Protocol Design and Throughput Analysis for Multi-user Cognitive Cooperative Systems

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Abstract

This paper deals with protocol design for cognitive cooperative systems with many secondary users. In contrast with previous cognitive configurations, the channel model considered assumes a cluster of secondary users which perform both a sensing process for transmitting opportunities and can relay data for the primary user. 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. The proposed protocols are studied from a networking point of view and the stable throughput for primary and secondary users is derived based on the principles of queueing theory.

Index Terms

Cognitive radio, cooperative diversity, relay channel, relay selection, queueing theory, stability analysis.

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 if 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. As new software defined radio (SDR) [3] and reconfigurable signal processing tools [4], [5] are developed and improved, CR has been introduced as a new radio design philosophy. At the same time, cooperative diversity has emerged as a promising technique to combat fading in wireless communications. It enables single-antenna users to "enjoy" space diversity benefits by sharing their physical resources through a virtual transmit and/or receive antenna array. Since the work of Sendonaris *et al.* [6], which introduced the notion of cooperative diversity, a number of relaying protocols have been proposed in the literature [7]-[11].

The combination of CR with cooperative diversity protocols 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 [12]-[17]. Appropriate cooperation between the cognitive users improves the quality of the detection and avoids the hidden node problem. Cooperation can also be used in order to improve the system performance. In [18] the proposed scheme allows the primary user to lease its own bandwidth for a fraction of time, in exchange for enhanced quality of service thanks to cooperation with the secondary nodes.

Protocol design for cooperative cognitive systems is an open research problem. From an information-theoretic point of view, the cooperative CR is modeled as a basic interference channel (one primary source, one secondary source and the corresponding destinations) with side-information about the primary transmission. The maximum capacity region is achieved by using DPC and by allowing the primary and secondary users to access the channel simultaneously. In [19] the problem is discussed for Gaussian channels under causal and noncausal knowledge of the primary message. In [20] the problem is extended for fading channels with different levels of side-information. However, the analysis of the cooperative CR under an information-theoretic framework does not take into account the bursty nature of the cognitive transmission. On the other hand, the analysis of the system at higher network layers considers the arrival statistics of the traffic data and characterizes the stable throughput region of the system by using queueing theory. In [21], Sadek *et. al.* study the stability as well as the time delay of a multi-access relay channel (MARC) in the context of a cognitive pure relay. However, in the proposed system the cognitive relay does not have its own data to transmit and is used only to enable cooperation in the periods of silence of the primary users. In [22], Simeone *et. al.* analyze the stability region of the basic cognitive four node configuration. Although their proposed system follows the principles of the cognitive design, the cooperative protocol uses dedicated slots for the relaying transmissions and therefore is not optimal from an information theory perspective.

In this paper, we design and characterize protocols for CRs with many secondary users. In contrast with previous single-user configurations, 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 DPC. It is shown that the DPC parameter [23] and its relation to the node selection policy provides a tradeoff between primary and cognitive performance. Specifically, 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. To the best of our knowledge, the application of DPC design in multi-cognitive radios as well as the related stability analysis is reported for first time in this paper.

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 stable 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 describe the clustered configuration and we introduce the basic system assumptions.

A. System configuration

We assume a simple cognitive configuration consisting of one primary user (P) and a cognitive cluster $S_{\text{relay}} = \{1, \ldots, K\}$ with K nodes. For convenience, we assume that the K secondary nodes are clustered relatively close together (location-based clustering) and have been selected by a long-term routing process [24], [25]. 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. The system model considered is depicted in Fig. 1.

Time is considered to be slotted and the transmission of each packet is performed in one slot. The packet arrival at each node are independent and stationary Bernoulli processes 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. In order to support this assumption, a cluster supervision block (CSB)[1] which controls and synchronizes all the activities of the cognitive cluster, is introduced. This central logic retains the common queue and is the interface between the cognitive cluster and the primary network. Secondary nodes can perfectly exchange information with the CSB without overhead.

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 $\mathbb{P}\{\mathcal{O}_{i,j}\} = 1 - f_{i,j}$, 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 [20]. 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 [9].

C. *Cooperative spectral sensing and synchronization*

Perfect spectral sensing (probability of detection $P_d = 1$, probability of false alarm $P_f = 0$) which allows the CR to access the channel only in the cases that the primary user is idle, it is assumed [21]. This assumption provides lower bounds for the system performance and is a guideline for more realistic configurations. The basic target of this work is to analyze cooperative protocols for CRs with clustered structures. Problems of spectral sensing and scenarios where cognitive users interfere with the primary user are beyond the scope of this paper and can be considered for future investigation [26]. However, for the clustered system model considered here, this assumption is reasonable [15]-[17]. An appropriate fusion and combination of the individual

[1]The CSB can be a secondary node which has been selected as a clusterhead.

sensing data improves the ability of the system and decreases the probability of detection error and false alarm.

Furthermore, perfect synchronization of the CR to the primary system is assumed. Based on a primary pilot channel, the cognitive cluster remains strictly time-syncronized with the primary user when implementing the proposed relaying schemes. A similar assumption can be found in [19], [20]. The impact of an imperfect time synchronization on the cooperative schemes is beyond the scope of this paper.

D. Queueing stability

As the arrival processes are assumed to be stationary by definition, and the departures processes are also stationary due to the stationary channel fading model described above, we can apply Loynes's theorem to check the stability of the queues [27]. Therefore, the basic constraint for a queue to be stable is that the average arrival rate be less than the average departure rate. It is worth noting that by considering perfect spectral sensing at the cognitive cluster, the problem of interacting queue is overcome and it still obeys the stationarity assumption.

III. Protocol design for cognitive cooperative radio and stability analysis

In this section, we investigate some cognitive cooperative protocols which efficiently combine the cognitive principle with the clustered structure under study. The selected performance metric is the maximum stable throughput for the system queues and is analyzed by using queueing theory. We note that the analysis is appropriate for applications where time delay is not a critical parameter [22].

