HERA: An Optimal Relay Assignment Scheme for Cooperative Networks

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***Abstract*—Exploiting the nature of broadcast and the relaying capability of wireless devices, cooperative communication is becoming a promising technology to increase the channel capacity in wireless networks. In cooperative communication, the scheme for assigning relay nodes to users plays a critical role in the resulting channel capacity. A significant challenge is how to make the scheme robust to selfish and cheating behavior of users while guaranteeing the social optimal system capacity. In this paper, we design an integrated optimal relay assignment scheme called HERA for cooperative networks. To avoid system performance degradation due to the selfish relay selections by the source nodes, we propose a payment mechanism for charging the source nodes to induce them to converge to the optimal assignment. To prevent relay nodes from manipulating the relay assignment by reporting transmission power untruthfully, we propose a payment mechanism to pay them for providing relaying service. We also show that HERA is budget-balanced, meaning that the payment collected from source nodes is no smaller than the payment paid to relay nodes.**

***Index Terms*—Relay assignment, cooperative communication, truthful auction.**

I. Introduction

THROUGH cooperative relaying from wireless devices (generally called relay nodes), cooperative communication (CC) [5] has been shown to have the potential to increase the channel capacity between two wireless devices. The essence of CC is to exploit the nature of broadcast and the relaying capability of other nodes to achieve spatial diversity. Two primary CC modes have been commonly used, *Amplify-and-Forward* (AF) and *Decode-and-Forward* (DF) [5], depending on how the relay node processes the received signal and transmits to the destination. Because an improper choice of the relay node for a source-destination pair can result in an even smaller capacity than that under direct transmission, the assignment of relay nodes plays a critical role in the performance of CC [1–3, 12, 21].

We consider the following scenario in this paper. In a wireless network, there are a number of source nodes and corresponding destination nodes. Other wireless devices in the network can function as relay nodes. We are interested in designing a relay assignment scheme, such that the total capacity under the assignment is maximized.

We call the network with CC the *cooperative network*. Designing a relay assignment scheme for cooperative networks is very challenging for the following reasons.

- *System Performance*: A relay assignment scheme should provide a relay assignment algorithm, which appropriately assigns relay nodes to source nodes such that the system capacity is maximized. The system capacity is the sum of the capacity of all source nodes.
- *Selfish Behavior*: Usually, wireless devices in cooperative networks are not owned by a single entity, but by many profit-maximizing independent entities. Therefore, even if an optimal relay assignment algorithm is developed, an individual source node may not want to follow the assignment, given the fact that it can improve its own capacity by selecting a different relay node. This selfish behavior can result in system performance degradation.
- *Potential Cheating*: As to relay nodes, most of the protocols in cooperative networks assume that all the wireless devices are cooperative, and in particular willing to participate in cooperative communications as relay nodes. However, the voluntary cooperativeness assumption may not be true in reality as relaying data for other network nodes can consume energy and other resources of the relay node. A naive solution is to make payments to the participating relay nodes as an incentive. The question arising from this naive solution is how much a relay node should be paid for helping with the cooperative communication. A simple payment mechanism is vulnerable to the dishonest behavior of relay nodes, in the sense that a relay node can profit from lying about its true relaying capability, e.g. transmission power.

In this paper, we design an integrated optimal relay assignment scheme for cooperative networks, called HERA, named after the Goddess of Marriage in Greek Mythology. **To the best of our knowledge, HERA is the first relay assignment scheme for cooperative networks, which considers both selfish and cheating behavior of network entities while guaranteeing socially optimal system performance.** HERA is composed of three components: 1) an optimal relay assignment algorithm, 2) a payment mechanism for source nodes, and 3) a payment mechanism for relay nodes. HERA is a centralized scheme, where a system administrator is responsible for collecting the payment from the source nodes and paying the relay nodes. HERA provides the following key features:

- HERA guarantees to find a relay assignment for the source nodes, such that the total capacity is maximized. The system model considered in this paper allows a relay node to be shared by multiple source nodes. Hence it is more general compared with the model in [12], where each relay node is restricted to be assigned to only one source node. Our assignment algorithm works

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regardless of which CC mode is used in the network. It is also independent of the relation between the number of source nodes and that of the relay nodes. In addition, our algorithm can guarantee that the achieved capacity of each source node under the assignment is no less than that achieved by direct transmission.

- HERA provides a payment mechanism to charge source nodes for using relaying service from the relay nodes. To cope with the selfish behavior of source nodes, our payment mechanism is designed in a way such that the system possesses a *Strictly Dominant Strategy Equilibrium* (SDSE), where each selfish source node plays the strategy that brings the maximum utility regardless of others' strategies. Furthermore, the SDSE achieves the socially optimal system capacity.
- HERA also provides a payment mechanism to pay relay nodes for providing relaying service. To prevent relay nodes from lying about their relaying ability (e.g. transmission power) to gain profits, the payment mechanism uses a VCG-based payment formula to calculate the payment. Under this payment mechanism, reporting true relaying ability is the dominant strategy for each relay node. In other words, the relay node can maximize its payment received from the system administrator by reporting its true relaying ability.
- Finally, from the perspective of the system administrator, HERA assures that the system administrator will not run the system with any loss. In other words, the total payment collected from source nodes is at least as much as the total payment paid to relay nodes.

The remainder of this paper is organized as follows. In Section II, we give a brief review of the related work in the literature. In Section III, we describe the system model considered in this paper. In Section IV, we present a polynomial time optimal algorithm to solve the relay assignment problem. In Section V, we study the selfish behavior of source nodes and design a payment mechanism to charge source nodes for using relaying service. In Section VI, we consider the potential cheating relay nodes in the system, design another payment mechanism to pay relay nodes for providing relaying service and prove the desired properties of the designed mechanism. We present our extensive experimental results in Section VII. We conclude this paper in Section VIII.

II. Related Work

In this section, we briefly review the related work on cooperative communication (CC), with the focus on relay assignment.

In [1], Bletsas *et al.* proposed a novel scheme to select the best relay node for a single source node from a set of available relays. However, this cannot be extended to a network consisting multiple source nodes, which is the model studied in this paper.

Some efforts have been made on the relay assignment or relay selection problem in cooperative networks. In [2], Cai *et al.* studied the problem of relay selection and power allocation for AF wireless relay networks. They first considered a simple network with only one source node, and then extended it to the multiple-source case. The proposed algorithm is an effective heuristic, but offers no performance guarantee. Xu *et al.* [17] studied a similar problem with a different objective, which is to minimize the total power consumption of the network. In [7], Ng and Yu jointly considered the relay node selection, cooperative communication and resource allocation for utility maximization in a cellular network. However, the algorithm is heuristic and not polynomial, as pointed out by Sharma *et al.* [12].

