Facilitating Flexible Multihop Communication via Spectrum Leasing

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***Abstract*—Spectrum leasing for cooperation is a promising paradigm that motivates relaying participation of non-altruistic nodes. It prescribes the trade where the node is rewarded for its relaying role with a fraction of source's bandwidth. Proposed spectrum leasing schemes typically involve hard decision at the source, whether to completely rely on the relay or preserve the whole bandwidth for itself. This approach can pose limitations in multihop networks, with the source refusing to share its bandwidth with multiple nodes on its route, and instead choosing to transmit directly to its destination. The benefits for both the source and potential relays would thus be lost. In this paper, we propose a two-hop spectrum leasing scheme that enables the source to employ the relay only to an extent it finds beneficial, preserving the remaining bandwidth for its direct transmission, if necessary. Unlike the previous mechanisms, the proposed scheme is based on explicit interaction and negotiation about the leased bandwidth. Stackelberg game is used to model this interaction. Comprehensive analysis for the proposed scheme and numerical results demonstrate significant benefits for all the participating nodes.**

I. Introduction

Cooperative relaying for wireless networks is a well accepted paradigm for increasing coverage and throughput in cellular, ad-hoc or hybrid networks [1][2]. In addition to improving network connectivity, it also implies decreased battery consumption, lower interference and reduced infrastructure requirements and cost. However, despite its tremendous advantages, it is often hindered due to the underlying assumption that relaying terminals agree to unconditionally assist communications they do not directly benefit from [3]. While such unconditionally altruistic behavior is the default mode for dedicated relays stations deployed with the exact goal of providing cooperation, it is arguably unrealistic for regular mobile stations.

To address this issue, spectrum leasing for cooperation [4]-[6] was proposed to motivate relaying participation of non-altruistic relaying nodes. Spectrum leasing prescribes that the nodes are rewarded for their relaying assistance through a fraction of source's bandwidth, and promises considerable gains for both the source and the relay. Potentials of spectrum leasing are recognized in variety of scenarios, e.g., for cooperative jamming-aided secure transmission [7][8].

Proposed spectrum leasing for cooperation schemes typically involve hard decision at the source whether to completely rely on relay, dedicating all spectrum to cooperative transmission, or to preserve all bandwidth for direct transmission [4]. Such an approach can pose limitations, particularly in networks with more than two hops, facing the source with a dilemma whether to share its resources with multiple nodes on its route or choose to refrain from cooperation. Thus, there is a threat of losing the significant benefits for both the source and potential relays.

In this paper, we propose a two-hop spectrum leasing scheme that enables the source to employ a relay only to an extent that it finds beneficial, preserving the remaining bandwidth for its direct transmission, if necessary. The scheme is designed with the motivation of providing a building block for flexible multihop architecture, where nodes may decide to relay or forward directly to the destination. We also extend the proposed scheme to include relay selection for a two-hop scenario with multiple available relays. Unlike the previous mechanisms, the proposed scheme is based on interaction and negotiation explicitly about the leased bandwidth.

The scheme is modeled in a Stackelberg framework [9], with source acting as the game leader and the potential relay as the follower. The strategy of the potential relay is the amount of bandwidth it will dedicate for cooperation, if properly rewarded. As a game leader, knowing that its decision will affect the strategy played by the potential relay, the source decides on the ratio between the spectrum reward and the cooperation amount determined by the follower. The relay's utility is designed in a way that effectively disables the source to take advantage from its leader role. Results show significant benefits for both nodes, in terms of transmitted bits to the common destination. It is also confirmed that the resulting bandwidth/slot division is flexible, in the sense that it allows the source to communicate using both cooperative and direct transmission in the same slot.

It is further noted that the scheme can be alternatively used as a practical solution for cognitive radio networks operating according to property-rights model [10]. In such networks, primary, i.e., licensed users may lease portions of the licensed spectrum to secondary, i.e., unlicensed users in exchange for some form of compensation. Here, the role of the primary node is played by the source and that of the secondary by the potential relay. Moreover, retribution from secondary to primary nodes is in the form of cooperative relaying. This enables on-the-air decisions and avoids the regulatory issues or money transactions that commonly hinder the implementation of the property-rights spectrum leasing concept.