A. Non-cooperation (NC)

The noncooperative scheme is used as a reference scenario. In this case, there is no interplay between the primary user and the secondary cluster and therefore the common relaying queue is not considered. The secondary (cognitive) transmitters sense the channel in each slot, and if they detect an idle slot, the relay with the best instantaneous link to the secondary receiver, transmits a packet (if there is any) from its queue.

1) Stability analysis: For the primary user, the service process can be modeled as $Y_P(t) = \mathbf{1}[\bar{\mathcal{O}}^t_{P,D_P}]$, where $\mathbf{1}[\cdot]$ is the indicator function, $\bar{\mathcal{O}}^t_{i,j}$ denotes the complement of the outage event between terminal i and the destination j at time t. The service process is stationary and has a finite mean given by $\mu_P^{(\max)} = E[Y_P(t)] = \mathbb{P}\{\bar{\mathcal{O}}^t_{P,D_P}\} = f_{P,D_P}$. According to Loynes' theorem, the stability of the primary queue requires

$$\lambda_P < \mu_P^{(\max)} = \ f_{P,D_P} = \ \exp\left(-\frac{2^{R_0}-1}{P_0}\right) \qquad \text{[packets/slot]}. \tag{1}$$

On the other hand, the secondary transmitters access the channel when the primary user does not have any packet in its queue. As perfect channel state information (CSI) is assumed at the cognitive cluster, the transmission policy which maximizes the total capacity requires the relay with the best link (with the secondary destination) to transmit at full power [28]. The service process for a secondary user can be expressed as $Y_k(t) = \mathbf{1}[\{Q_P(t) = 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}^t_{k,D_S}]$, where $\mathbb{P}\{Q_P(t) = 0\}$ denotes the probability that the primary queue is empty at the time slot t, Δ^t_k denotes the event that relay k is selected for transmission ($k = k^*$) and $k^* = \arg\max_{k\in S_{\text{relay}}}\{\gamma_{k,D_S}\}$ denotes the selected node with $\gamma_{i,j}$ equal to the instantaneous signal-to-noise (SNR) of the link $i \to j$. By using Little's theorem [29], we have $\mathbb{P}\{Q_P(t) = 0\} = (1 - \lambda_P/\mu_P^{(\max)})$ and therefore Loyne's constraint for the stability of the secondary transmitters gives

$$\lambda_S < \mu_S^{(\max)} = E[Y_k(t)] = \mathbb{P}\{Q_P(t) = 0\}\mathbb{P}\{\Delta^t_k\}\mathbb{P}\{\bar{\mathcal{O}}^t_{k^*,D_S}\} = \frac{1}{K}\left[1 - \frac{\lambda_P}{\mu_P^{(\max)}}\right] f_{k^*,D_S}, \tag{2}$$

where $f_{k^*,D_S} = 1 - \left[1 - \exp\left(-(2^{R_0}-1)/P_0(1-d)^{-\beta}\right)\right]^K$ is calculated by using order statistics [31]. We note that due to the clustered configuration of the secondary nodes, the average channels between them and the secondary destination are assumed to be statistically equivalent [25]. Therefore, each relay can access the channel with the same probability and this behavior yields a long-term transmission fairness among the nodes.

B. 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. It is an extension of the protocol proposed in [22] for a single-cognitive configuration. More specifically, according to the cognitive principle, the primary user transmits its packets without taking into account the existence of the relay cluster. However, in contrast with the non-cooperative scheme where the primary node removes a packet from its queue when is successfully received at the destination, here, it can also drop a packet when it is successfully received by the cognitive cluster. In the case that a packet is not successfully delivered at the primary destination but is decoded by at least one secondary node of the cognitive cluster, the packet is added to the common relaying queue (which is accessible from all the nodes of the cluster) and an ACK signal is broadcasted by the cluster. More specifically, all the cognitive nodes which successfully decode the source message convey their packets to the central CSB. After a basic processing of the received packets (replica packets are discarded), the CSB enters the source packet to the common queue and transmits an ACK signal. It is assumed that the conventional non-cooperative ACK/NACK mechanism is modified and allows the cognitive cluster to notify the primary user for successful decoding of a transmitted packet [21]. Furthermore, according to the previous description of the cognitive structure, the relay cluster can decode the transmitted signal if at least one relay can decode it. If such a relay exists, it is obvious that the link between the primary user and the cognitive relay with the best instantaneous channel conditions is not in outage [30].

1) 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 $k^\dagger = \arg\max_{k \in S_{\text{relay}}}\{\gamma_{P,k}\}$. Accordingly, $Y_P(t)$ is a stationary process with mean

$$\mu_P^{(\max)} = E[Y_P(t)] = \mathbb{P}\{\bar{\mathcal{O}}^t_{P,D_P}\} + \mathbb{P}\{\mathcal{O}^t_{P,D_P}\}\mathbb{P}\{\bar{\mathcal{O}}^t_{P,k^\dagger}\} = f_{P,D_S} + f_{P,k^\dagger} - f_{P,D_S} f_{P,k^\dagger}, \quad (3)$$

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 [31]. In contrast with the analysis of the non-cooperative case, here the maximum stable throughput of the primary user also depends on the stability of the cluster relaying queue. More specifically, when the primary source is inactive (the primary queue is empty) the cognitive cluster either transmits a packet from the common queue, or allows a relay to transmit a packet from its own queue to the secondary receiver. As the priority of the cooperative CR is to optimize the performance of the primary user, it is assumed that if the relaying queue is not empty, it is always selected for transmission. On the other hand, in the case that primary and common queues are both empty, a cognitive relay is selected to transmit its own data to the secondary destination. Accordingly, as CSI is available at the CR, the transmission policy which maximizes the capacity can be viewed as opportunistic scheduling. Therefore, for the case of the common queue, the relay with the best $k \rightarrow D_P$ link is selected for transmission (primary opportunistic scheduling) and for the case of an individual queue, the relay with the best $k \rightarrow D_S$ link (secondary opportunistic scheduling). 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. The departure process is defined as $Y_{PS}(t) = \mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \bar{\mathcal{O}}^t_{k_1,D_P}\right]$, where $k_1 = \arg\max_{k \in S_{\text{relay}}}\{\gamma_{k,D_P}\}$, and the mean of the departure process is given as

$$\mu_{PS} = \left(1 - \frac{\lambda_P}{\mu_P^{(\max)}}\right) \cdot \underbrace{\left[1 - \left[1 - \exp\left(-\frac{2^{R_0} - 1}{P_0(1-d)^{-\beta}}\right)\right]^K\right]}_{f_{k_1,D_P}}. \tag{5}$$

