)} = 1$. Otherwise, we set $u_{ij'} = 0$ and continue to find another possible relay. Note that such conflict means that a relay node transmits on more than one channel simultaneously.

VI. Solution of the RCNC problem

In this section, we apply the similar optimization technique to solve the RCNC problem. The constraint (16) can be replaced by:

$$\bar{C}_i^{NC} \leq \ln\Big(\sum_{k=1}^{l}(v_{ik}W_k)\Big) + \ln\Big(\sum_{j=0}^{m}(u_{ij}I_{ij})\Big) + \ln\big(\sum_{j=1}^{m}(u_{ij}\sum_{k=1}^{n}u_{kj}) + u_{i0}\big) - \ln\Big(\sum_{k=1}^{l}(v_{ik}\sum_{j=1}^{n}v_{jk})\Big) - \ln\big(\sum_{j=1}^{m}(u_{ij}\sum_{k=1}^{n}u_{kj}) + u_{i0} + 1\big). \quad (32)$$

Comparing to the objective function of the RC problem, we notice that the additional effort is to linearize the third and fifth terms in (32). First of all, the multiplication operation $u_{ij}\sum_{k=1}^{n}u_{kj}$ in both term can be replaced by a new variable ϕ_{ij} as we have done to $v_{ik}\sum_{j=1}^{n}v_{jk}$ in the last section. The associated linear constraints are:

$$u_{ij} - n + \sum_{k=1}^{n}u_{kj} \leq \phi_{ij} \leq \sum_{k=1}^{n}u_{kj}, \quad \forall i, j, 1 \leq i \leq n, 1 \leq j \leq m, \quad (33)$$

$$0 \leq \phi_{ij} \leq n \cdot u_{ij}, \forall i, j, 1 \leq i \leq n, 1 \leq j \leq m. \quad (34)$$

To linearize the third term $\ln(\sum_{j=1}^{m}\phi_{ij} + u_{i0})$ in (32), we define:

$$\psi_i = \sum_{j=1}^{m}\phi_{ij} + u_{i0}, \quad (35)$$

such that the non-linear constraint involved in the final formulation $\alpha_i \leq \ln\psi_i$ can be replaced by a number of linear constraints:

$$\alpha_i \leq \ln\frac{t+1}{t}(\psi_i - t) + \ln t, \forall i, t. \quad (36)$$

Such constraint approximation guarantees the equivalency of the formulation because function $\ln\psi_i$ is convex and ψ_i is an integer variable.

Finally, the non-linear constraint $\beta_i \leq -\ln(\psi_i + 1)$ due to the fifth term in (32) can be replaced by a linear constraint:

$$\beta_i \leq g^{(q)}(\psi_i + 1, \psi_i^{(q-1)} + 1) \quad (37)$$

at the q-th iteration of the corresponding SPCA process.

To find the global optimal solution of the relaxed RCNC problem, denoted as RRCNC, the same process as in Algorithm 1 is applied except that the LP formulation LP_RRC in line 5 should be replaced by the following:

LP_RRCNC: $\max \bar{\mathcal{C}}^{NC}$, s.t.

$$\bar{\mathcal{C}}^{NC} \leq \bar{C}_i^{NC}, \forall i, 1 \leq i \leq n, \quad (38)$$

$$\bar{C}_i^{NC} \leq \Big(\sum_{k=1}^{l}(v_{ik}\ln W_k)\Big) + \Big(\sum_{j=0}^{m}(u_{ij}\ln I_{ij})\Big) + \alpha_i + \eta_i' + \beta_i$$

$$(4) - (9), (22), (23), (25), (29), (33) - (37)$$

To adopt to the RCNC problem, Algorithm 2 in finding the feasible integer solution is extended only in the step of relay selection in line 9 of Algorithm 2. To check the performance improvement for each (s_i, d_i), we should consider these cases: (1) direct transmission, (2) regular CC, (3) CC with network coding. The scheme with the most improvement is applied to the unicast session (s_i, d_i).

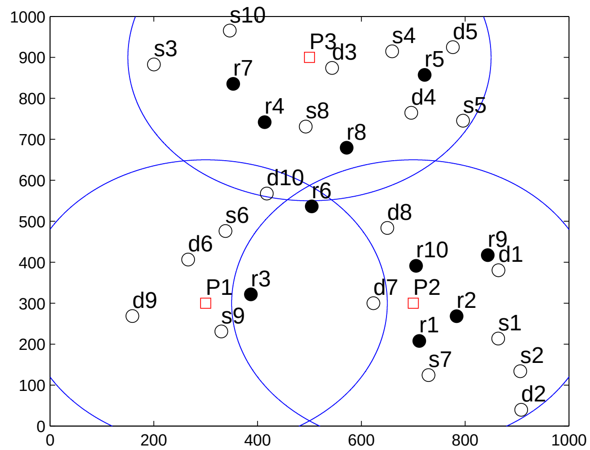

Fig. 5. A network with 10 source-destination pairs and 10 relay nodes

VII. Numerical results

In this section, we present some numerical results to illustrate the performance of our proposed algorithms. We first study example networks to examine how an efficient resource allocation can be achieved by our proposed algorithm. Then we present the average performance over 20 random network instances each network setting with various number of n, m and l.

