Stability Analysis for Cognitive Radio with Cooperative Enhancements

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***Abstract*— This paper deals with protocol design for cognitive cooperative systems with many secondary users. Appropriate relaying improves the throughput of the primary users and can increase the transmission opportunities for the cognitive users. Based on different multi-access protocols, the schemes investigated enable relaying either between the primary user and a selected secondary user or between two selected secondary users. This collaboration can be a simple distributed multiple-input single-output transmission of the primary data or a simultaneous transmission of primary and secondary data using dirty-paper coding (DPC). The parametrization of DPC as well as its combination with opportunistic relay selection yields an interesting trade-off between the primary and the secondary performance which is investigated by theoretical and simulation results under the perspective of a desired primary throughput.**

I. INTRODUCTION

Cognitive radio (CR) has been suggested as an efficient method that may enable more efficient use and reuse of the radio spectrum [1], [2]. This suggestion is based on the observation that some spectrum is used in a bursty fashion, and allows secondary (unlicensed) users to access the spectrum when it is unoccupied by the primary (licensed) users. Such sharing relies on the ability of a secondary radio or radio network to respond to various changes in the spectrum and adapt its operations to the surrounding environment.

The combination of CR with cooperative diversity protocols [3]-[5] could significantly improve the bandwidth utilization and improve performance tradeoffs for both primary and secondary users. In most of the existing literature on these combined topics, cooperative diversity is used as a means to improve the sensing ability of the CRs [6]. Appropriate cooperation between the cognitive users improves the quality of the detection and avoids the hidden node problem. Cognitive cooperation can also be used in order to improve the system performance without extra resources in bursty applications. In [7], the authors study the stability as well as the time delay of a multi-access relay channel (MARC) in the context of a cognitive pure relay.

In this paper, we design and characterize protocols for CRs with many secondary users. In contrast with previous single-user configurations [8], [9] a new cognitive structure is introduced, in which a cluster of nodes sense the radio spectrum for transmission opportunities. The cognitive cluster is equipped with a common (for all the nodes of the cluster) relaying queue in order to relay data for the primary user. The basic problem is to study the interplay among the primary user, the common relaying queue, and the secondary queues as well as the optimization target. Previously reported single-user schemes do not provide efficient solutions for this scenario and motivate the investigation of new cooperative protocols that take into account the multi-user nature of the setup. Based on different MAC protocols, the proposed schemes in the cooperative mode enable simultaneous transmissions for the primary user and a secondary user, or two secondary users. Both transmitters can transmit the same primary data by creating a virtual multiple-input single-output (MISO) system, or a combination of primary and secondary data by using dirty-paper coding (DPC) [8], [9]. It is shown that the parameter of the DPC and its relation to the node selection policy provides a tradeoff between primary and cognitive performance. The optimization target of the system is to maximize the secondary throughput given a specified (pre-selected) primary throughput. The proposed schemes are studied at the network layer by using queueing theory, and it is proven that their suitability depends on the average system parameters.

The remainder of the paper is organized as follows. Section II introduces the system model and presents the basic assumptions. Section III presents the proposed cooperative protocols and analyzes their related throughput regions. Numerical results are shown and discussed in Section IV, followed by concluding remarks in Section V.

II. SYSTEM MODEL

In this Section, we introduce the system configuration and we define the basic system assumptions.

A. System configuration

We assume a simple cognitive configuration consisting of one primary user (P) and a cognitive cluster $S_{\text{relay}} = \{1, \dots, K\}$ with K nodes. The primary user communicates with a primary destination (D_P) and each node of the cluster has data to transmit to a common cognitive destination (D_S). For the sake of simplicity, a normalized linear geometry is assumed, with the distance between the source and the cognitive cluster equal to $0 < d < 1$ and the distance between the cognitive cluster and the destination (D_P, D_S) equal to $1 - d$. The total transmitted power for each slot is equal to P_0 (i.e. symmetrically distributed in the case of two simultaneous transmissions) and path-loss attenuation is taken into account by assuming received power decreases proportional to $d_{i,j}^{-\beta}$ where $d_{i,j}$ is the Euclidean distance between transmitter i and receiver j and β $(2 \leq \beta \leq 5)$ is the path-loss exponent.