Based on Loyne's constraint for the stability of a stationary queue, from Eq.'s (3), (4) and (5) we have that the maximum stable average throughput of the primary user is equal to

$$\lambda_P < \frac{\left(f_{P,D_P} + f_{P,k^\dagger} - f_{P,D_P} \cdot f_{P,k^\dagger}\right) f_{k_1,D_P}}{f_{k_1,D_P} + (1 - f_{P,D_P})f_{P,k^\dagger}}. \tag{6}$$

Finally, for the individual relay queues, the departure process is defined as $Y_k(t) = \mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \{Q_{PS}(t) = 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}^t_{k,D_S}\right]$ which results a stable throughput for the secondary user equal to

$$\lambda_S < \mu_S^{(\max)} = E[Y_k(t)] = \frac{1}{K}\left(1 - \frac{\lambda_P}{\mu_P^{\max}} - \frac{\lambda_P}{\mu_P^{\max}} \frac{(1 - f_{P,D_P})f_{P,k^\dagger}}{f_{k_1,D_P}}\right) f_{k^*,D_S}. \tag{7}$$

C. 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

[23] when the common queue is served. More specifically, as the common queue is "shared" by all the nodes of the cluster via the CSB, 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 [19], [23]. 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 [20, Sec. 5.4] and yields an achievable rate region for the simultaneous transmissions equal to

$$R_{PS}(\alpha) \leq \log\left(1+\frac{\left|h_{k_1,D_P}\right|^2 P_0+\alpha\left|h_{k_2,D_P}\right|^2 P_{k_2}}{1+(1-\alpha)\left|h_{k_2,D_P}\right|^2 P_{k_2}}\right), \quad R_{k_2}(\alpha) \leq \log\left(1+(1-\alpha)\left|h_{k_2,D_S}\right|^2 P_{k_2}\right) \tag{8}$$

where $k_1, k_2 \in S_{\text{relay}}$ denote the relay that serves the common queue and its own queue, respectively, $P_k = P_0(1-d)^{-\beta}$, $h_{i,j}$ 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 [23]. The above expressions refer to a normalized AWGN variance according to the considered system model (Sec. II.B). We note that the above DPC technique does not take into account the knowledge of the links $S_{\text{relay}} \rightarrow D_P$ and therefore it is a suboptimal technique. However, according to [20], it has a performance close to the full-feedback DPC with a lower complexity. In addition to this property, this suboptimal DPC technique satisfies the scope of this paper and simplifies analytical results (outage probabilities).

According to Eq. (8), 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 can be optimized according to various criteria. In this work, we focus on 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. The relay selection scheme that is now described is an efficient solution for this cognitive scenario. More specifically, the relay with the maximum instantaneous channel conditions to the primary destination is selected to serve the common relaying queue. This assumption optimizes the primary throughput and protects the primary link from the secondary user's interference. However, selecting the other cognitive node (which serves its own queue) based on the second best link to the primary destination, introduces severe interference on the relaying link without significantly contributing to the relaying performance. On the other hand, the selection of this node based on the quality of the secondary link can optimize the secondary throughput by simultaneously protecting the relaying link from interference. Therefore, the selection strategy is a secondary-based opportunistic scheduling among the remaining $(K-1)$ nodes. A more detailed analysis for the impact of the relay selection on the DPC design can be found in [32]. The proposed selection policy can be expressed as

$$k_1 = \arg\max_{k \in S_{\text{relay}}} \{\gamma_{k,D_P}\}, \qquad k_2 = \arg\max_{k \in \{S_{\text{relay}} - k_1\}} \{\gamma_{k,D_S}\} \tag{9}$$

Regarding the implementation of this scheme, in a manner equivalent to the CC protocol, CSB takes the selection decisions and synchronizes the DPC transmission. Based on an internal cluster communication (the secondary nodes exchange information perfectly with the CSB), each secondary node informs CSB about the quality of their links with both destinations [20]. Therefore, when a time slot is sensed to be empty, the CSB applies the above selection rules and supplies the relaying node with a packet from the common queue.

In the case that the primary and the common queues are both empty the CR can access the radio in order to serve an individual relay queue. For this transmission, a secondary link-based opportunistic scheduling maximizes the total capacity of the system. In comparison with the conventional protocol, the integration of DPC gives more opportunities to the secondary users to access the channel, as a relay can also transmit its own data during the service of the common queue.

1) Stability analysis: In a similar fashion to the conventional cooperative scheme, the maximum average departure for the primary user is given by Eq. (3). Furthermore, the constraint for the maximum stable arrival throughput for the primary user is obtained by studying the stability of the common queue. The arrival process in the common queue is described by Eq. (4) and 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

Appendix I. By applying Loyne's stability theorem to the common relaying queue, the average throughput of the primary user is constrained as follows

$$\lambda_P(\alpha) < \frac{\Big(f_{P,D_P} + f_{P,k^\dagger} - f_{P,D_P} \cdot f_{P,k^\dagger}\Big) f_{k_1,D_P}(\alpha)}{f_{k_1,D_P}(\alpha) + (1 - f_{P,D_P}) f_{P,k^\dagger}}. \tag{10}$$