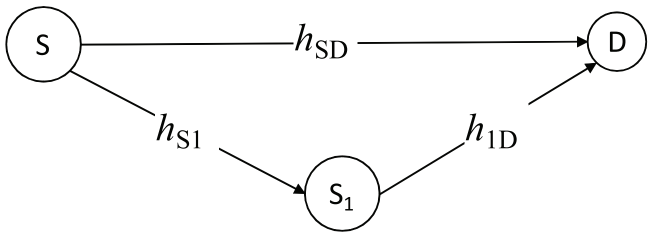

Figure 1. System model.

II. System Model and Notation

A three-node scheme involving the source S, destination D, and node S_1 is considered, as illustrated in Figure 1. The nodes are non-cooperative and self-interested [9]. The communication medium is the property of the node S, that needs to communicate with D. Node S_1 also wants to transmit its data to D, but avails no bandwidth. On the other hand, S would benefit from relaying services from S_1, but the latter is unwilling to unconditionally assist the communication that excludes its data. Thus, the situation occurs where a trade between S and S_1 can possibly benefit both nodes. Namely, the node S can employ the node S_1 as a relay, compensating it with a fraction of S' bandwidth/transmission slot for transmission of S_1's own data.

Denote the transmission resource, e.g., the time slot, of node S as T [sec]. Denote the time that S_1 will relay, expecting reward in return, as $\alpha < T$ [sec]. For generality, we also allow that S_1 is willing to altruistically relay for the time α_0. The spectrum reward from node S is a non-decreasing non-negative function of α_0 and α, $f(\alpha_0 + \alpha)$ [sec]. For simplicity, we use a linear function $f(\alpha_0 + \alpha) = k(\alpha_0 + \alpha)$, where k is a parameter determined by S. The model for interaction between S and S_1 to determine the parameters α and k is elaborated in Section III-C.

The channels between nodes are independent complex Gaussian random variables. The channel power gains for links between S and D, S and S_1, and S_1 and D, are denoted as h_{SD}, h_{S1} and h_{1D}, respectively. In addition to the knowledge of channel state information of the relevant channels at receivers, i.e., S_1 and D know the values of h_{S1} and h_{1D}, respectively, it is also assumed that S_1 has knowledge of h_{1D} and that the node S is aware of all the channel gains in the system. We note that the assumption of channel state information is common in the literature on game-theoretic applications to wireless networks (see, e.g., [4] and discussion therein) and provides an interesting framework for analysis.

The transmission power of nodes S and S_1 is denoted as P_S and P_1, respectively, while the single-sided spectral density of the independent white Gaussian noise at receivers is N_0. Throughout the paper, we assume signaling using Gaussian codebooks. The generic formula for the link rates is thus given as

$$R = \log_2\left(1 + \frac{hP}{N_0}\right). \quad (1)$$

The rates on links S-D, S-S_1, and S_1-D are denoted as R_{SD}, R_{S1} and R_{1D}, respectively, and calculated applying appropriate channel gain and power value in (1). Finally, we note that a possible malicious nodes' behavior is out of the scope of this paper.

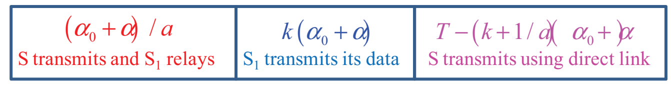

Figure 2. Slot allocation.

III. Analysis

In this section, we analyze the system performance. We first discuss the slot allocation in Section III-A. In Section III-B, utilities of nodes S and S_1 are introduced. In Section III-C, interaction between nodes is cast as a Stackelberg game, while the analysis of the system performance in equilibrium is elaborated in Section III-D. The scheme is extended to the relay selection problem in a two-hop multi-relay scenario in Section III-E.