In [12], Sharma *et al.* studied the relay assignment problem in a network environment, such that the minimum capacity among all source nodes is maximized. Following this work, Zhang *et al.* [20] considered the relay assignment problem with interference mitigation. In both models in [12] and [20], a relay node is restricted to be assigned to at most one source node. In contrast, our model in this paper is more general in the sense that it allows multiple source nodes to share the same relay node. In addition, different from [12], our objective is to maximize the total capacity of all pairs. Although Zhang *et al.* [20] had the same objective as ours, they only provided a heuristic algorithm.

There are few studies on the scheme design for cooperative communications in the networking literature, among which the works in [4, 13, 14, 19] are most related to our work. In [13], Shastry and Adve proposed a pricing-based system to stimulate the cooperation via payment to the relay nodes. The goal in their scheme is to ensure both the access point and the relay nodes benefit from cooperation. In [14], Wang *et al.* employed a buyer/seller Stackelberg game, where a single buyer tries to buy services from multiple relays. The buyer announces its selection of relays and the required transmission power, then the relays ask proper prices to maximize their profits. In [4], Huang *et al.* proposed two auction mechanisms, which are essentially repeated games. In each auction mechanism, each user iteratively updates its bid to maximize its own utility function with the knowledge of others' previous bids. With a common drawback, none of the above works guarantees the optimal system capacity or considers truthfulness of relay nodes. In [19], Yang *et al.* designed a truthful auction scheme for cooperative communications, which satisfies truthfulness, individual rationality, and budget balance properties. Similarly, the scheme cannot guarantee the optimal system capacity.

III. System Model

We consider a static wireless network. There is a set $\mathcal{S} = \{\mathbf{s}_1, \mathbf{s}_2, \cdots, \mathbf{s}_n\}$ of n source nodes and a set $\mathcal{D} = \{\mathbf{d}_1, \mathbf{d}_2, \cdots, \mathbf{d}_n\}$ of corresponding destination nodes, where $\mathbf{s}_i$ transmits to $\mathbf{d}_i$. Other nodes in the network function as relay nodes. We assume that there is a collection $\mathcal{R} = \{\mathbf{r}_1, \mathbf{r}_2, \ldots, \mathbf{r}_m\}$ of m relay nodes. As in [12], we assume that orthogonal channels are available in the network (e.g. using OFDMA) to mitigate interference. We further assume that each node is equipped with a single transceiver and can either transmit or receive at a time. Let P_i^s denote the transmission power of source node $\mathbf{s}_i$ and P_j^r denote the transmission power of relay node $\mathbf{r}_j$. Let $P^s = (P_1^s, P_2^s, \ldots, P_n^s)$ and

$P^r = (P_1^r, P_2^r, \ldots, P_m^r)$. When node u transmits a signal to node v with power P_u, the signal-to-noise ratio (SNR) at node v, denoted as SNR_{uv}, is $SNR_{uv} = \frac{P_u}{N_0 \cdot ||u,v||^\alpha}$, where N_0 is the abient noise, $||u,v||$ is the Euclidean distance between u and v, and α is the path loss exponent which is between 2 and 4 in general.

For the transmission model, we assume that each source node has an option to use cooperative communication (CC) with the help of a relay node. A recent work by Zhao *et al.* [21] showed that it is sufficient for a source node to choose the best relay node even when multiple relay nodes are available to achieve full diversity. Therefore, it is reasonable to assume that each source node will either transmit directly or use CC with the help of only one relay node. When source node s transmits to destination node d directly, the achievable capacity is $c_{DT}(s,d) = W \log_2(1 + SNR_{sd})$, where W is the bandwidth of the channel. There are two different CC modes, *Amplify-and-Forward* (AF) and *Decode-and-Forward* (DF) [5]. Let r denote the relay node and P_r be the transmission power of r. The achievable capacity from s to d under the AF mode is

$$c_{AF}(s,r,d) = \frac{W}{2} \log_2 \left(1 + SNR_{sd} + \frac{SNR_{sr} \cdot SNR_{rd}}{SNR_{sr} + SNR_{rd} + 1}\right).$$

The achievable capacity from s to d under the DF mode is

$$c_{DF}(s,r,d) = \frac{W}{2} \min\{ \log_2(1 + SNR_{sr}), \log_2(1 + SNR_{sd} + SNR_{rd})\}.$$

Note that, for given s and d, both c_{AF} and c_{DF} are functions of P_r, $||s,r||$ and $||r,d||$. Thus whether a source node can obtain larger capacity by using CC than it can by transmitting directly depends on the relay node assigned. The scheme designed in this paper is *independent* of the CC mode. We use c_R to denote the achievable capacity under CC. Let $\bar{\mathcal{S}} = \mathcal{S} \cup \{\mathbf{s}_0\}$ and $\bar{\mathcal{R}} = \mathcal{R} \cup \{\mathbf{r}_0\}$, where $\mathbf{s}_0$ is a *virtual source node* and $\mathbf{r}_0$ is a *virtual relay node*. Let $\mathcal{A} = \{(\mathbf{s}_1, \mathbf{r}_{j_1}), (\mathbf{s}_2, \mathbf{r}_{j_2}), \ldots, (\mathbf{s}_n, \mathbf{r}_{j_n})\} \subseteq \mathcal{S} \times \bar{\mathcal{R}}$ denote a relay assignment. If $(\mathbf{s}_i, \mathbf{r}_j) \in \mathcal{A}$, relay node $\mathbf{r}_j$ is *assigned* to source node $\mathbf{s}_i$ under assignment $\mathcal{A}$. If $(\mathbf{s}_i, \mathbf{r}_0) \in \mathcal{A}$, $\mathbf{s}_i$ transmits to $\mathbf{d}_i$ directly under the relay assignment $\mathcal{A}$. Note that it is possible to have $(\mathbf{s}_i, \mathbf{r}_j), (\mathbf{s}_k, \mathbf{r}_j) \in \mathcal{A}$, for $\mathbf{s}_i \neq \mathbf{s}_k$. This is a major difference between our model and the model in [12], where a relay node is assigned to at most one source node. Since we do not enforce such constraints, our model is more general.