Time is considered to be slotted and the transmission of each packet is performed in one slot. The packet arrival processes at each node are independent and stationary Bernoulli with mean λ_P (packets per slot) for the primary user and λ_S (packets per slot) for each cognitive user. Due to impairments on the radio channel, if a packet is received erroneously at the destination, it requires retransmission until it is successfully decoded. The retransmission process is based on an Acknowledgement/Negative-acknowledgement (ACK/NACK) mechanism, in which short length error-free packets are broadcast by the destinations in order to inform the network for the reception status.

All the nodes (primary and cognitive) have a buffer of infinite capacity to store incoming packets, where Q_P denotes the primary queue and Q_k the queue of the node $k \in S_{\text{relay}}$. The cognitive cluster is equipped with a common relaying queue Q_{PS} which is used for cooperation and is accessible from all the cognitive nodes. It is a simple model for the case in which each cognitive node has a "relaying" queue that is identical, operated on identically and stays synchronized.

Perfect spectral sensing (probability of detection $P_d = 1$, probability of false alarm $P_f = 0$) allows the CR to access the channel only in the cases that the primary user is idle [7]. This assumption provides some lower bounds for the performance of the system and is a guideline for more realistic configurations with imperfect spectral sensing.

B. Physical channel

All wireless links exhibit fading and additive white Gaussian noise (AWGN). The fading is assumed to be stationary, frequency non-selective and Rayleigh block fading *i.e.* the fading coefficients remain constant during one packet, but change independently from one packet time to another according to a circularly symmetric complex Gaussian distribution with zero mean and unit variance. Furthermore, the variance of the AWGN is taken to be unity. Each link $i \rightarrow j$ is characterized by an outage event $\mathcal{O}_{i,j}$, which characterizes the case that the instantaneous capacity is lower than the required data rate R_0 with an outage probability equal to $\Pr\{\mathcal{O}_{i,j}\} = 1 - f_{i,j}$, where $f_{i,j}$ is the probability of success. Because the cognitive cluster has a high degree of sensing, it assumed that the channel coefficients of the links $S_{\text{relay}} \rightarrow D_P, D_S$ are *a priori* known at the cognitive cluster [9]. This assumption is reasonable due to the continuous broadcasting of ACK/NACK packets by the destinations, which are received from all the nodes of the network [4].

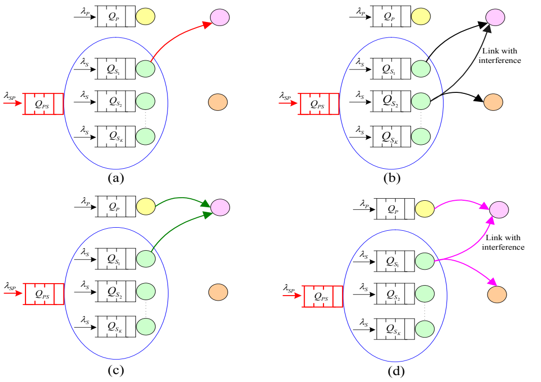

Fig. 1. The proposed cognitive cooperative protocols: (a) CC, (b) CC+DPC, (c) MC, (d) MC+DPC.

III. PROTOCOL DESIGN FOR COGNITIVE COOPERATIVE RADIO AND STABILITY ANALYSIS

In this Section, we present the proposed cooperative strategies and we derive their stable throughput regions. Fig. 1 schematically summarizes the proposed cooperative schemes.

A. Conventional cooperation (CC)

Conventional cooperation is the first protocol that allows secondary transmitters to deliver packets of the primary user that have not been successfully received via the primary link. More specifically, if a primary packet cannot be decoded at the primary destination but can be decoded by the cognitive cluster, it exits the primary queue and remains in the common relaying queue for cognitive relaying transmission. It is an obvious extension of the protocol proposed in [10] for a single-cognitive configuration by considering an opportunistic selection for the source-relay (primary transmission) and relay-destinations (relaying, secondary transmission) links. Due to the space limitations, the CC protocol is used for comparison purposes and its analytical description can be found in [11].