A. Slot Allocation

It is clear from Section II that the fraction $k(\alpha + \alpha_0)$ is allocated for S_1's transmission of its data. It remains to find the time t used for relaying, that is, for S_1 to receive and then transmit the S' message to D. The relaying rate of the node S with the assistance from S_1 reads

$$R = \min\left((t - \alpha - \alpha_0) R_{S1}, (\alpha + \alpha_0) R_{1D}\right). \quad (2)$$

The optimum t is the minimum that satisfies $(t - \alpha - \alpha_0) R_{S1} = (\alpha + \alpha_0) R_{1D}$, yielding

$$t = \frac{(\alpha + \alpha_0)(R_{S1} + R_{1D})}{R_{S1}}.$$

Denote $a = R_{S1}/(R_{S1} + R_{1D})$. Then, the part of the slot allocated for the relaying is $(\alpha_0 + \alpha)/a$. The remaining $T - (k+1/a)(\alpha_0+\alpha)$ is used for S' direct transmission to D. This allocation is illustrated in Figure 2.

B. Utilities

As discussed in Section II, node S is looking to recruit S_1 if it can increase its rate. In particular, S is willing to compensate the potential relay with a time $k(\alpha + \alpha_0)$ for relay's own data transmission while preserving the remaining time for its direct and cooperative transmission. Utility of the node S is the number of bits it can deliver to D:

$$U(k, \alpha) = (\alpha_0 + \alpha) R_{1D} + \left(T - \left(k + \frac{1}{a}\right)(\alpha_0 + \alpha)\right) R_{SD}. \quad (3)$$

In order for cooperation to be profitable for S, condition

$$(\alpha_0 + \alpha) R_{1D} > \left(k + \frac{1}{a}\right)(\alpha_0 + \alpha) R_{SD}$$

needs to be satisfied, i.e., $k < k_{coop}$, where

$$k_{coop} = \frac{R_{1D}}{R_{SD}} - \frac{1}{a} = R_{1D}\left(\frac{1}{R_{SD}} - \frac{R_{1D}+R_{S1}}{R_{1D}R_{S1}}\right). \quad (4)$$

As parameter k cannot be negative, constraint $k < k_{coop}$ also subsumes the constraint of the conventional relaying model

$$\frac{R_{1D}R_{S1}}{R_{1D}+R_{S1}} - R_{SD} \geq 0. \quad (5)$$

Unlike the node S that 'starts' with non-zero number of delivered bits, TR_{SD}, the node S_1 can not transmit any bits unless involved in relaying/reward scheme. To model such a node, one needs to carefully design its utility so as to prevent it from being taken advantage of, e.g., from being unrewarded, while preserving its goal of transmitting bits. A typical utility design [4] [9], also adopted here, is the difference between the satisfaction from accessing the spectrum and the cost for achieving such an access. In particular, we define utility as

$$W(\alpha;k) = \log\left(1 + k\left(\alpha_0 + \alpha\right)R_{1D}\right) - c\alpha. \quad (6)$$

Such a choice is justified by the requirement that the satisfaction term needs to be a function with diminishing returns [9], which is achieved by using the logarithmic function. In particular, the satisfaction term is the function with diminishing returns of the number of successfully delivered bits by S_1, $k(\alpha_0{+}\alpha)R_{1D}$. Penalty term is given as $c \cdot \alpha$, where the constant c $[1/\text{sec}]$ is given by the system and represents the (un)willingness of node to relay, e.g., due to the battery expenditure. In other words, large/small value of c would characterize a node that requires a significant/modest spectrum reward. Notice that utility (6) has no units. In the following subsection, it will be also shown that utility design (6) disables the source from taking advantage of S_1. It is also worth noting that the notation $W(\alpha;k)$ emphasizes that S_1 has control only over parameter α.

Utility W in (6) is clearly concave. In order for such a function to attain a larger value for some $\alpha > 0$ than $\alpha = 0$, i.e., for S_1 to be valuable to participate as the relay, the condition $\partial W/\partial\alpha > 0$ must hold at $\alpha = 0$, resulting in $c\alpha_0 < 1$ and $k > k_w$ where

$$k_w = \frac{c}{R_{1D}\left(1 - c\alpha_0\right)}. \quad (7)$$

C. Stackelberg Model

To mimic a non-altruistic behavior, the nodes are defined as *selfish* and *rational* [9], and game theory is used as appropriate framework to analyze interaction between such nodes. Specifically, a convenient setting here is the *Stackelberg game* [9], with one agent, termed follower, acting subject to the strategy chosen by the other agent, leader, which in turns seeks maximization of its own utility. Here, the game leader and the follower are S and S_1, respectively. The source's optimal strategy k^* and the corresponding S_1's choice $\alpha^*(k^*)$ are jointly referred to as the *Stackelberg equilibrium*.