Now let us consider the case where the same relay node is assigned to multiple source nodes. In this case, we use $\mathcal{S}_j$ to denote the set of source nodes being assigned $\mathbf{r}_j$, i.e., $\mathcal{S}_j = \{\mathbf{s}_i | (\mathbf{s}_i, \mathbf{r}_j) \in \mathcal{A}\}$. Note that $\mathcal{S}_j$ is dependent on relay assignment $\mathcal{A}$. We assume that $\mathbf{r}_j$ equally provides service to all the source nodes employing it. This can be achieved for example by using a reservation-based TDMA scheduling. The relay node serves each source node in a round-robin fashion. Each frame is dedicated to a single source node for CC. Each source node gets served every n_j frames, where $n_j = |\mathcal{S}_j|$. Therefore, the average achievable capacity for each source node $\mathbf{s}_i \in \mathcal{S}_j$ is $\frac{c_R(\mathbf{s}_i, \mathbf{r}_j, P_j^r, \mathbf{d}_i)}{n_j}$. Let $c(\mathbf{s}_i, \mathbf{r}_j, \mathcal{A}, P^r)$ denote the achievable capacity of $\mathbf{s}_i$ under relay assignment $\mathcal{A}$, where $(\mathbf{s}_i, \mathbf{r}_j) \in \mathcal{A}$. *Hereafter we also omit* $\mathbf{d}_i$ *in the capacity expression.* Thus we have

$$c(\mathbf{s}_i, \mathbf{r}_j, \mathcal{A}, P^r) = \begin{cases} \frac{c_R(\mathbf{s}_i, \mathbf{r}_j, P_j^r)}{n_j}, & \text{if } \mathbf{r}_j \neq \mathbf{r}_0, \\ c_{DT}(\mathbf{s}_i), & \text{if } \mathbf{r}_j = \mathbf{r}_0. \end{cases}$$

In the expressions above, we take P^r (or P_j^r) as a parameter, because a relay node may lie about its transmission power in the problem to be studied in Section VI. We will explain it in detail later. We define the *system capacity*, denoted by $C(\mathcal{S}, \mathcal{R}, \mathcal{A}, P^r)$, corresponding to relay assignment $\mathcal{A}$ and transmission power P^r, as the total capacity of all the source nodes in $\mathcal{S}$, i.e., $C(\mathcal{S}, \mathcal{R}, \mathcal{A}, P^r) = \sum_{\mathbf{s}_i \in \mathcal{S}, (\mathbf{s}_i, \mathbf{r}_j) \in \mathcal{A}} c(\mathbf{s}_i, \mathbf{r}_j, \mathcal{A}, P^r)$.

The ultimate goal in the design of the relay assignment scheme can be defined as the following optimization problem.

Definition 1: (Relay Assignment Problem (RAP)): Given $\mathcal{S}$, $\mathcal{D}$, $\mathcal{R}$, and P^r, the *Relay Assignment Problem* seeks for a relay assignment $\mathcal{A}$ such that $C(\mathcal{S}, \mathcal{R}, \mathcal{A}, P^r)$ is maximized among all possible relay assignments. □

RAP is different from the problem studied in [12], whose objective is to maximize the minimum capacity among all source nodes. Let $\mathcal{A}^*(\mathcal{S}, \mathcal{D}, \mathcal{R}, P^r)$ be the optimal solution to RAP. For notational simplicity, we use $\mathcal{A}^*$ to denote $\mathcal{A}^*(\mathcal{S}, \mathcal{D}, \mathcal{R}, P^r)$ and C to denote $C(\mathcal{S}, \mathcal{R}, \mathcal{A}, P^r)$ when the context is clear. Correspondingly, C^* denotes $C(\mathcal{S}, \mathcal{R}, \mathcal{A}^*, P^r)$. In the next section, we focus on designing an optimal algorithm to solve RAP.

IV. An Optimal Relay Assignment Algorithm

Due to the possibility of sharing a common relay node among multiple source nodes, solving RAP becomes a challenging task. Nonetheless, we can design a polynomial time optimal algorithm to solve RAP by exploiting some special properties of the problem.

The design of the optimal algorithm for RAP is based on Lemma 1 and Lemma 2. Due to space limitations, all the proofs in this section are omitted and can be found in [18].

Lemma 1: Let $\mathcal{A}$ be a relay assignment, where relay node $\mathbf{r}_j \in \mathcal{R}$ is assigned to $n_j > 1$ source nodes. Let $\mathbf{s}_i \in \mathcal{S}_j$ be the source node with the minimum c_R, i.e., $c_R(\mathbf{s}_i, \mathbf{r}_j, P_j^r) = \min_{\mathbf{s}_k \in \mathcal{S}_j} c_R(\mathbf{s}_k, \mathbf{r}_j, P_j^r)$. If we let $\mathbf{s}_i$ transmit to the destination $\mathbf{d}_i$ directly, instead of using $\mathbf{r}_j$, while keeping others the same, the total capacity will be increased. That is $C(\mathcal{S}, \mathcal{R}, \mathcal{A}', P^r) > C(\mathcal{S}, \mathcal{R}, \mathcal{A}, P^r)$, where $\mathcal{A}' = \mathcal{A} \setminus \{(\mathbf{s}_i, \mathbf{r}_j)\} \cup \{(\mathbf{s}_i, \mathbf{r}_0)\}$. □

According to Lemma 1, we can always improve the system capacity if there exists a relay node shared by more than one source node in the current relay assignment. Unfortunately, the example in [18, Section 4.A] shows that this procedure may lead to a *local optimum*. Nonetheless, Lemma 1 implies a nice property pertaining to the optimal relay assignment for RAP.

Lemma 2: Let $\mathcal{A}^*$ be an optimal solution to RAP. Each relay node is assigned to at most one source node in $\mathcal{A}^*$. □

Surprisingly, although our model allows multiple source nodes to share a common relay node, an optimal relay assignment preferably assigns a relay node to at most one source node to achieve the maximum system capacity. On the other hand, we know that each source node will either employ a relay node for CC or transmit to the destination directly, but not both at the same time. This one-to-one matching relation in the optimal solution indicates that we can transform any instance of RAP into that of the *Maximum Weighted Bipartite Matching* (MWBM) problem [15] and solve it using corresponding algorithms.

Now we are ready to present our optimal algorithm for RAP. The pseudo-code is illustrated in Algorithm 1.

Algorithm 1: ASGMNT$(\mathcal{S}, \mathcal{R}, \mathcal{D}, P^r)$

Construct a set $\mathcal{U}$ of n vertices corresponding to $\mathcal{S}$;
Construct a set $\mathcal{V}$ of $n+m$ vertices corresponding to $\mathcal{D} \cup \mathcal{R}$;
Construct a set $\mathcal{E}$ of edges, where $(\mathbf{s}_i, v) \in \mathcal{E}$ if $v = \mathbf{d}_i$ or $v \in \mathcal{R}$;
for $i = 1$ **to** n **do**
  $w(\mathbf{s}_i, \mathbf{d}_i) \leftarrow c_{DT}(\mathbf{s}_i)$;
end
for $\forall \mathbf{s}_i \in \mathcal{U}$ and $\forall \mathbf{r}_j \in \mathcal{R}$ **do**
  $w(\mathbf{s}_i, \mathbf{r}_j) \leftarrow c_R(\mathbf{s}_i, \mathbf{r}_j, P_j^r)$;
end
Apply an MWBM algorithm to find a maximum weighted matching $\mathcal{M}^*$ in graph $G = (\mathcal{U}, \mathcal{V}, w)$;
$\mathcal{A}^* \leftarrow \emptyset$;
for $(\mathbf{s}_i, v) \in \mathcal{M}^*$ **do**
  if $v \in \mathcal{R}$ **then** $\mathcal{A}^* \leftarrow \mathcal{A}^* \cup \{(\mathbf{s}_i, v)\}$;
  else $\mathcal{A}^* \leftarrow \mathcal{A}^* \cup \{(\mathbf{s}_i, \mathbf{r}_0)\}$;
end
return $\mathcal{A}^*$.