B. Conventional cooperation and dirty-paper coding (CC+DPC)

This cooperative protocol requires a cluster with $K > 1$ relay nodes. It is similar to the conventional scheme, but allows two relays to simultaneously access the channel using DPC when the common queue is served (when the primary user is idle). More specifically, as the common queue is "shared" by all the nodes of the cluster, DPC allows a relay to serve its own queue (establish a communication with the secondary destination) at the same time that another relay serves the common queue. For the link between the relay and the secondary destination, the common queue data is regarded as an *a priori* known interference and thus an appropriate precoding technique at the relay can mitigate interference [8]. On the other hand, the link between the relay that serves the common queue and the primary destination is affected by interference from the secondary link (the Z-interference channel). Therefore, an appropriate design of the DPC parameters is required in order to efficiently optimize both links. The considered DPC technique can be found in

[9, Sec. 5.4] and yields an achievable rate region for the simultaneous transmissions equal to

$$\begin{aligned} R_{PS}(\alpha) &\leq \log\left(1+\frac{\left|h_{k_1,D_P}\right|^2 P_{k_1}+\alpha\left|h_{k_2,D_P}\right|^2 P_{k_2}}{1+(1-\alpha)\left|h_{k_2,D_P}\right|^2 P_{k_2}}\right), \\ R_{k_2}(\alpha) &\leq \log\left(1+(1-\alpha)\left|h_{k_2,D_S}\right|^2 P_{k_2}\right), \end{aligned} \tag{1}$$

where $k_1, k_2 \in S_{\text{relay}}$ denote the relay that serves the common queue and its own queue, respectively, $P_k = P_0(1-d)^{-\beta}/2$, $h_{i,j}$ denotes the fading coefficient for the link $i \rightarrow j$, and α is the DPC parameter which denotes the fraction of power that is allocated to the interference component. We note that the above expressions correspond to a normalized AWGN variance.

According to (1), relay selection and the parameter α have an important impact on the performance of the DPC design. They characterize the trade-off between primary and secondary throughput and they can be optimized according to various criteria. In this study we adapt a primary protection scenario, where the system will set-up these parameters in order to maximize the secondary throughput while supporting a pre-selected primary throughput. As has been shown in [11], reasonable selection policy consists of an opportunistic selection for the common relaying queue and a secondary-based opportunistic scheduling among the remaining $(K-1)$ nodes for the relay that serves its own queue. The proposed selection policy can be expressed as

$$k_1 = \arg\max_{k \in S_{\text{relay}}}\{\gamma_{k,D_P}\}, \;\; k_2 = \arg\max_{k \in \{S_{\text{relay}}-k_1\}}\{\gamma_{k,D_S}\}, \tag{2}$$

where $\gamma_{i,j}$ denotes the instantaneous SNR for the link $i \rightarrow j$, k_1 denotes the relay that serves the common relay queue and k_2 is the relay which serves its own queue.

In case the primary and the common queues are both empty, a CR can access the spectrum in order to serve its individual queue. For this transmission, a secondary link-based opportunistic scheduling maximizes the total capacity of the system, where $k^* = \arg\max_{k \in S_{\text{relay}}}\{\gamma_{k,D_S}\}$ denotes the selected relay. It is worth noting that this cognitive strategy is applied to all the proposed cooperative protocols.