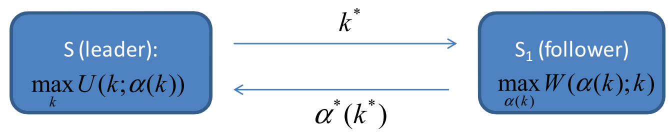

Figure 3. Stackelberg interaction between S and S_1.

Interaction between S and S_1 is shown in Figure 3. Node S informs node S_1 about parameter k and the latter optimizes the relaying time α towards the goal of maximizing its utility W, given by (6). Since $W(\alpha;k)$ is concave in α, the solution of S_1's problem

$$\alpha^*(k) = \arg\max_{\alpha(k)} W\left(\alpha\left(k\right);k\right) \quad (8)$$

reads

$$\alpha^*(k) = \left[\frac{1}{c} - \frac{1}{kR_{1D}} - \alpha_0\right]^+, \quad (9)$$

where $[x]^+ = \max(x,0)$. Notice from (9) that the pricing mechanism prevents S from preserving an unfairly large amount of bandwidth by using low k, as this would in turn typically implicate a small relaying time $\alpha^*(k)$ or even lead to a relaying denial, $\alpha^*(k) = 0$.

Node S, on the other hand, acting as the game leader, determines k towards the goal of maximizing its utility (3), knowing that its decision will affect the strategy selected by S_1:

$$k^* = \arg\max_{k} U\left(k, \alpha^*\left(k\right)\right), \quad (10)$$

where $\alpha^*(k)$ is given by (9). Equations (9) and (10) constitute the Stackelberg equilibrium for the described model. In the next subsection, we elaborate on (10).

D. Stackelberg Equilibrium

We shall use Figure 4 to guide us through investigating the Stackelberg equilibrium of the system. The S_1's part of equilibrium, $\alpha^*(k)$, shown in the upper plot in Figure 4, is already given by (9). It thus remains to analyze optimization (10), illustrated in the lower plot of Figure 4, to completely describe the equilibrium. Notice several critical points, namely k_{tr}, k_{opt}, k_{lim} and k_{coop}. The latter is already given by (4) and corresponds to the maximum k that brings benefits from cooperation to the node S. In the following, we will elaborate on each of the three remaining points, which will lead us to the final equation for the equilibrium.

First we find the minimum k that will motivate S_1 to relay, i.e., $\alpha > 0$. Looking at (9), it is easily obtained that $k^* \geq k_{tr}$, where

$$k_{tr} = \frac{c}{R_{1D}\left(1 - c\alpha_0\right)} \qquad c\alpha_0 < 1. \quad (11)$$

Notice that (11) is identical to (7). We now move to the point k_{opt}, which is the maximum of unconstrained optimization of

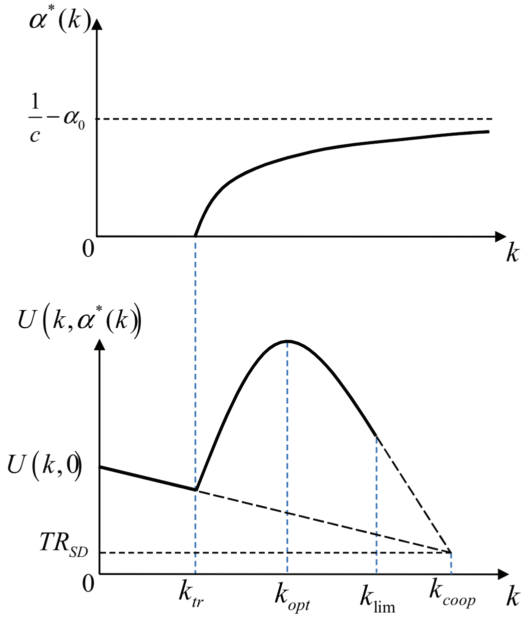

Figure 4. Illustration of $U\left(k, \alpha^{*}(k)\right)$

(3), applying (9) and ignoring its brackets. Utility $U\left(k, \alpha^{*}(k)\right)$ becomes concave in k for $k>0$ with optimum

$$
\begin{aligned}
k_{opt} &= \sqrt{\frac{\left(R_{1D}-\frac{R_{SD}}{a}\right) c}{R_{1D} R_{SD}}} \qquad (12)\\
&= \sqrt{\frac{1}{R_{SD}}-\frac{R_{1D}+R_{S1}}{R_{1D} R_{S1}}}.
\end{aligned}
$$