The correctness and the computational complexity of Algorithm 1 are guaranteed by Theorem 1.

Theorem 1: Algorithm 1 guarantees to find an optimal relay assignment $\mathcal{A}^*(\mathcal{S}, \mathcal{R}, \mathcal{D}, P^r)$ for RAP in time bounded by $O(n^2 m)$.

V. Mechanism Design for Selfish Users

System capacity maximization is only desirable from a global point of view, not from the point of view of an individual selfish user. Yet most wireless devices in the network are owned by independent profit-maximizing entities. In this section, we use the term *selection* instead of *assignment*, because selection is from the user's point of view while assignment is from the system's point of view. When selfish users have their own preferences on relay selection, several questions may arise: Is there a *stable state*, where no user has the incentive to deviate from its current selection? How can users reach such a state? If the system performance is not optimized in the stable state, how can the system administrator exert influence on the relay selection to achieve social optimum? These questions will be the focus of this section.

A. Strategic Game Model and Game Theory Concepts

To study the relay selection problem with selfish entities, we model it by a game, called *Relay Selection Game* (RSG). In this game, the source nodes are *players*, because they make relay selections. The *strategy* of each player is its relay selection $\gamma_i \in \bar{\mathcal{R}}$. The strategy profile $\gamma = (\gamma_1, \gamma_2, \ldots, \gamma_n)$ is a vector of all players' strategies. Let $\gamma_{-i} = (\gamma_1, \ldots, \gamma_{i-1}, \gamma_{i+1}, \ldots, \gamma_n)$ denote the strategy profile excluding player $\mathbf{s}_i$'s strategy. Hence, $\gamma = (\gamma_i, \gamma_{-i})$ is a strategy profile where $\mathbf{s}_i$ plays γ_i and others play γ_{-i}. Given a strategy profile γ, we can construct the corresponding relay assignment $\mathcal{A} = \{(\mathbf{s}_1, \gamma_1), (\mathbf{s}_2, \gamma_2), \ldots, (\mathbf{s}_n, \gamma_n)\}$. Given a relay assignment $\mathcal{A} = \{(\mathbf{s}_1, \mathbf{r}_{j_1}), (\mathbf{s}_2, \mathbf{r}_{j_2}), \ldots, (\mathbf{s}_n, \mathbf{r}_{j_n})\}$, we have the corresponding strategy profile γ, where $\gamma_i = \mathbf{r}_{j_i}$ for each $\mathbf{s}_i \in \mathcal{S}$. In this game, each player $\mathbf{s}_i$ selects a strategy γ_i to maximize its own *utility*, which is defined as its achieved capacity $u_i^s(\gamma) = c(\mathbf{s}_i, \gamma_i, \mathcal{A}, P^r)$. If $u_i^s(\gamma_i, \gamma_{-i}) > u_i^s(\gamma_i', \gamma_{-i})$, we say that player $\mathbf{s}_i$ prefers γ_i to γ_i' when others play γ_{-i} .

A strategy γ_i is called a *best response* strategy of player $\mathbf{s}_i$ if it maximizes $\mathbf{s}_i$'s utility function when others play γ_{-i}, i.e., $u_i^s(\gamma_i, \gamma_{-i}) \geq u_i^s(\gamma_i', \gamma_{-i})$ for any $\gamma_i' \in \bar{\mathcal{R}}$. A strategy profile $\gamma^{ne} = (\gamma_1^{ne}, \gamma_2^{ne}, \ldots, \gamma_n^{ne})$ is called a *Nash Equilibrium* (NE) [9], if for every player $\mathbf{s}_i \in \mathcal{S}$, we have $u_i^s(\gamma_i^{ne}, \gamma_{-i}^{ne}) \geq u_i^s(\gamma_i, \gamma_{-i}^{ne})$ for any $\gamma_i \in \bar{\mathcal{R}}$. In other words, every player is playing its best response strategy in an NE and therefore has no incentive to deviate from its current strategy unilaterally. A stronger concept than best response strategy is *strictly dominant strategy* [10]. A strategy γ_i is called a strictly dominant strategy of player $\mathbf{s}_i$ if it gives strictly larger utility than any other strategy regardless of the strategies others play. Correspondingly, a strategy profile $\gamma^{sd} = (\gamma_1^{sd}, \gamma_2^{sd}, \ldots, \gamma_n^{sd})$ is called a *Strictly Dominant Strategy Equilibrium* (SDSE), if $\forall \mathbf{s}_i \in \mathcal{S}, \forall \gamma_{-i}, \forall \gamma_i \neq \gamma_i^{sd}$, we have $u_i(\gamma_i^{sd}, \gamma_{-i}) > u_i(\gamma_i, \gamma_{-i})$. Obviously, an SDSE is an NE, but not vice versa. If a game has an SDSE, then the SDSE is the unique NE of the game.

B. Nonoptimality of Nash Equilibrium

As a motivation to the design of our payment mechanism, we show that an NE of RSG is not necessarily social optimal. Note that RSG is closely related to the *Congestion Game* introduced by Rosenthal [11]. Specifically, RSG can be reduced to the *Congestion Game with Player-specific Payoff Function*, which was studied by Milchtaich [6]. Due to space limitations, we make reference to [6] for the existence proof of NE and the algorithm for computing an NE. This does not degrade the rigor of our paper, as the result in this subsection only serves as a *motivation* to the design of our payment mechanism.