Stability analysis: For the primary user, the service process can be modeled as $Y_P(t) = \mathbf{1}\left[\bar{\mathcal{O}}^t_{P,D_P}\right] + \mathbf{1}\left[\mathcal{O}^t_{P,D_P} \bigcap \bar{\mathcal{O}}^t_{P,k^\dagger}\right]$, where $\mathbf{1}[\cdot]$ is the indicator function and $k^\dagger = \arg\max_{k \in S_{\text{relay}}}\{\gamma_{P,k}\}$ denotes the relay with the best instantaneous source-relay link (the cluster can decode the primary packet when $P \rightarrow k^\dagger$ is not in outage). Accordingly, $Y_P(t)$ is a stationary process with mean

$$\begin{aligned} \mu_P^{(\max)} &= E[Y_P(t)] = \Pr\{\bar{\mathcal{O}}^t_{P,D_P}\} + \Pr\{\mathcal{O}^t_{P,D_P}\}\Pr\{\bar{\mathcal{O}}^t_{P,k^\dagger}\} \\ &= f_{P,D_S} + f_{P,k^\dagger} - f_{P,D_S} f_{P,k^\dagger}, \end{aligned} \tag{3}$$

where the result $f_{P,k^\dagger} = 1 - \left[1 - \exp\left(-(2_0^R - 1)/P_0 d^{-\beta}\right)\right]^K$ is given by order statistics. However, the constraint for the maximum stable arrival throughput for the primary user is obtained by studying the stability of the common queue. For the common queue, the arrival process is defined as $X_{PS}(t) = \mathbf{1}\left[\{Q_P(t) \neq 0\} \bigcap \mathcal{O}^t_{P,D_P} \bigcap \bar{\mathcal{O}}^t_{P,k^\dagger}\right]$, with a mean

$$\lambda_{PS} = E[X_{PS}(t)] = \frac{\lambda_P}{\mu_P^{(\max)}}(1 - f_{P,D_P}) f_{P,k^\dagger}, \tag{4}$$

where we have used Little's theorem to obtain the RHS [11]. The departure process is defined as $Y_{PS}(t) = \mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \bar{\mathcal{O}}^t_{k_1,D_P}(\alpha)\right]$ with mean $\mu_{PS}(\alpha) = E[Y_{PS}(t)] = (1 - \lambda_P/\mu_P^{(\max)}) f_{k_1,D_P}(\alpha)$, where the probability $f_{k_1,D_P}(\alpha)$ is given in [11]. By applying Loyne's stability theorem to the common relaying queue, the average throughput of the primary user is constrained as follows

$$\lambda_P(\alpha) < \frac{\left(f_{P,D_P} + f_{P,k^\dagger} - f_{P,D_P} \cdot f_{P,k^\dagger}\right) f_{k_1,D_P}(\alpha)}{f_{k_1,D_P}(\alpha) + (1 - f_{P,D_P}) f_{P,k^\dagger}}. \tag{5}$$

According to the protocol description, a cognitive relay can serve its own queue either simultaneously with the common queue (DPC scheme) or via a dedicated channel when the primary and the common queues are both empty. Based on this assumption, the departure process for a cognitive relay k can be expressed as

$$\begin{aligned} Y_k(t) = &\mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \{Q_{PS} \neq 0\} \bigcap A^t_k \bigcap \bar{\mathcal{O}}^t_{k,D_S}(\alpha)\right] \\ &+ \mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \{Q_{PS}(t) = 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}^t_{k,D_S}\right], \end{aligned} \tag{6}$$

where A^t_k denotes the event that relay k is selected for DPC transmission and Δ^t_k denotes the event that relay k is selected for individual transmission. The above expression results in a maximum throughput for the cognitive relay equal to

$$\begin{aligned} &\lambda_S(\alpha) < \mu_S = \frac{1}{K}\left(1 - \frac{\lambda_P}{\mu_P^{(\max)}}\right) \\ &\times \left[f_{k_2,D_S}(\alpha) - \frac{\frac{\lambda_P}{\mu_P^{(\max)}} \cdot (1 - f_{P,D_P}) \cdot f_{P,k^\dagger}}{\left(1 - \frac{\lambda_P}{\mu_P^{(\max)}}\right) \cdot f_{k_1,D_P}(\alpha)}\left(f_{k_2,D_S}(\alpha) + f_{k^*,D_S}\right)\right], \end{aligned} \tag{7}$$

where the probability $f_{k_2,D_S}(\alpha)$ is given also in [11, App. I].