Clearly, we need $k_{opt}>k_{tr}$, otherwise $U\left(k>k_{tr}, \alpha^{*}(k)\right)$ would decrease with k and $k=0$ would maximize U. This constraint can be derived from (11) and (12) and reads

$$
\frac{c}{\left(1-c a_{0}\right)^{2}}<\frac{R_{1D}}{R_{SD}}\left(R_{1D}-\frac{R_{SD}}{a}\right). \qquad (13)
$$

The final critical point k_{lim} is the maximum k so as to guarantee that the slot duration is not exceeded, $\left(\alpha_{0}+\alpha\right)(k+1/a) \leq T$. This value can be calculated by applying (9):

$$
\left(k+\frac{1}{a}\right)\left(\frac{1}{c}-\frac{1}{k R_{1D}}\right) \leq T. \qquad (14)
$$

This is a simple quadratic inequality with solution $k \leq k_{lim}$, where

$$
\begin{aligned}
k_{lim}= & -\left(\frac{1}{2a}-\frac{c}{2R_{1D}}-\frac{Tc}{2}\right) \qquad (15)\\
& +\sqrt{\left(\frac{1}{2a}-\frac{c}{2R_{1D}}-\frac{Tc}{2}\right)^{2}+\frac{c}{aR_{1D}}}.
\end{aligned}
$$

It is also worth noting that the point k_{coop} becomes obsolete under constraint (13), as it can be easily proved that k_{coop} is larger than any of the remaining three points under (13).

Having found the critical points k_{tr}, k_{opt} and k_{lim}, the equilibrium is given by (9) and

$$
k^{*}=\begin{cases}\min\left(k_{opt}, k_{lim}\right) & k_{tr}<\min\left(k_{opt}, k_{lim}\right), \text{ and} \\ & U\left(\min\left(k_{opt}, k_{lim}\right)\right)>U(k=0), \\ 0, & \text{otherwise.}\end{cases} \qquad (16)
$$

Moreover, the constraints for the scheme and cooperation to take place are

$$
\begin{gathered}
\frac{R_{1D} R_{S1}}{R_{1D}+R_{S1}}-R_{SD}>0, \qquad (17)\\
\alpha_{0} c<1.
\end{gathered}
$$

E. Multiple Intermediate Relays

Proposed framework can also be applied to the relay selection problem in a two-hop scenario involving multiple potential relays. Such a scheme with N nodes $\mathrm{S}_{i=1,..,N}$ is depicted in Figure 5. Given k by the source, each node S_i performs optimization that leads to its side of equilibrium $\alpha_i^{*}(k)$, as given in (9). In addition to the parameter k, the source would also have to indicate the index of the 'winning' relay, i.e., the one that would mostly contribute to the source's utility. The equilibrium will thus read

$$
\left(k^{*}, i^{*}\right)=\arg \max_{k, i} U\left(k, \alpha_{i=1,..,N}^{*}(k)\right). \qquad (18)
$$

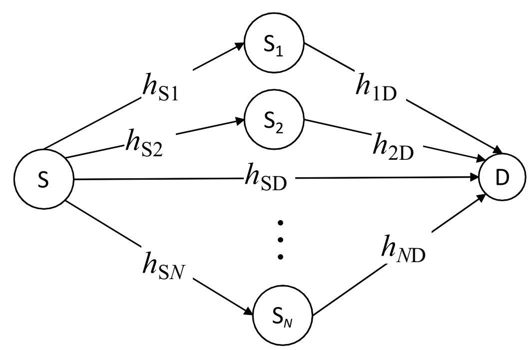

Figure 5. System model with *N* potential relays.