A. Results of example networks

We first consider an example network with 10 source-destination pairs as well as 10 relay nodes randomly distributed within a 1000×1000 square region as shown in Fig. 5. Three channels b_1, b_2, and b_3 with identical bandwidth 22MHz are registered by three primary users $P1$, $P2$ and $P3$, respectively. Transmission at all source and relay nodes are made at unit power. Parameter h_{ij} describing the path-loss component between nodes i and j with a distance $||i-j||$ is given by $|h_{ij}|^2 = ||i-j||^{-4}$, in which 4 is the path-loss exponent. We set the background noise power at each node to 10^{-10} unit.

In this example network, it is easy to see that although r_6 is the best relay candidate for pair (s_8, d_8), it cannot assist the transmission since they are not allowed to work on the same channel ($\mathcal{B}(r_9) = \{b_3\}$ and $\mathcal{B}(s_8) \cap \mathcal{B}(d_8) = \{b_1\}$). The results of the RC problem returned by our algorithm are shown in Table I. Compared with the minimum transmission rate of 5.7214 under direct transmission, our algorithm can increase the transmission rate to 9.7373, by employing relay r_7 for source-destination pair (s_3, d_3) under channel b_1. This pair also shares channel b_2 with pairs (s_5, d_5) and (s_8, d_8). Network coding can be applied at r_4 and our algorithm for the RCNC problem returns the minimum transmission rate of 10.4200 as shown in Table II.

We also evaluate the performance of RC and RCNC by comparing their results with the optimal solutions obtained by exhaustive search in 20 random network instances that contain 8 source-destination pairs, 5 relay nodes and 3 channels. As

TABLE I
RESULTS OF THE RC PROBLEM

Pair	Relay	Channel	Rate
(s_1, d_1)	-	b_3	16.7251
(s_2, d_2)	-	b_3	30.8386
(s_3, d_3)	r_7	b_1	9.7373
(s_4, d_4)	-	b_2	46.3504
(s_5, d_5)	-	b_1	24.7484
(s_6, d_6)	-	b_3	29.2863
(s_7, d_7)	-	b_3	12.0030
(s_8, d_8)	r_8	b_1	10.4200
(s_9, d_9)	-	b_3	15.5257
(s_{10}, d_{10})	r_4	b_2	10.5325

TABLE II
RESULTS OF THE RCNC PROBLEM

Pair	Relay	Channel	Rate
(s_1, d_1)	-	b_3	16.7251
(s_2, d_2)	-	b_3	30.8386
(s_3, d_3)	r_4	b_2	12.9290
(s_4, d_4)	-	b_1	46.3504
(s_5, d_5)	-	b_1	24.7484
(s_6, d_6)	-	b_3	29.2863
(s_7, d_7)	-	b_3	12.0030
(s_8, d_8)	r_8	b_1	10.4200
(s_9, d_9)	-	b_3	15.5257
(s_{10}, d_{10})	r_4	b_2	14.0433

shown in Fig. 6, the results of our algorithms are very close to the optimal solution.

B. Results of random networks

We study the performance of our proposed algorithms in the form of average results over 20 random network instances. The influence of channel number is first investigated by changing its value from 3 to 8 in the networks with 15 source-destination pairs and 10 relay nodes. The bandwidth of each channel is randomly distributed within the range $[20MHz, 30MHz]$ and the other simulation settings are the same as the ones used in the example study. As shown in Fig. 7, the performance of all the schemes increases as the channel number grows since the contention of network resources is alleviated when a larger number of channels are available. The proposed RC and RCNC always outperform the direct transmission scheme and their performance gap increases as the channel number grows. Moreover, network coding brings more gains with the smaller number of channels. The performance ratio between RC and RCNC is 1.34 in 3-channel networks. When the channel number increases to 8, this ratio decreases to 1.05. This is because more pairs may work over the same channel when the available channels are less such that the coding probability increases.

We then study the effect of the number of source-destination pairs on the max-min rate. Under fixed 10 relays and 5 available channels in the networks, as shown in Fig. 8, the max-min rate decreases as the pair number increases for all the transmission schemes. The performance of RC and RCNC is obviously higher than that of direct transmission and the coding gain is larger in the networks with more source-destination pairs. We attribute this phenomenon to the fact that