C. MISO cooperation (MC)

In contrast with previous cooperative schemes, in which the primary user removes a packet from its queue if it is decoded successfully either by the primary destination or the cognitive cluster, here we assume that the packet remains in the primary queue until is received successfully at the receiver. This new MAC protocol of the primary user allows a packet to coexist in the primary and the common queue. This coexistence corresponds to the case in which a packet is not correctly received at the destination, but it is successfully decoded by the cognitive cluster. In the proposed protocol, servicing of the relaying queue does not wait for idle time slots, and it is served whenever it is not empty, independent of the behavior of the primary user. If at the same time the primary user retransmits the lost packet, the protocol corresponds to a conventional MISO scheme, in which the primary user and the common queue (relay) transmit the same data via two independent channels. On the other hand, when the primary user has no data to transmit (the common queue becomes empty), a CR establishes a communication between itself and the secondary destination. According to the previous discussion, an opportunistic scheduling mechanism is an appropriate transmission technique for both cases. As the main target of this paper is the analysis of the DPC-based protocols, the stability analysis of the MC is beyond the scope of this paper and is given in [11].

D. MISO cooperation and dirty paper coding (MC+DPC)

In this protocol, the primary user follows the same behavior as the MC scheme and therefore a replica of the same primary packet can be contained in both the primary and the relaying queues. However, in contrast to the previous scheme in which both transmitters, primary user and cognitive relay, broadcast the same packet without further processing, here it is assumed that the cognitive relay applies DPC. More specifically, the proposed protocol allows a cognitive relay to serve its own queue simultaneously with the retransmission of the primary user. Given that a packet which is added to the common queue will be forwarded by the primary user in the next time slot, a cognitive relay can precode its own information by considering the primary packet as *a priori* interference known at the transmitter. The DPC scheme allows the cognitive relay to establish “clean” communication with the secondary destination but causes some interference to the primary link. In this case, an appropriate design of the DPC parameter is again required in order to achieve an efficient trade-off between both links. Equivalent to Section II.B, the considered DPC scheme provides an achievable rate region for the simultaneous transmissions which is given by

$$\begin{aligned} R_P(\alpha) &\leq \log\left(1+\frac{\left|h_{P,D_P}\right|^2 P_0/2+\alpha\left|h_{k^*,D_P}\right|^2 P_{k^*}}{1+(1-\alpha)\left|h_{k^*,D_P}\right|^2 P_{k^*}}\right), \\ R_{k^*}(\alpha) &\leq \log\left(1+(1-\alpha)\left|h_{k^*,D_S}\right|^2 P_{k^*}\right). \end{aligned} \tag{8}$$

In this DPC scheme, the node selection strategy is more complicated and introduces an interesting trade-off between primary and secondary performance. More specifically, for high α ($\rightarrow 1$), a primary-based opportunistic selection optimizes the performance of the primary user by decreasing the secondary performance. On the other hand, a secondary opportunistic selection optimizes the performance of the secondary users by decreasing the primary performance. The appropriate selection depends on the optimization target of the system. For the sake of presentation, here we deal with a secondary-based opportunistic selection as it results in an efficient trade-off between both links. This selection policy maximizes the performance of the CR and achieves an efficient trade-off for the primary user by limiting the generated interference. Finally, in the case that the primary user becomes idle (common queue is empty), the cognitive relay with the best instantaneous $k \rightarrow D_S$ link is also selected for transmission.

Stability analysis: The service process in the primary queue can be expressed as

$$Y_P(t) = \mathbf{1}\left[\bar{\mathcal{O}}_{P,D_P}\right] + \mathbf{1}\left[\mathcal{O}^t_{P,D_P} \bigcap \bar{\mathcal{O}}^t_{P,k^\dagger} \bigcap \bar{\mathcal{O}}^t_{P;k^*,D_P}(\alpha)\right], \tag{9}$$

with a mean equal to

$$\mu_P^{(\max)} = f_{P,D_P} + (1-f_{P,D_P}) \cdot f_{P,k^\dagger} \cdot f_{P;k^*,D_P}(\alpha), \tag{10}$$