IV. Numerical Results

In this section, we provide some insights into the proposed relaying motivation scheme using numerical results. We use a simple geometrical model where the node S_1 is placed in the middle of the line connecting S and D, and the distance between S and D is normalized to 1. Consequently, considering the path propagation model with $h=d^{-\gamma}$, where d is the distance and γ is the propagation factor, the channel power gains read $h_{SD}=1$ and $h_{S1}=h_{1D}=2^{\gamma}$. Thus, the propagation factor γ is considered here in the sense of quality of relaying channels. We further set $P_S/N_0=P_1/N_0=-10$ [dB] and $T=1$ [sec]. All the results describe the system equilibrium.

Figure 6 illustrates slot allocation versus propagation factor γ, for $\alpha_0=0$ and two values of pricing parameter $c=0.1,\ 5$

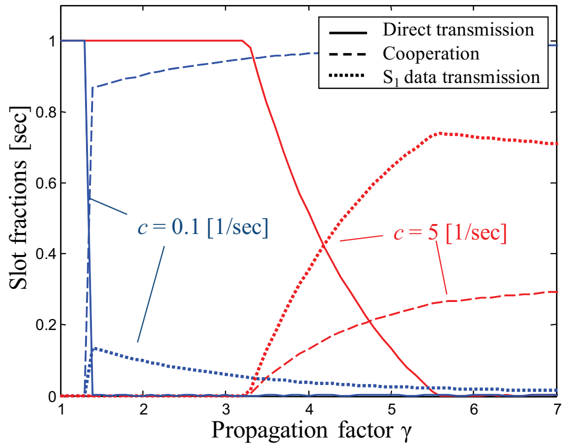

Figure 6. Slot allocation versus propagation factor γ, $\alpha_0 = 0$.

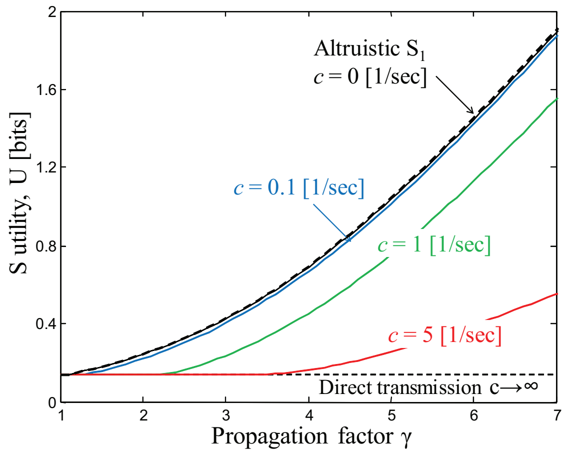

Figure 7. Utility U of node S versus propagation factor γ, $\alpha_0 = 0$.

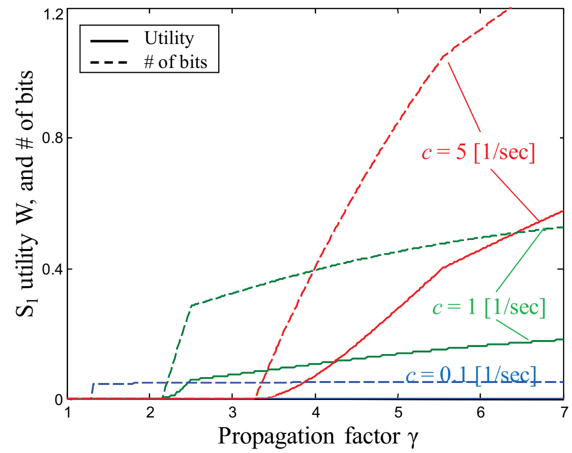

Figure 8. Utility W and number of transmitted bits $k^*\alpha^*R_{1D}$ of node S_1 versus propagation factor γ, $\alpha_0 = 0$.