It is worth noting that Eq. (10) differs from (6) in that it allows an optimization of λ_P by optimizing the parameter α. 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

$$Y_k(t) = \mathbf{1}\Big[\{Q_P(t) = 0\} \bigcap \{Q_{PS} \neq 0\} \bigcap A_k^t \bigcap \bar{\mathcal{O}}_{k,D_S}^t(\alpha)\Big] + \mathbf{1}\Big[\{Q_P(t) = 0\} \bigcap \{Q_{PS}(t) = 0\} \bigcap \Delta_k^t \bigcap \bar{\mathcal{O}}_{k,D_S}^t\Big] \tag{11}$$

where A_k^t denotes the event that relay k is selected for DPC transmission ($k = k_2$). The above expression results in a maximum throughput for the cognitive relay equal to

$$\lambda_S(\alpha) < \mu_S = \frac{1}{K}\left(1 - \frac{\lambda_P}{\mu_P^{(\max)}}\right)\left[f_{k_2,D_S}(\alpha) - \frac{\frac{\lambda_P}{\mu_P^{(\max)}} \cdot (1 - f_{P,D_P}) \cdot f_{P,k^\dagger}}{\left(1 - \frac{\lambda_P}{\mu_P^{(\max)}}\right) \cdot f_{k_1,D_P}(\alpha)}\Big(f_{k_2,D_S}(\alpha) + f_{k^*,D_S}\Big)\right], \tag{12}$$

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

D. *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. It is worth noting that the proposed MC scheme requires a time-synchronization of the cognitive cluster to the primary system. This requirement can be ensured via a beacon channel, which is continuously (or periodically) broadcasted by the primary users [19], [20] and allows the cognitive users to adjust their local clocks according to the primary system. 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. Therefore, for the service of the common queue, the node with the best $k \rightarrow D_P$ link is selected, and for the case of the secondary transmission, the node with the best $k \rightarrow D_S$ link.

1) Stability analysis: For the primary user, the departure process can be expressed as

$$Y_P(t) = \mathbf{1}\left[\bar{\mathcal{O}}^t_{P,D_P}\right] + \mathbf{1}\left[\mathcal{O}^t_{P,D_P} \bigcap \bar{\mathcal{O}}^t_{P,k^\dagger} \bigcap \bar{\mathcal{O}}^t_{P;k_1,D_p}\right], \tag{13}$$

where $\mathcal{O}_{i;j,l}$ denotes the event that the MISO link ($i \rightarrow l$, $j \rightarrow l$) is in outage. Therefore, the maximum throughput for the primary user is given as

$$\mu_S^{(\max)} = E[Y_P(t)] = f_{P,D_P} + (1 - f_{P,D_P}) f_{P,k^\dagger} f_{P;k_1,D_P}. \tag{14}$$

where $f_{P;k_1,D_P}$ is given in Appendix II. On the other hand, the arrival process in the common queue 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 equal to $\lambda_{PS} = (\lambda_P/\mu_P^{(\max)}) \cdot (1 - f_{P,D_P}) f_{P,k^\dagger}$. Furthermore, the departure process in the common queue is expressed as $Y_{PS} = \mathbf{1}\left[\bar{\mathcal{O}}_{P;k_1,D_P}\right]$ with a mean equal to $\mu_{PS} = f_{P;k_1,D_P}$. Therefore, by using Loyne's stability theorem for the primary and common queue, the maximum stable throughput for the primary user is given as

$$\lambda_P < \begin{cases} f_{P,D_P} + (1 - f_{P,D_P}) f_{P,k^\dagger} f_{P;k_1,D_P} & \text{if } f_{P;k_1,D_P} > (1 - f_{P,D_P}) f_{P,k^\dagger} \\ \frac{\left[f_{P,D_P} + (1 - f_{P,D_P}) f_{P,k^\dagger} f_{P;k_1,D_P}\right] f_{P;k_1,D_P}}{(1 - f_{P,D_P}) f_{P,k^\dagger}} & \text{if } f_{P;k_1,D_P} \leq (1 - f_{P,D_P}) f_{P,k^\dagger} \end{cases} \tag{15}$$

Finally, according to the proposed protocol a cognitive relay accesses the channel whenever the primary queue becomes idle. This behavior can be expressed by the departure process $Y_k(t) = \mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}^t_{k,P_D}\right]$ which results a maximum arrival throughput equal to

$$\lambda_S < \frac{1}{K}\left(1 - \frac{\lambda_P}{\mu_P^{(\max)}}\right) f_{k^*,D_S}. \tag{16}$$

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

In this protocol, the primary user follows the same behavior as the MC cooperative 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.C, the considered DPC scheme provides an achievable rate region for the simultaneous transmissions which is given by

$$R_P(\alpha) \leq \log\left(1 + \frac{\left|h_{P,D_P}\right|^2 P_0 + \alpha\left|h_{k^*,D_P}\right|^2 P_{k^*}}{1 + (1-\alpha)\left|h_{k^*,D_P}\right|^2 P_{k^*}}\right), \quad R_{k^*}(\alpha) \leq \log\left(1 + (1-\alpha)\left|h_{k^*,D_S}\right|^2 P_{k^*}\right) \tag{17}$$

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.

1) Stability Analysis: The departure process in the primary queue can be expressed as

$$Y_P(t) = \mathbf{1}\left[\bar{\mathcal{O}}_{P,D_P}\right] + \mathbf{1}\left[\mathcal{O}^t_{P,D_P} \bigcap \bar{\mathcal{O}}^t_{P,k^\dagger} \bigcap \bar{\mathcal{O}}^t_{P;k^*,D_P}(\alpha)\right], \tag{18}$$

with a mean equal to

$$\mu_P^{(\max)} = f_{P,D_P} + (1 - f_{P,D_P}) \cdot f_{P,k^\dagger} \cdot f_{P;k^*,D_P}(\alpha) \tag{19}$$

where $f_{P;k^*,D_P}(\alpha)$ is given in Appendix 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 the Loyne's stability theorem, the maximum throughput of the primary user is constrained as

$$\lambda_P(\alpha) < \begin{cases} f_{P,D_P} + (1 - f_{P,D_P}) f_{P,k^\dagger} f_{P;k^*,D_P}(\alpha) & \text{if } f_{P;k^*,D_P}(\alpha) > (1 - f_{P,D_P}) f_{P,k^\dagger} \\ \frac{\left[f_{P,D_P} + (1-f_{P,D_P}) f_{P,k^\dagger} f_{P;k^*,D_P}(\alpha)\right] f_{P;k^*,D_P}(\alpha)}{(1-f_{P,D_P}) f_{P,k^\dagger}} & \text{if } f_{P;k^*,D_P}(\alpha) \leq (1 - f_{P,D_P}) f_{P,k^\dagger} \end{cases} \tag{20}$$