where $f_{P;k^*,D_P}(\alpha)$ denotes the probability that the MISO link $(P, k^* \rightarrow D_P)$ is not in outage and is given in [11, App. III]. For the common queue, the departure process can be defined as $Y_{PS}(t) = \mathbf{1}[\bar{\mathcal{O}}^t_{P;k^*,D_P}(\alpha)]$ with a mean equal to $\mu_{PS} = E[Y_{PS}(t)] = f_{P;k^*,D_P}(\alpha)$. On the other hand the arrival process is similar to the MC protocol. Therefore, by applying Loyne’s stability theorem, the maximum throughput of the primary user is constrained as [11]

$$\lambda_P(\alpha) < \begin{cases} f_{P,D_P} + (1-f_{P,D_P}) f_{P,k^\dagger} f_{P;k^*,D_P}(\alpha) & \text{if } \theta, \\ \frac{\left[f_{P,D_P}+(1-f_{P,D_P}) f_{P,k^\dagger} f_{P;k^*,D_P}(\alpha)\right] f_{P;k^*,D_P}(\alpha)}{(1-f_{P,D_P}) f_{P,k^\dagger}} & \text{if } \overline{\theta} \end{cases} \tag{11}$$

where $\theta \triangleq f_{P;k^*,D_P}(\alpha) > (1-f_{P,D_P}) f_{P,k^\dagger}$ and $\overline{\theta}$ denotes the inverse condition. Finally, according to this protocol, a cognitive relay serves its own queue, either simultaneously with the common queue by using DPC or via a dedicated time slot when the primary user is idle. Furthermore, the criterion for secondary selection is the best $k \rightarrow D_S$ link. Therefore, the departure process for an individual relay queue is defined as

$$\begin{aligned} Y_k(t) =& \mathbf{1}\left[\{Q_P(t) \neq 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}_{k,D_S}(\alpha)\right] \\ &+ \mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}_{k,D_S}\right], \end{aligned} \tag{12}$$

which yields a maximum throughput for the primary user equal to

$$\lambda_S(\alpha) < \mu_S = \frac{1}{K}\left[\frac{\lambda_P(\alpha)}{\mu_P^{(\max)}} f_{k^*,D_S}(\alpha) + \left(1-\frac{\lambda_P(a)}{\mu_P^{(\max)}}\right) f_{k^*,D_S}\right], \tag{13}$$

where $f_{k^*,D_S}(\alpha)$ is given in [11, App. III].

E. Optimizing the DPC superposition factor

The definition of the parameter α introduces an interesting optimization problem that depends on the perspectives of the CRs. In this work, cognitive cooperation is used as an efficient way to protect the primary user and deliver its data at the same average rate as the primary source-destination link by improving the diversity gain of the overall link. In this view of the CRs, the appropriate parameter α of the DPC-based protocols is this one which maximizes the cognitive throughput (λ_S) while supporting the specified (pre-selected) primary throughput ($\lambda_{P_0} < \mu_P^{(\max)}$). The optimization problem can be written as

$$\begin{aligned} &a^* = \arg\max\nolimits_\alpha \left\{\lambda_S(\alpha)\right\} \\ &\textbf{s.t. } \lambda_{P_0} \leq \lambda_P(\alpha) \text{ with } \alpha \in [0\ 1]. \end{aligned} \tag{14}$$