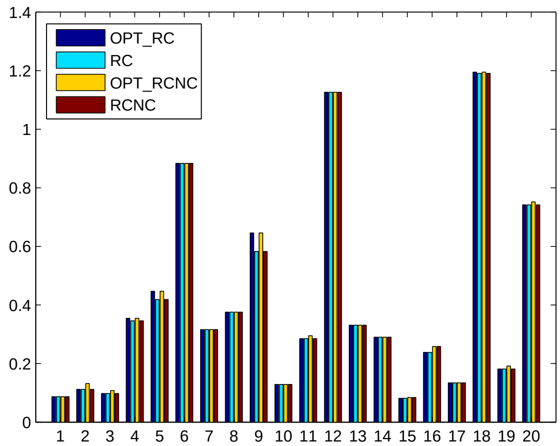

Fig. 6. Comparison with optimal solution in 20 random network instances

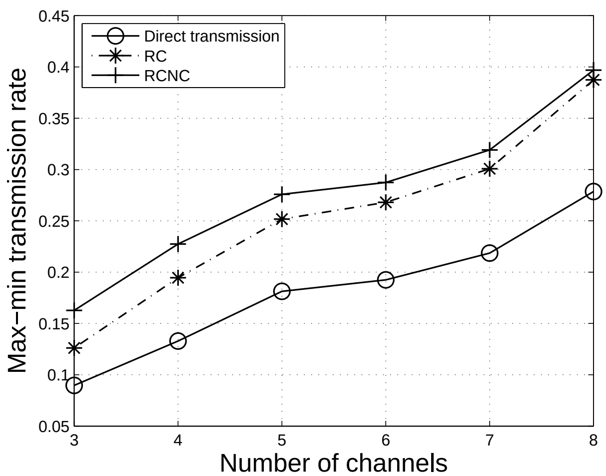

Fig. 7. The max-min transmission rate versus the number of channels

more pairs work over the same channel such that the coding probabilities increases in the networks with a larger number of source-destination pairs

Finally, we evaluate the performance under different numbers of relay nodes. The number of source-destination pairs and the channel number are fixed to 15 and 5, respectively. As shown in Fig. 9, when the number of relays is 6, the RC and RCNC increase the max-min rate of the direct transmission by 5% and 11%, respectively. The improvement increases to 65% and 74%, respectively, as the number of relay nodes increases to 14. This gain comes from the assistance of a larger number of relay nodes. Moreover, we observe that increasing trends of the RC and RCNC slow down when the relay number is larger than 10. This is because each source-destination pair has already found a relay node with good performance under such scenarios. Further increasing the relay number results in limited performance improvement.

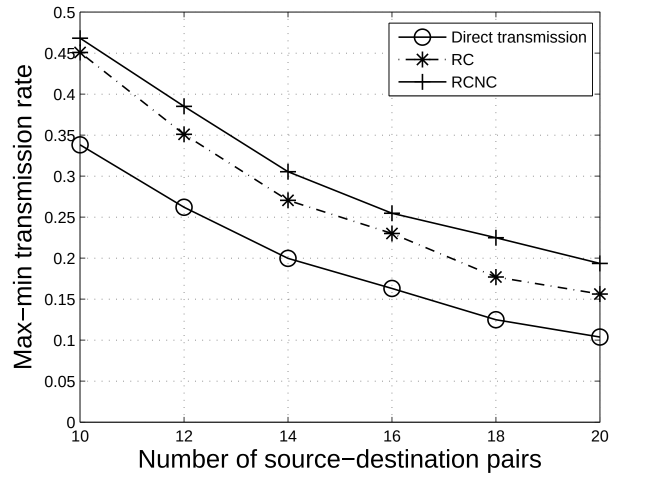

Fig. 8. The max-min transmission rate versus the number of source-destination pairs

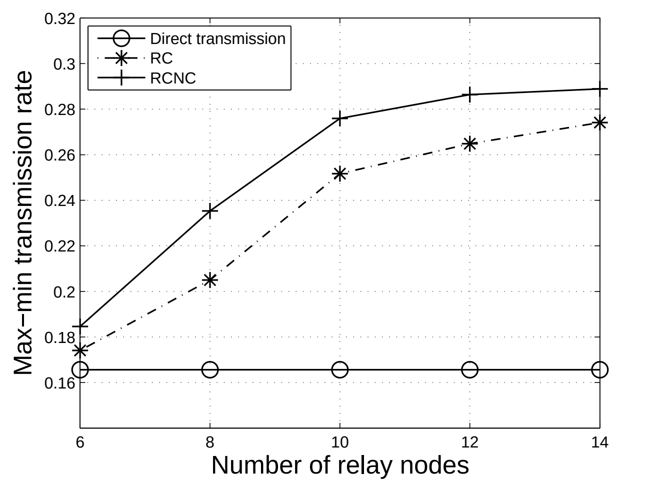

Fig. 9. The max-min transmission rate versus the number of relay nodes

VIII. Conclusion

In this paper, we study the problem of maximizing the minimum transmission rate among multiple source-destination pairs using cooperative communication in a cognitive radio network. The relay assignment and channel allocation are jointly considered and network coding is exploited to improve the spectrum efficiency. Such max-min rate problems are proved to be NP-hard and formulated as MINLPs. Reformulation and linearization techniques are applied to produce high competitive solutions in a timely manner.

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