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

$$Y_k(t) = \mathbf{1}\left[\{Q_P(t) \neq 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}_{k,D_S}(\alpha)\right] + \mathbf{1}\left[\{Q_P(t) = 0\} \bigcap \Delta^t_k \bigcap \bar{\mathcal{O}}_{k,D_S}\right] \tag{21}$$

which yields a maximum throughput for the primary user equal to

$$\lambda_S(\alpha) < \mu_S = \frac{1}{K} \cdot \left[\frac{\lambda_P(\alpha)}{\mu_P^{(\max)}} \cdot f_{k^*,D_S}(\alpha) + \left(1 - \frac{\lambda_P(a)}{\mu_P^{(\max)}}\right) f_{k^*,D_S}\right] \tag{22}$$

where $f_{k^*,D_S}(\alpha)$ is given in Appendix III. We note that the analysis of the DPC design with a primary-based opportunistic selection follows the above methodology and is taken into account in the numerical results. Fig. 2 schematically summarizes the proposed cooperative schemes.

F. Optimizing the DPC parameter

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. However, the potential capacity benefits increase secondary transmission opportunities and can maximize the secondary throughput. 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

$$a^* = \arg\max_{\alpha} \left\{\lambda_S(\alpha)\right\}$$
$$\textbf{s.t.} \;\; \lambda_{P_0} \leq \lambda_P(\alpha) \text{ with } \alpha \in [0\ 1], \tag{23}$$

As the DPC approaches are based on the CC and MC protocols, they can not offer a primary throughput over these schemes. Therefore, the validation of the above constraint corresponds to a direct application of Eq.'s (6) and (15), respectively. If this constraint is satisfied ($\lambda_{P_0} < \mu_P^{\max}$), the solution of the optimization problem requires the solution of the inequality $\lambda_{P_0} \leq \lambda_P(\alpha)$ for α. Furthermore, if $\Psi \subseteq [0\ 1]$ denotes the solution of this inequality, the appropriate parameter α which solves the above optimization problem is $\alpha^* = \min\{\Psi\}$, as R_k is a monotonically decreasing function with α.

IV. Numerical results

Computer simulations were carried out in order to validate the performance of the proposed schemes. Fig. 3 plots the primary throughput (λ_P) versus the maximum secondary throughput ($\mu_S^{(\max)}$) of the proposed cooperative schemes; a specified (pre-defined) primary throughput is used for the DPC-based approaches. The simulation parameters are: $K = 2$ users, $d = 0.6$, $R_0 = 2$ bits per channel use (BPCU), $P_0 = 6$ dB, $\lambda_{P_0}^{\text{CC}} = 0.65$ and $\lambda_{P_0}^{\text{MC}} = 0.77$ (packets/slot) for the CC and MC, respectively. It is worth noting that cooperation for cognitive systems is an interesting solution only when the direct links are in deep-fading and both branches of the relaying link are strong enough in order to establish communication [21], which motivated our particular choice of simulation parameters. 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 improves 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 cognitive communication with a non-zero throughput.

Fig. 4 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 choice 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 $\lambda_{P_0}^{\mathrm{MC}} = 0.77$). With respect to the flat behavior of the curves for some regions of α, it is justified by the outage expressions in Appendices I and III. More specifically, in the MC+DPC case, for a $Z > \alpha/[1-\alpha]$ ($Z = 3$ for the considered scenario (see definition in Appendices I, III)) we have $f_{P;k^*,D_P}(\alpha) \rightarrow 0$ and therefore DPC does not help either the primary or the secondary performance. Accordingly, in the CC+DPC protocol, for a $Z < \alpha/(1-\alpha)$ we have $f_{k_1,D_P}(\alpha) \simeq f_{k_1,D_P}(Z/[1+Z])$ and therefore the corresponding throughput does not change.

In Fig. 5, we present the impact of the geometry on the performance (throughput) of the proposed schemes for the above system configuration. As can be seen, the cooperative protocols are improved as the cognitive cluster is closer to the destination. For cognitive cooperation, the critical link is the one between the cluster and the primary destination. As the quality of this link improves (the cluster is closer to the destinations), the service ability of the system improves and optimizes the global throughput. From this figure, it can be seen that for the considered simulation parameters, the location of the cluster at $d = 0.9$ gives the best trade-off between primary and secondary users.

Fig. 6 presents the throughput performance of the proposed schemes versus the quality of the direct link. The other simulation parameters are similar to the previous ones and parameter α is pre-defined equal to 0.8 (optimal from the primary user's point of view). For low SNRs, the conventional cooperation outperforms the proposed schemes. In this SNR region, DPC schemes introduce a severe interference to the primary transmission without a major gain throughput for the secondary users. Furthermore, MC schemes are not efficient for low SNRs. The poor quality of the primary user results in a low performance for the cooperation between primary and secondary users. In Fig. 7, we present the maximum throughput of the primary user for the proposed schemes and for different number of users. The number of users is related to the decoding ability of the cognitive cluster and the relay selection for the service of the relaying queue. As the number of users increases, the outage probability between primary user and cluster is decreased and thus the decoding ability of the cluster is improved. Furthermore, for the cooperative protocols where the service of the relaying queue follows an primary opportunistic selection, the increase of the number of relays yields a better primary throughput. However, for the adopted MC+DPC protocol where the service of the primary queue is not based on a relay selection, its performance is independent of the number of the relays. An interesting observation here, is that setting the number of relays $K = 5$ is enough in order to achieve the maximum performance.