IV. NUMERICAL RESULTS

Computer simulations were carried out in order to validate the performance of the proposed schemes. Fig. 2 plots the primary throughput (λ_P) versus the maximum secondary throughput ($\mu_S^{(\max)}$) of the proposed cooperative schemes. The simulation parameters are: $K = 2$ users, $d = 0.6$, $R_0 = 2$ bits per channel use (BPCU), $P_0 = 6$ dB (which corresponds to a poor direct link), $\lambda_{P_0}^{\text{CC}} = 0.65$ and $\lambda_{P_0}^{\text{MC}} = 0.77$ (packets/slot) for the CC and MC, respectively. The first observation is that cooperation significantly improves the throughput for both primary and secondary users. Cooperation protects the primary transmission via diversity gain and thus optimizes the primary throughput while providing more opportunities to cognitive users for transmission. Furthermore, the MC protocol achieves the maximum throughput for the primary user as it uses all the available system resources in order to serve the primary queue. As far as the DPC approach is concerned, it can be seen that it optimizes the secondary throughput while supporting the required primary throughput. For the selected primary throughput, the optimal values of α are equal to $\alpha \approx 0.7$ and $\alpha \approx 0.8$ for CC+DPC and MC+DPC, respectively. It is worth emphasizing that although the demanding CC primary throughput is largest, the DPC approach allows a cognitive communication with a non-zero throughput.

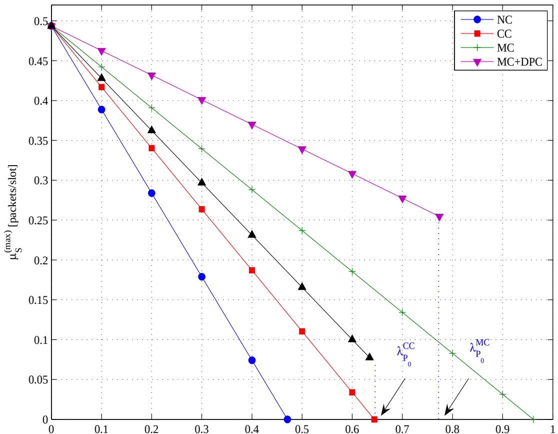

Fig. 2. Maximum throughput μ_S versus λ_P for non-cooperation (NC), CC, CC+DPC, MC, and MC+DPC; $R_0 = 2$ BPCU, $K = 2$ cognitive users, $d = 0.6$, $P_0 = 6$ dB, $\alpha^{\text{CC}} = 0.7$, $\alpha^{\text{MC}} = 0.8$.

Fig. 3 shows the impact of the parameter α on the performance of the DPC-based schemes. The simulation environment is based on the above parameters. As can be seen, for the CC+DPC protocol, there is an α which jointly optimizes primary and secondary users. Since the performance of the primary user does not change for $\alpha > 0.7$ and the performance of the secondary user decreases with α, $\alpha \approx 0.7$ is a reasonable for both users. On the other hand, the behavior of the MC+DPC curve shows that the primary throughput is increased with α by resulting in a zero throughput for the secondary throughput at its maximum value. This figure also validates the previously used MC+DPC value for the parameter α ($\alpha = 0.8$ for $\lambda_{P_0}^{\text{MC}} = 0.77$).

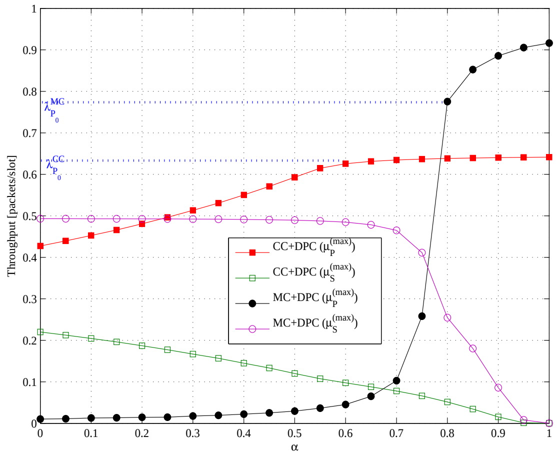

Fig. 3. Maximum throughput for primary and cognitive user versus α for CC+DPC and MC+DPC; $R_0 = 2$ BPCU, $K = 2$ cognitive users, $d = 0.6$, $P_0 = 6$ dB.

V. CONCLUSION

This paper has dealt with protocol design in cognitive cooperative systems with a clustered cognitive structure. The investigated protocols allow simultaneous transmission of relaying and secondary data based on DPC. We demonstrated that an appropriate definition of the DPC parameter as well as a selection of the relay nodes can support a desired primary throughput by simultaneously improving the secondary throughput.

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