	$\mathbf{s}_1$	$\mathbf{s}_2$	$\mathbf{s}_3$	$\cdots$	$\mathbf{s}_n$
$\mathbf{r}_0$	1	1	1	$\cdots$	1
$\mathbf{r}_1$	10	1	1	$\cdots$	5
$\mathbf{r}_2$	10	10	1	$\cdots$	1
$\mathbf{r}_3$	1	5	10	$\cdots$	1
$\mathbf{r}_4$	1	1	5	$\cdots$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\mathbf{r}_m$	1	1	1	$\cdots$	10

(a) $C^{ne} = 10 + 5(n-1)$

	$\mathbf{s}_1$	$\mathbf{s}_2$	$\mathbf{s}_3$	$\cdots$	$\mathbf{s}_n$
$\mathbf{r}_0$	1	1	1	$\cdots$	1
$\mathbf{r}_1$	10	1	1	$\cdots$	5
$\mathbf{r}_2$	10	10	1	$\cdots$	1
$\mathbf{r}_3$	1	5	10	$\cdots$	1
$\mathbf{r}_4$	1	1	5	$\cdots$	1
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
$\mathbf{r}_m$	1	1	1	$\cdots$	10

(b) $C^* = 10n$

TABLE I: An example with $POA = \frac{10+5(n-1)}{10n} \approx \frac{1}{2}$

A common concept to quantify how the selfish behavior of players can affect the social performance is called *Price of Anarchy (POA)*, which is defined as $POA = \min_{\gamma^{ne}} \frac{C^{ne}}{C^*}$, where C^{ne} is the system capacity when players are playing NE strategy γ^{ne}. Recall that C^* is the optimal system capacity. A simple example in Table I shows that the selfishness of players can degrade the system performance by half.

C. Mechanism Design to Achieve Social Optimality

To achieve the optimal relay assignment, we need to exert influence on players' selection of relay nodes. Here we require players to make payments for using relaying service.

As in many existing scheme designs, we assume *virtual currency* exists in the system. Each source node (player) needs to pay certain amount of currency to the administrator based on its relay node selection. In particular, given the strategy profile γ and the corresponding $\mathcal{A}$, we define the payment of player $\mathbf{s}_i$ as

$$p_i^s = \begin{cases} c(\mathbf{s}_i, \gamma_i, \mathcal{A}, P^r) + \left(g(\gamma_i, \gamma_i^*) - \frac{1}{n-1} \sum_{k \neq i} g(\gamma_k, \gamma_k^*) \right), & \text{if } \gamma_i \neq \mathbf{r}_0, \\ g(\gamma_i, \gamma_i^*) - \frac{1}{n-1} \sum_{k \neq i} g(\gamma_k, \gamma_k^*), & \text{if } \gamma_i = \mathbf{r}_0. \end{cases}$$

Here $g(\gamma_i, \gamma_i^*) = l \cdot |x - y|$, where $\gamma_i = \mathbf{r}_x$ and $\gamma_i^* = \mathbf{r}_y$, $l = \max_{\mathbf{s}_i \in \mathcal{S}} c_{DT}(\mathbf{s}_i) + \varepsilon$ and $\varepsilon > 0$ is a constant. In other words, $g(\gamma_i, \gamma_i^*)$ is equal to l times the difference between the indices of the relay node selected by $\mathbf{s}_i$ and the relay node assigned in the optimal solution. Intuitively, a source node needs to pay for using relaying service if it selects a relay node. Each source node also pays (or receives) a penalty (resp. bonus) depending on how much more (resp. less) it deviates from the optimal strategy γ^* than others. Here γ^* is the strategy profile corresponding to the optimal solution $\mathcal{A}^*$ of RAP computed by Algorithm 1. The utility of player $\mathbf{s}_i$ is then defined as

$$u_i^s(\gamma_i, \gamma_{-i}) = c(\mathbf{s}_i, \gamma_i, \mathcal{A}, P^r) - p_i^s. \quad (1)$$

A similar payment mechanism was also used by Wu *et al.* to solve a different problem [16]. We call the Relay Selection Game with utility function (1) the *Incentive-added Relay Selection Game* (IRSG). Next we prove that γ^* is an SDSE in IRSG.

Theorem 2: Let γ^* be the strategy profile corresponding to the optimal solution $\mathcal{A}^*$ of RAP. Then γ^* is an SDSE for IRSG. Therefore, γ^* is the unique NE of IRSG. □

Proof: To prove this theorem, it suffices to prove that $\forall \mathbf{s}_i \in \mathcal{S}$, $\forall \gamma_{-i}, \forall \gamma_i \neq \gamma_i^*$, we must have $u_i^s(\gamma_i^*, \gamma_{-i}) > u_i^s(\gamma_i, \gamma_{-i})$. Plugging the payment p_i^s into (1), we have

$$u_i^s(\gamma_i, \gamma_{-i}) = \begin{cases} \frac{1}{n-1} \sum_{k \neq i} g(\gamma_k, \gamma_k^*) - g(\gamma_i, \gamma_i^*), & \text{if } \gamma_i \neq \mathbf{r}_0, \\ c_{DT}(\mathbf{s}_i) - \left(g(\gamma_i, \gamma_i^*) - \frac{1}{n-1} \sum_{k \neq i} g(\gamma_k, \gamma_k^*) \right), & \text{if } \gamma_i = \mathbf{r}_0. \end{cases}$$

Assume player $\mathbf{s}_i$ plays strategies γ_i^* and $\gamma_i \neq \gamma_i^*$, respectively. We consider all the possible cases:

Case 1: $\gamma_i^* \neq \mathbf{r}_0$ and $\gamma_i \neq \mathbf{r}_0$.

$$\begin{aligned} u_i^s(\gamma_i^*, \gamma_{-i}) - u_i^s(\gamma_i, \gamma_{-i}) &= g(\gamma_i, \gamma_i^*) - g(\gamma_i^*, \gamma_i^*) \\ &= g(\gamma_i, \gamma_i^*) > 0, \end{aligned}$$

where the second equality and the last inequality follow from the definition of $g(\cdot, \cdot)$ and the assumption that $\gamma_i \neq \gamma_i^*$.

Case 2: $\gamma_i^* \neq \mathbf{r}_0$ and $\gamma_i = \mathbf{r}_0$.

$$\begin{aligned} u_i^s(\gamma_i^*, \gamma_{-i}) - u_i^s(\gamma_i, \gamma_{-i}) &= g(\gamma_i, \gamma_i^*) - c_{DT}(\mathbf{s}_i) - g(\gamma_i^*, \gamma_i^*) \\ &= g(\gamma_i, \gamma_i^*) - c_{DT}(\mathbf{s}_i) > 0, \end{aligned}$$

where the last inequality follows from the definition of $g(\cdot, \cdot)$.