In Fig. 8, we compare the performance of the proposed DPC-based protocols for different relay selection policies. More specifically, we compare the non-selection scheme, the primary opportunistic selection and the adopted selection policy under a specified primary throughput (see Section III. E). The simulation parameters are: $K = 4$ users, $d = 0.6$, $R_0 = 2$ BPCU and $P_0 = 6$ dB, $\lambda_{P_0}^{\text{CC}} = 0.65$, $\lambda_{P_0}^{\text{MC}} = 0.8$ packets/slot and the optimal value of the parameter α is equal to 0.6 and 0.8 for CC and MC, respectively. As can be seen, relay selection significantly improves the throughput for both the primary and the secondary cluster. For the CC+DPC protocol, the proposed selection outperforms the full primary opportunistic selection as it gives a higher secondary throughput while satisfying the selected $\lambda_{P_0}^{\text{CC}}$. On the other hand, the relay selection introduces a trade-off for the MC+DPC protocol. In this case, a primary opportunistic selection improves the primary throughput and a secondary opportunistic selection improves the secondary throughput by reducing the primary throughput. However, for the selected primary throughput, the proposed scheme is the appropriate selection policy. In this figure, we present also the theoretical approximation for the case of the CC+DPC protocol (Appendix I). The corresponding curve is very close to the true performance, and this observation validates our simplified expression. These simulation results are supported also by Fig. 9, where the maximum primary and secondary throughput versus the parameter α is depicted. For the CC+DPC scheme, the proposed selection outperforms the competitive selection for all the cases and as can be seen $\alpha \approx 0.6$ is the optimal value of the parameter α for the above specified primary throughput. On the other hand, for the MC+DPC scheme, we can observe that the proposed selection outperforms the competitive scheme for low α and achieves an efficient trade-off between primary and secondary performance for high α. More specifically, for the selected primary throughput ($\lambda_{P_0}^{\text{MC}} = 0.8$) the adopted relay selection supports this throughput while optimizing the secondary performance. However, if the target of the cognitive system is the maximization of the primary performance (specified primary throughput higher than the maximum supported from the proposed selection), a primary opportunistic selection and $a \approx 0.9$ seems to be a suitable parametrization of the system.

V. CONCLUSION

This paper has dealt with protocol design in cognitive cooperative systems with a clustered cognitive structure. The considered configuration enables cooperation between a primary and a cognitive cluster in order to support a desired primary throughput and give more transmission opportunities to the secondary users. The investigated protocols allow simultaneous transmission of relaying and secondary data based on DPC. The DPC parameter as well as its relation with opportunistic relay node selection introduces a trade-off between primary and cognitive performance. This trade-off is studied under a primary protection scenario where the optimization target is to maximize the secondary throughput while supporting a specified primary throughput. The investigated protocols are analyzed based on the stability throughput region and their enhancement are provided by simulation and analytical results. An interesting topic for future investigation is the analysis of the proposed schemes under a realistic imperfect cognitive sensing.

APPENDIX I
CONVENTIONAL COOPERATION WITH DPC

The computation of the outage probability for the relaying data requires the computation of the cumulative distribution function (CDF) of the random variable (R.V.) Z, defined as $Z = X + \alpha Y/(1+(1-\alpha))Y$, where X is the maximum among K i.i.d. exponential R.V.s with parameter λ, and Y is also an exponential R.V. with parameter λ with $Y < X$. In order to simplify the analytical expression, we relax the constraint $Y < X$ and we assume that X, Y are independent. However, it can be easily shown that this constraint is "automatically" supported as K is increased. More specifically,

$$\begin{aligned}\mathbb{P}\{X < Y\} &= \int_0^\infty \mathbb{P}\{X < y\} u_Y(y)dy = \int_0^\infty \Big[1-\exp(-\lambda y)\Big]^K \lambda \exp(-\lambda y)dy \\ &= \sum_{m=0}^{K}\binom{K}{m}(-1)^m \lambda \int_0^\infty \exp(-\lambda y[m+1])dy = \frac{1}{K+1} \to 0 \text{ (as } K \text{ increases)},\end{aligned} \tag{24}$$

where $u_Y(\cdot)$ denotes the PDF of Y and for the above expression we have used the binomial theorem $(x+y)^n = \sum_{m=0}^{n}\binom{n}{m}x^{n-m}y^m$. It is worth noting that numerical results in Fig. 8 validate the efficiency of our simplified expression.

The CDF of Z can be written as

$$\begin{aligned}&\mathbb{P}\left\{\frac{X+\alpha Y}{1+(1-\alpha)Y} \le z\right\} = \mathbb{P}\{X \le z + Y\big[z(1-\alpha)-\alpha\big]\} \\ &= \begin{cases} \int_0^\infty \sum_{m=0}^{K}\binom{K}{m}(-1)^m \exp\Bigg(-\lambda m[z+y[z(1-\alpha)-\alpha]]\Bigg)u_y(y)dy & \text{if } z \ge \frac{\alpha}{1-\alpha} \\ \int_0^{\frac{z}{z(\alpha-1)+\alpha}} \sum_{m=0}^{K}\binom{K}{m}(-1)^m \exp\Bigg(-\lambda m[z+y[z(1-\alpha)-\alpha]]\Bigg)u_y(y)dy & \text{if } z < \frac{\alpha}{1-\alpha}\end{cases} \\ &= \begin{cases} \sum_{m=0}^{K}\binom{K}{m}(-1)^m \frac{1}{m[z(1-\alpha)-\alpha]+1}\exp(-\lambda m z) & \text{if } z \ge \frac{\alpha}{1-\alpha} \\ \sum_{m=0}^{K}\binom{K}{m}(-1)^m \frac{\exp(-\lambda m z)}{m[z(1-\alpha)-\alpha]+1}\exp\left(\frac{-\lambda z\big[m[z(1-\alpha)-\alpha]+1\big]}{z(\alpha-1)+\alpha}\right) & \text{if } z \le \frac{\alpha}{1-\alpha}\end{cases}\end{aligned} \tag{25}$$