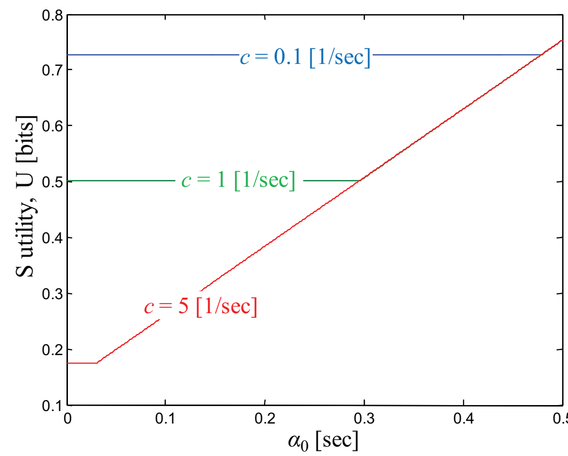

Figure 9. Utility U of node S versus α_0, $\gamma = 4$.

[1/sec]. The large values of γ are used for demonstration purposes. The pricing value reflects the level of cooperative attitude of node S_1, i.e., of its requirement for large (large c) or small (small c) compensation. For each c, the sum of the slot fraction equals $T = 1$ [sec]. It can be seen that the less demanding S_1 activates for smaller γ, and it is more inclined to cooperation. In fact, small value $c = 0.1$ resembles closely the performance of conventional altruistic relaying. Node S_1 with large pricing factor c can attain larger slot fractions, but only for very large values of γ. Moreover, notice that the smooth shape of curves for slot fractions dedicated to cooperation and S_1 data breaks at $\gamma \approx 1.3$ for $c = 0.1$ and $\gamma \approx 5.5$ for $c = 5$. At these points, the slot fraction dedicated for direct transmission drops to zero, and S can play more aggressively.

In Figure 7 and Figure 8 we plot utility U of node S and utility W and the number of transmitted bits $k^*\alpha^*R_{1D}$ of node S_1, respectively, versus the propagation factor γ, for $\alpha_0 = 0$ and $c = 0.1,\ 1,\ 5$ [1/sec]. As expected, utility U benefits from relaying when propagation factor γ increases. It can be also seen that for small c, the mechanism yields performance of S as in conventional relaying. As for the node S_1, small c will lead to S_1 activation over the large range of γ, but yielding only a small utility and number of transmitted bits. Demanding node S_1 can achieve large utility, but only for very large γ, risking to transmit no data for low values of γ. These results corroborate the above discussion for Figure 6.

Utility U of node S and utility W and number of transmitted bits $k^*(\alpha_0 + \alpha^*)R_{1D}$ of node S_1 versus α_0 are shown in Figure 9 and Figure 10, respectively, for $\gamma = 4$ and $c = 0.1,\ 1,\ 5$ [1/sec]. Notice that the utility U of S and the number of transmitted bits of S_1 are constant and the utility W linearly increases for relatively small α_0. At this interval, value $\alpha_0+\alpha^*$ is constant (recall (9)) and α^* decreases linearly with α_0. For, e.g., $c = 1$ [1/sec], approximately at $\alpha_0 \approx 0.29$ [sec] the value of α^* drops to zero, and node S can choose $k = 0$, i.e., no rewarding for S_1, and use the remaining slot fraction for its direct transmission.

We now turn to the scenario where the source can select one of multiple relays, as described in Section III-E. For this purpose, we assume Rayleigh fading on relay links, with $\mathbb{E}[h_{S1}] = \mathbb{E}[h_{1D}] = \sqrt{2/\pi}\cdot 2^{\gamma}$. In Figure 11 and Figure 12 we plot utility of node S and utility and number of transmitted bits

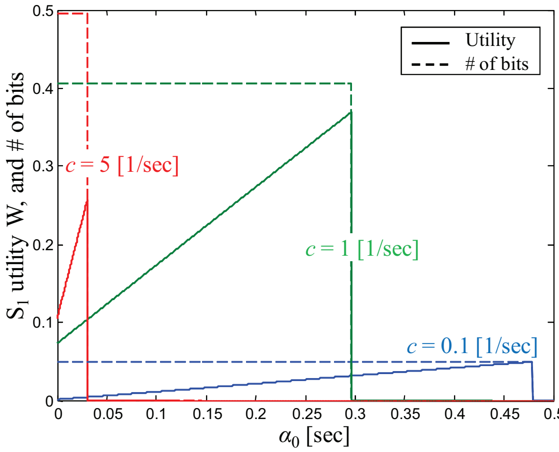

Figure 10. Utility W and number of transmitted bits $k^*(\alpha_0 + \alpha^*)R_{1D}$ of node S_1 versus α_0, $\gamma = 4$.