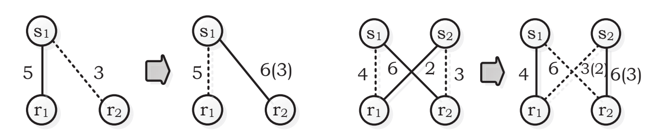
Case 3: $\gamma_i^* = \mathbf{r}_0$ and $\gamma_i \neq \mathbf{r}_0$.

$$\begin{aligned} u_i^s(\gamma_i^*, \gamma_{-i}) - u_i^s(\gamma_i, \gamma_{-i}) &= c_{DT}(\mathbf{s}_i) + g(\gamma_i, \gamma_i^*) - g(\gamma_i^*, \gamma_i^*) \\ &= c_{DT}(\mathbf{s}_i) + g(\gamma_i, \gamma_i^*) > 0. \end{aligned}$$

We have proved that γ^* is an SDSE of IRSG. Hence, γ^* is the unique NE of IRSG. ■

VI. Mechanism Design to Prevent Relay Nodes from Cheating

Relay nodes involved in the final assignment help source nodes with cooperative communications at the cost of their own energy and other resources. Without an attractive incentive, a relay node may not be willing to participate in cooperative communications. A naive solution to this problem is to pay each relay node the achieved capacity of cooperative communications involving it (while the relay assignment $\mathcal{A}$ is computed based on the reported transmission power, the achieved capacity is computed based on the true transmission power and the relay assignment $\mathcal{A}$). However, such a simple payment mechanism could result in relay nodes' lying about their transmission power. For example, a relay node would not be selected if it reports its transmission power honestly, but could be selected if it reports a larger transmission power instead. Likewise, a relay node would be assigned to cooperate with a source node, resulting in a small capacity, if it reports its transmission power honestly. But it could cooperate with another source node by lying, resulting in a larger capacity. These two examples are shown in Fig. 1. In both examples, the relay node receives a larger payment by lying about its transmission power.



(a) $\mathbf{r}_2$ increases its payment from 0 to 3. The system capacity is decreased from 5 to 3.

(b) $\mathbf{r}_2$ increases its payment from 2 to 3. The system capacity is decreased from 8 to 7.

Fig. 1: Examples showing that a relay node can increase its payment by lying. Solid links represent the relay assignment. The numbers beside the links represent the achieved capacities calculated based on reported transmission power (outside the parentheses) and based on the true transmission power (inside the parentheses) if it is different from the reported transmission power.

Obviously, the dishonest behavior of relay nodes may influence the relay assignment and further degrade the system performance. Hence it is essential to design a payment mechanism such that every relay node will report its transmission power truthfully to maximize its payment.

A. Necessary Concepts

In the conventional terminology of mechanism design [8], every agent i has its private information t_i called its *type*, which is only known to itself. Let $t = (t_1, t_2, \ldots, t_m)$ be the type profile consisting of types from all the agents. Each agent i plays a strategy $\lambda_i \in \Lambda_i$ (reports a value of its type), where Λ_i is its strategy space. Let $\lambda = (\lambda_1, \lambda_2, \ldots, \lambda_m)$ be the strategy profile consisting of strategies from all the agents. Similarly, we have $\lambda_{-i} = (\lambda_1, \ldots, \lambda_{i-1}, \lambda_{i+1}, \ldots, \lambda_m)$ and $\lambda = (\lambda_i, \lambda_{-i})$. A mechanism then provides an *output* function $o = o(\lambda_1, \lambda_2, \ldots, \lambda_m)$ and a *payment* function $p_i = p_i(\lambda_1, \lambda_2, \ldots, \lambda_m)$ for each agent i based on the reported profile. For each output o, each agent has a valuation $v_i(t_i, o)$. Then the utility of agent i is $u_i(t_i, o) = v_i(t_i, o) + p_i$. All the agents are assumed to be *rational*, in the sense that each agent will always maximize its utility by playing the best strategy. A strategy λ_i is called a *dominant strategy* of agent i if it maximizes i's utility no matter what strategies others play. A payment mechanism is *truthful* (or strategyproof, incentive compatible), if reporting true type is a dominant strategy for each agent. A payment mechanism satisfies *individual rationality*, if the agent's utility of participating in the mechanism is guaranteed to be non-negative when the agent reports its type truthfully. In this paper, we design a VCG-based payment mechanism [8].

B. Design Details

In our design, we assume that each relay node $\mathbf{r}_j$ is an agent and the type of $\mathbf{r}_j$ is its transmission power P_j^r. Before the relay assignment, each relay node $\mathbf{r}_j$ reports a transmission power T_j, which may or may not be equal to P_j^r. Let $P^r = (P_1^r, P_2^r, \ldots, P_m^r)$ be the *true transmission power* profile and $T = (T_1, T_2, \ldots, T_m)$ the *reported transmission power* profile. ASGMNT$(\mathcal{S}, \mathcal{D}, \mathcal{R}, T)$ (illustrated in Algorithm 1) is then applied to compute an optimal relay assignment $\mathcal{A}^*(T)$, which is optimal with respect to T. According to Lemma 2, each relay node $\mathbf{r}_j$ is assigned to at most one source node under $\mathcal{A}^*(T)$. Under $\mathcal{A}^*(T)$, let $\sigma_j(T) \in \bar{\mathcal{S}}$ denote the source node, to which $\mathbf{r}_j$ is assigned. If $\sigma_j(T) = \mathbf{s}_0$, it indicates that $\mathbf{r}_j$ is not assigned to any source node. Let $\sigma(T) = (\sigma_1(T), \sigma_2(T), \ldots, \sigma_m(T))$ be the source nodes corresponding to all the relay nodes in $\mathcal{R}$. Let $\Psi(\mathcal{S}, \mathcal{R}, T)$ denote the optimal capacity of the system consisting of $\mathcal{S}$ and $\mathcal{R}$ based on T, i.e., $\Psi(\mathcal{S}, \mathcal{R}, T) = C(\mathcal{S}, \mathcal{R}, \mathcal{A}^*(T), T)$. Let $\mathcal{S}_{-\mathbf{s}_i} = \mathcal{S} \setminus \{\mathbf{s}_i\}$, $\mathcal{R}_{-\mathbf{r}_j} = \mathcal{R} \setminus \{\mathbf{r}_j\}$, and $T_{-j} = (T_1, \ldots, T_{j-1}, T_{j+1}, \ldots, T_m)$. We define the payment to relay node $\mathbf{r}_j$ (for a given T) by the following

$$p_j^r(T) = \begin{cases} 0, & \sigma_j(T) = \mathbf{s}_0, \\ c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r) - (\Psi(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) & \\ -\Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j})), & o/w, \end{cases} \quad (2)$$

where $c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r)$ is the achieved capacity in the cooperative communication, and $\Psi(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) - \Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j})$ is a charge determined by the system administrator, based on T.