The outage probability for the primary link can be expressed as

$$\mathbb{P}\{\mathcal{O}_{k_1,D_P}(\alpha)\} = \mathbb{P}\left\{\frac{|h_{k_1,D_P}|^2\rho_c + \alpha|h_{k_2,D_P}|^2\rho_c}{1+(1-\alpha)|h_{k_2,D_P}|^2\rho_c} < 2^{R_0}-1\right\}, \tag{26}$$

which can be calculated by using the previous probability expression, with $X = |h_{k_1,D_P}|^2\rho_c$, $Y = |h_{k_2,D_P}|^2\rho_c$, $\rho_c = (1-d)^{-\beta}$, $\lambda = \rho_c^{-1}$ and $z = 2^{R_0} - 1$. The outage probability for the secondary link can be expressed as

$$\mathbb{P}\{\mathcal{O}_{k_2,D_S}(\alpha)\} = \mathbb{P}\left\{\log\left(1 + (1-\alpha)|h_{k_2,D_S}|^2\rho_c/2\right) < R_0\right\} = \left[1 - \exp\left(-\frac{2(2^{R_0}-1)}{(1-\alpha)\rho_c}\right)\right]^{K-1}. \tag{27}$$

APPENDIX II
MISO COOPERATION

The computation of the outage probability requires the computation of the CDF of the R.V.s Z defined as $Z = X + Y$ where X is an exponential R.V. with parameter λ_x and Y is the maximum between K exponential R.V. with parameter λ_y. We have,

$$\begin{aligned}\mathbb{P}\{X + Y \leq z\} = \mathbb{P}\{Y \leq z - X\} &= \int_0^z \left[1 - \exp\big(-\lambda_y(z-x)\big)\right]^K \lambda_1 \exp(-\lambda_x x)dx \\ &= \lambda_x \sum_{m=0}^{K} \binom{K}{m} (-1)^m \frac{\exp(-\lambda_y m z)}{\lambda_x - \lambda_y m}\left[1 - \exp\big(-z(\lambda_x - \lambda_y m)\big)\right]. \end{aligned} \tag{28}$$

The probability under question ($f_{P;k_1,D_P}$) corresponds to $z = 2(2^{R_0} - 1)/P_0$, $\lambda_x = 1$ and $\lambda_y = (1-d)^{-\beta}$.

APPENDIX III
MISO COOPERATION AND DPC

The computation of the outage probability for the relaying data requires the computation of the CDF of the R.V. Z, defined as $Z = X + \alpha Y/(1 + (1-\alpha))Y$, where X, Y are exponential R.V. with parameters λ_x and λ_y, respectively. We have

$$\mathbb{P}\left\{\frac{X+\alpha Y}{1+(1-\alpha)Y} \leq z\right\} = \mathbb{P}\{X \leq z + Y\big[z(1-\alpha)-\alpha\big]\}$$
$$= \begin{cases} \int_0^{\infty} U_x\Big(z + y\big[z(1-\alpha)-\alpha\big]\Big)u_y(y)dy & \text{if } z \geq \frac{\alpha}{1-\alpha} \\ \int_0^{\frac{z}{z(\alpha-1)+\alpha}} U_x\Big(z + y\big[z(1-\alpha)-\alpha\big]\Big)u_y(y)dy & \text{if } z < \frac{\alpha}{1-\alpha} \end{cases}$$
$$= \begin{cases} 1-\lambda_y \exp(-\lambda_x z)\frac{1}{\lambda_x\big[z(1-\alpha)-\alpha\big]+\lambda_y} & \text{if } z \geq \frac{\alpha}{1-\alpha} \\ 1-\exp(-\lambda_y \frac{z}{z(\alpha-1)+\alpha}) - \frac{\lambda_y \exp(-\lambda_x z)}{\lambda_x[z(1-\alpha)-\alpha]+\lambda_y}\left[1-\exp\left(-\frac{z(\lambda_x[z(1-\alpha)-\alpha]+\lambda_y)}{z(\alpha-1)+\alpha}\right)\right] & \text{if } z < \frac{\alpha}{1-\alpha} \end{cases} \quad (29)$$

The outage probability for the primary link can be expressed as

$$\mathbb{P}\{\mathcal{O}_{P;k^*,D_P}(\alpha)\} = \mathbb{P}\left\{\frac{|h_{P,D_P}|^2\rho_a + \alpha|h_{k^*,D_P}|^2\rho_c}{1+(1-\alpha)|h_{k^*,D_P}|^2\rho_c} < 2^{R_0}-1\right\}, \quad (30)$$

where it can be computed by using the above probability function with $\rho_a = P_0$, $\rho_c = P_0(1-d)^{-\beta}$, $X = |h_{P,D_P}|^2\rho_a$, $Y = |h_{k^*,D_P}|^2\rho_c$, $\lambda_x = \rho_a^{-1}$, $\lambda_y = \rho_c^{-1}$ and $z = 2^{R_0}-1$. The outage probability for the secondary link can be expressed as

$$\mathbb{P}\{\mathcal{O}_{k^*,D_S}(\alpha)\} = \mathbb{P}\left\{\log\left(1+(1-\alpha)|h_{k^*,D_S}|^2\rho_c\right) < R_0\right\} = \left[1-\exp\left(-\frac{2(2^{R_0}-1)}{(1-\alpha)\rho_c}\right)\right]^K, \quad (31)$$

where the last expression results from using order statistics [31].