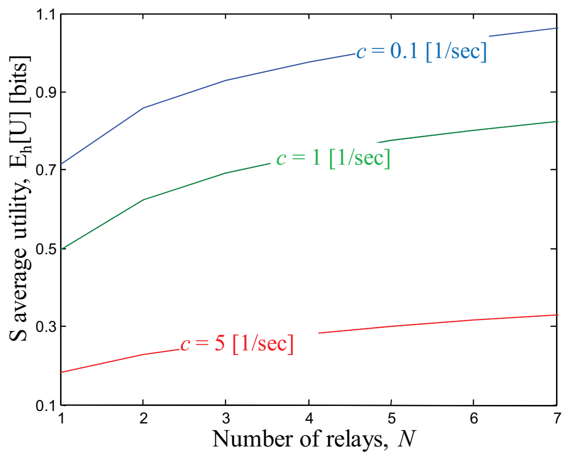

Figure 11. Average utility $\mathbb{E}[U]$ of node S versus number of relays N, $\gamma = 4$, $\alpha_0 = 0$.

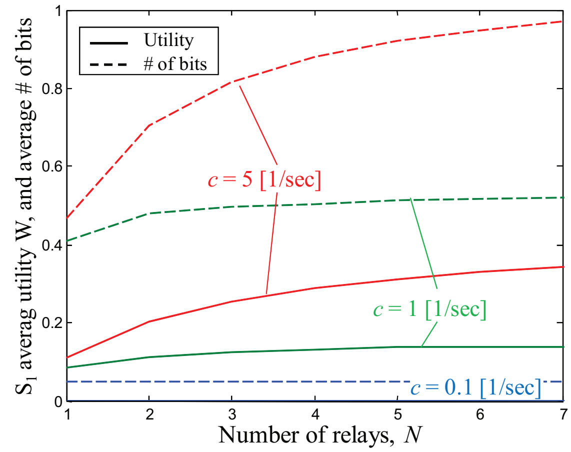

Figure 12. Average utility $\mathbb{E}_h[W]$ and average number of transmitted bits $\mathbb{E}_h\left[k^*(\alpha_0 + \alpha^*)R_{1D}\right]$ of a chosen relay versus number of relays N, $\gamma = 4$, $\alpha_0 = 0$.

of chosen relay node S_1, respectively, averaged over channel realizations, that is $\mathbb{E}_h[U]$, $\mathbb{E}_h[W]$ and $\mathbb{E}_h\left[k^*(\alpha_0 + \alpha^*)R_{1D}\right]$, versus the number of available relays N, and $\alpha_0 = 0$, $\gamma = 4$ and $c = 0.1,\ 1,\ 5$ [1/sec]. The benefits of increased number of relays for the source can be clearly observed. Similar holds for the chosen relay, but one must recall that the utilities and rates of relays that are not chosen are zero. We also note that, in the case of competitive relays, as discussed in Section III-E, source should achieve even greater performance improvements. We are currently investigating such a competitive scenario.

V. Concluding Remarks

In this paper, we have proposed a game-theoretic framework for relaying motivation, based on the spectrum leasing for cooperation concept. Interaction between the nodes is framed as a Stackelberg game. Analytical and numerical results corroborate the benefits for all involved nodes, despite their selfish nature. The scheme is particularly designed to provide flexibility for the source to concurrently exploit cooperative and direct transmission, if necessary. Such a design will enable the spectrum leasing implementation in a network with more than two hops. Namely, the source will be able to employ and share its resources with only the relays it finds beneficial, and only to an extent it finds beneficial, preserving if necessary a part of its bandwidth for the direct transmission. Extension of the proposed scheme to multihop networking with more than two hops is the focus of our ongoing research. It was further demonstrated that the proposed scheme is easily extendable to the relay selection problem for a multi-relay two-hop case. We are currently investigating the relay selection scenario that addresses competitive nature of potential relays.

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