Before proving the properties of the designed payment mechanism, we note the fact that

$$\begin{aligned} & c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r) + \Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) \\ = \; & C(\mathcal{S}, \mathcal{R}, \mathcal{A}(T'), T'), \end{aligned} \quad (3)$$

where $T' = (P_j^r, T_{-j})$ and $\mathcal{A}(T')$ is *some* relay assignment for the RAP instance given by $(\mathcal{S}, \mathcal{D}, \mathcal{R}, T')$. The intuition behind this fact is that, after the optimal assignment $\mathcal{A}^*(T)$ is computed, the values of $c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r)$ and $\Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j})$ are independent of T_j, and only dependent on T'. In addition, their sum is the system capacity under $\mathcal{A}(T')$, which may be different from $\mathcal{A}^*(T')$. Similarly, if relay node $\mathbf{r}_j$ reports its true transmission power P_j^r and other relay nodes report T_{-j}, we have

$$\begin{aligned} & c(\sigma_j(T'), \mathbf{r}_j, \mathcal{A}^*(T'), P^r) + \Psi(\mathcal{S}_{-\sigma_j(T')}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) \\ = \; & C(\mathcal{S}, \mathcal{R}, \mathcal{A}^*(T'), T'). \end{aligned} \quad (4)$$

Theorem 3: The payment mechanism to pay relay nodes defined in (2) is individually rational. □

Proof: Let $\mathbf{r}_j$ be any relay node and $T' = (P_j^r, T_{-j})$. Then the payment to relay node $\mathbf{r}_j$ is

$$\begin{aligned} & p_j^r(T') \\ = \; & c(\sigma_j(T'), \mathbf{r}_j, \mathcal{A}^*(T'), P^r) + \Psi(\mathcal{S}_{-\sigma_j(T')}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) \\ & -\Psi(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) \\ = \; & C(\mathcal{S}, \mathcal{R}, \mathcal{A}^*(T'), T') - \Psi(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) \quad (5) \\ = \; & C(\mathcal{S}, \mathcal{R}, \mathcal{A}^*(T'), T') - C(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, \mathcal{A}^*(T_{-j}), T_{-j}) \\ \geq \; & 0, \end{aligned}$$

where (5) follows from (4). This completes the proof. ■

Theorem 4: The payment mechanism to pay relay nodes defined in (2) is truthful. □

Proof: Assume $\mathbf{r}_j$ reports a transmission power $T_j \neq P_j^r$. Let $T' = (P_j^r, T_{-j})$. Then the difference between its received payment and that when reporting truthfully is

$$\begin{aligned} & p_j^r(T') - p_j^r(T) \\ = \; & c(\sigma_j(T'), \mathbf{r}_j, \mathcal{A}^*(T'), P^r) + \Psi(\mathcal{S}_{-\sigma_j(T')}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) \\ & - \big(c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r) + \Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j})\big) \\ = \; & C(\mathcal{S}, \mathcal{R}, \mathcal{A}^*(T'), T') - (c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r) \\ & +\Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j})\big) \quad (6) \\ = \; & C(\mathcal{S}, \mathcal{R}, \mathcal{A}^*(T'), T') - C(\mathcal{S}, \mathcal{R}, \mathcal{A}(T'), T') \quad (7) \\ \geq \; & 0, \quad (8) \end{aligned}$$

where (6) follows from (4), (7) follows from (3), and (8) follows from the optimality of $\mathcal{A}^*(T')$. ■

In Section V, we designed a payment mechanism to charge source nodes for using relaying service. In this section, we designed another payment mechanism to pay relay nodes for providing relaying service. A question arising naturally is whether HERA is *budget-balanced*. That is, whether the payment collected from all the source nodes is enough to pay all the relay nodes. The following theorem confirms the budget-balance property of HERA.

Theorem 5: HERA is budget-balanced. □

Proof: By Theorem 2, we know that all the source nodes will follow the optimal relay assignment. Let $T = (T_1, T_2, \ldots, T_m)$ be the reported transmission power profile. Let γ^* be the strategy profile of source nodes corresponding to $\mathcal{A}^*(T)$. Therefore, the total payment collected from all source nodes is

$$p^s = \sum_{\mathbf{s}_i \in \mathcal{S}} p_i^s = \sum_{\mathbf{s}_i \in \mathcal{S}, \gamma_i^* \neq \mathbf{r}_0} c(\mathbf{s}_i, \gamma_i^*, \mathcal{A}^*(T), P^r). \quad (9)$$

The total payment paid to all the relay nodes is

$$\begin{aligned} p^r &= \sum_{\mathbf{r}_j \in \mathcal{R}} p_j^r \\ &= \sum_{\mathbf{r}_j \in \mathcal{R}, \sigma_j(T) \neq \mathbf{s}_0} c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r) \\ &\quad - \sum_{\mathbf{r}_j \in \mathcal{R}, \sigma_j(T) \neq \mathbf{s}_0} \left(\Psi(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) - \Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j})\right), \end{aligned}$$

where the second equality follows the fact that

$$\begin{aligned} & \textstyle\sum_{\mathbf{s}_i \in \mathcal{S}, \gamma_i^* \neq \mathbf{r}_0} c(\mathbf{s}_i, \gamma_i^*, \mathcal{A}^*(T), P^r) \\ = & \textstyle\sum_{\mathbf{r}_j \in \mathcal{R}, \sigma_j(T) \neq \mathbf{s}_0} c(\sigma_j(T), \mathbf{r}_j, \mathcal{A}^*(T), P^r). \end{aligned}$$

The profit of the administrator is

$$\begin{aligned} & p^s - p^r \\ = & \sum_{\mathbf{r}_j \in \mathcal{R}, \sigma_j(T) \neq \mathbf{s}_0} \left(\Psi(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) - \Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j})\right) \\ \geq & 0, \end{aligned} \quad (10)$$

where (10) follows from the fact that $\Psi(\mathcal{S}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) - \Psi(\mathcal{S}_{-\sigma_j(T)}, \mathcal{R}_{-\mathbf{r}_j}, T_{-j}) \geq 0$. ■

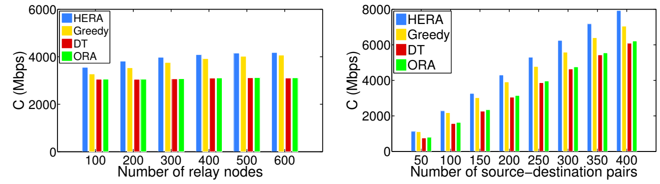
VII. Evaluations

A. Experiment Setup

We considered a wireless network, where wireless nodes are randomly distributed in a $1000m \times 1000m$ square. We followed the same parameter settings as in [12]. The only exception was the transmission power, which in our setting is uniformly distributed over $(0, 1]$, i.e., $P_i^s, P_j^r \in (0, 1]$ Watt for all $\mathbf{s}_i \in \mathcal{S}$ and $\mathbf{r}_j \in \mathcal{R}$. We set the bandwidth W to 22 MHz for all channels. For the transmission model, we assumed that the path loss exponent $\alpha = 4$ and the abient noise $N_0 = 10^{-10}$. In most of the experiments, we varied both n and m from 50 to 400 with increment of 50. For each setting, we randomly generated 100 instances and averaged the results.

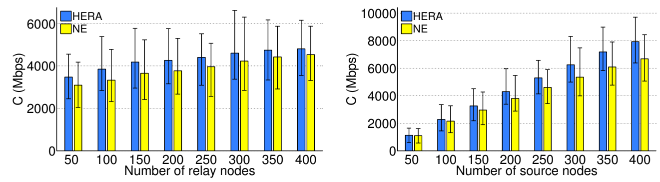
1) Assignment Algorithm: Since this paper is the first work on the design of relay assignment scheme for cooperative networks with the objective to maximize the total capacity, we compared our algorithm with the algorithms listed below.

- *Greedy Assignment Algorithm (Greedy):* This algorithm proceeds iteratively. In each iteration, it greedily assigns a relay node to the source node or lets the source node transmit directly, such that the system capacity under the current assignment is maximized.
- *Direct Transmission Algorithm (DT):* In this algorithm, each source node transmits to its destination directly. The system capacity under this assignment is $C = \sum_{\mathbf{s}_i \in \mathcal{S}} c_{DT}(\mathbf{s}_i)$. *DT* serves as a lower bound of the system capacity of the network under any relay assignment.
- *ORA [12]:* The basic idea of *ORA* is to adjust the assignment iteratively, starting from any arbitrary initial assignment. In each iteration, *ORA* identifies the source node with currently minimum capacity among all the source nodes and searches a better relay node for it. Although *ORA* is not intentionally designed for RAP, we include it in the comparison for the sake of completeness.



(a) Varying m (b) Varying n

Fig. 2: Comparison among relay assignment algorithms. For (a), $n = 200$. For (b), $m = 200$.



(a) Varying m (b) Varying n

Fig. 3: Impact of selfish behavior of source nodes on system capacity. For (a), $n = 200$. For (b), $m = 200$. The maximum and minimum values among 100 random instances are shown as error bars.

2) Cheating Report Distribution: We assume that a relay node can cheat by reporting a transmission power larger than its true transmission power. If P_j^r is the transmission power of relay node $\mathbf{r}_j$, then its reported transmission power is $P_j^r + \delta$, where δ is a random number uniformly distributed over $(\Delta, \Delta + 1]$ and Δ is a parameter.

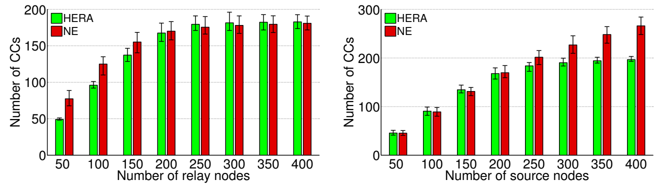
The performance metrics in the experiments include the system capacity and the number of cooperative communications.

B. Evaluation of Assignment Algorithms

Fig. 2 shows the system capacity under the assignments returned by different algorithms. As expected, HERA has the best performance while *DT* has the worst. Surprisingly, the performance of *Greedy* is only slightly worse than that of HERA, especially when $m > n$. The reason is that some source nodes may not need to compete with other source nodes for their best relay nodes. Therefore, we may have the same assignment for these source nodes in both HERA and *Greedy*. Another observation is that when the number of relay nodes exceeds that of the source nodes, the system capacity tends to keep the same.

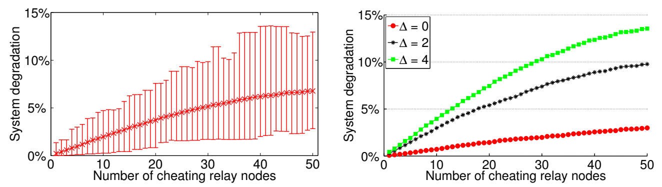
C. Impact of Selfishness on System Performance

We have shown in an example in Section V that the *POA* of the Relay Selection Game can be as small as $\frac{1}{2}$. We turn to evaluate how the selfish behavior of source nodes affects the system performance in randomly generated networks. Fig. 3



(a) Varying m (b) Varying n

Fig. 4: Number of source nodes using CC. For (a), $n = 200$. For (b), $m = 200$. The maximum and minimum values among 100 random instances are shown as error bars.



(a) System capacity (b) Impact of Δ

Fig. 5: Impact of cheating behavior of relay nodes on system capacity where $n = m = 50$. For (a), $\Delta = 4$.

plots the capacities of the systems when HERA is applied and when it is not. We note that the degradation of NE over HERA decreases with the increase of m, as shown in Fig. 3(a). This is because source nodes do not need to compete with each other for relay nodes when there are enough relay nodes. Another observation is that the degradation becomes worse with the increase of n, as shown in Fig. 3(b). This can be explained by the same reason above, as source nodes sharing the same relay node can improve the system capacity if one of them changes to direct transmission. Fig. 4 illustrates the number of source nodes using CC in both HERA and NE. We observe that, when the number of relay nodes is more than that of the source nodes, there are more source nodes competing relay nodes for CC in NE than there are in HERA. This verifies our analysis on the results shown in Fig. 3.

D. Impact of Cheating on System Performance

Next we focus on the impact of cheating behavior of relay nodes on system performance. Fig. 5 shows the system degradation due to the cheating behavior in a network consisting of 50 source nodes and 50 relay nodes. In Fig. 5(a), we set $\Delta = 4$. Our first observation is that when the number of cheating relay nodes is small, the system performance is not affected significantly. This is because a small number of cheating relay nodes will unlikely affect the matching process in the algorithm. Another observation is that the degradation increases with the increase of the number of cheating relay nodes, which is as expected.

We then evaluate the impact of parameter Δ. Intuitively, the larger Δ is, the more a relay node can untruthfully report its transmission power. Fig. 5(b) shows the system performance degradation in the networks with different values of Δ. We see that the degradation increases when the value of Δ increases. The reason is that a relay node reporting a large transmission power has a high probability to be selected in the relay assignment. However, its true transmission power may be very small. Hence the final system capacity is degraded.

VIII. Conclusions

In this paper, we designed HERA, an integrated optimal relay assignment scheme for cooperative networks. It is composed of three components: an optimal relay assignment algorithm, a payment mechanism to charge source nodes for using relaying service, and a payment mechanism to pay relay nodes for proving relaying service. HERA induces selfish source nodes to converge to the optimal assignment and prevents relay nodes from reporting transmission power untruthfully to gain profit. In addition, HERA satisfies budget-balance property, which means the payment collected from source nodes is no less than the payment paid to relay nodes.

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