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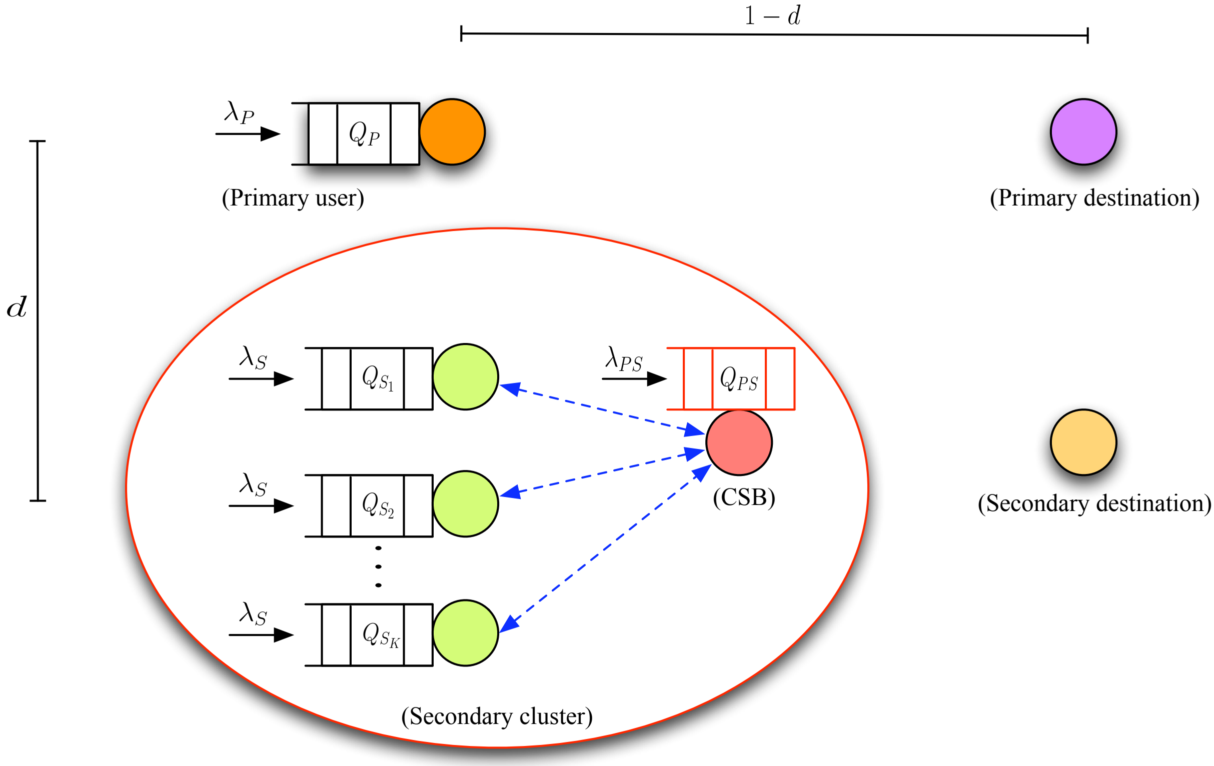

Fig. 1. System model.

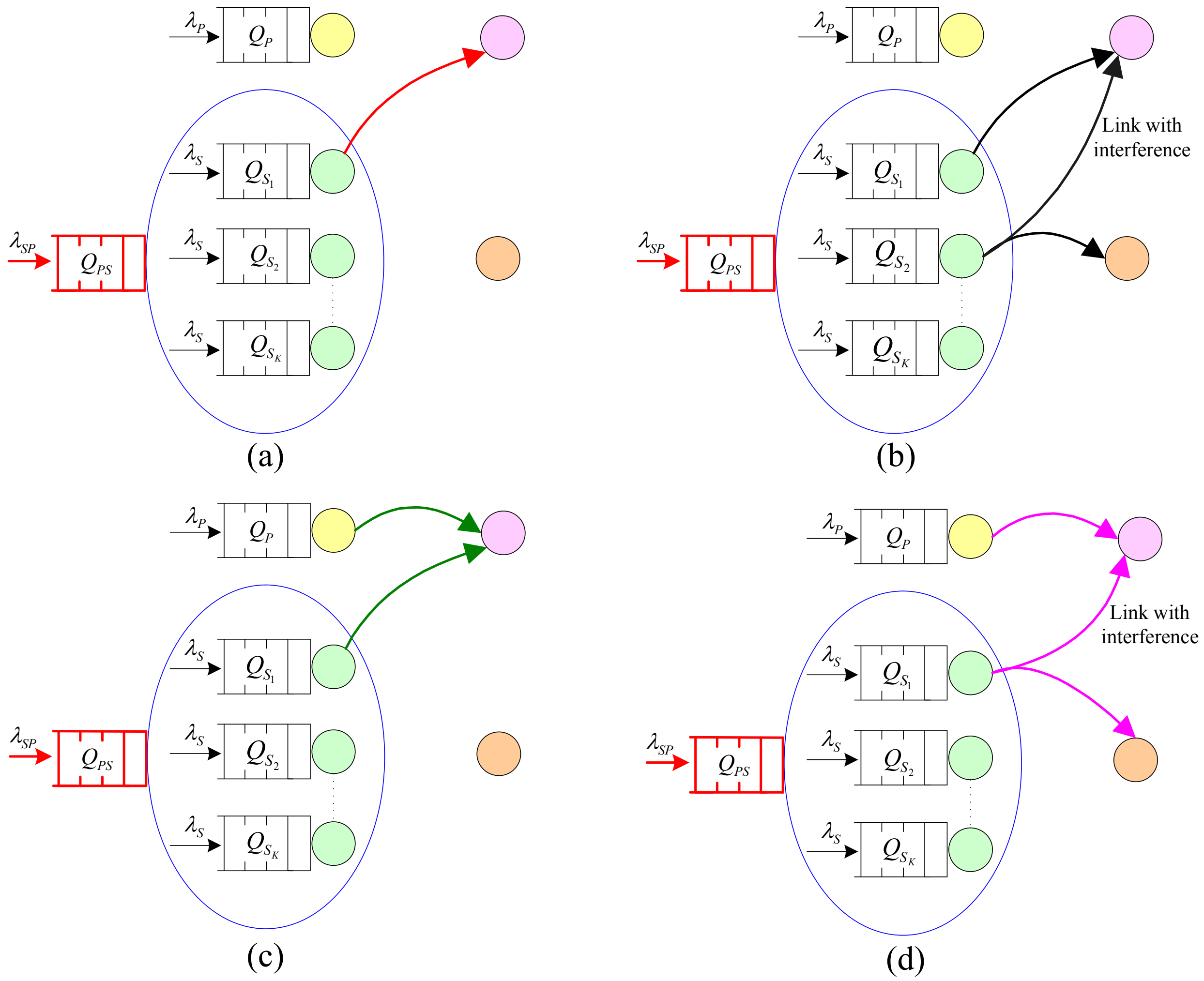

Fig. 2. The proposed cognitive cooperative protocols: (a) CC, (b) CC+DPC, (c) MC, (d) MC+DPC.

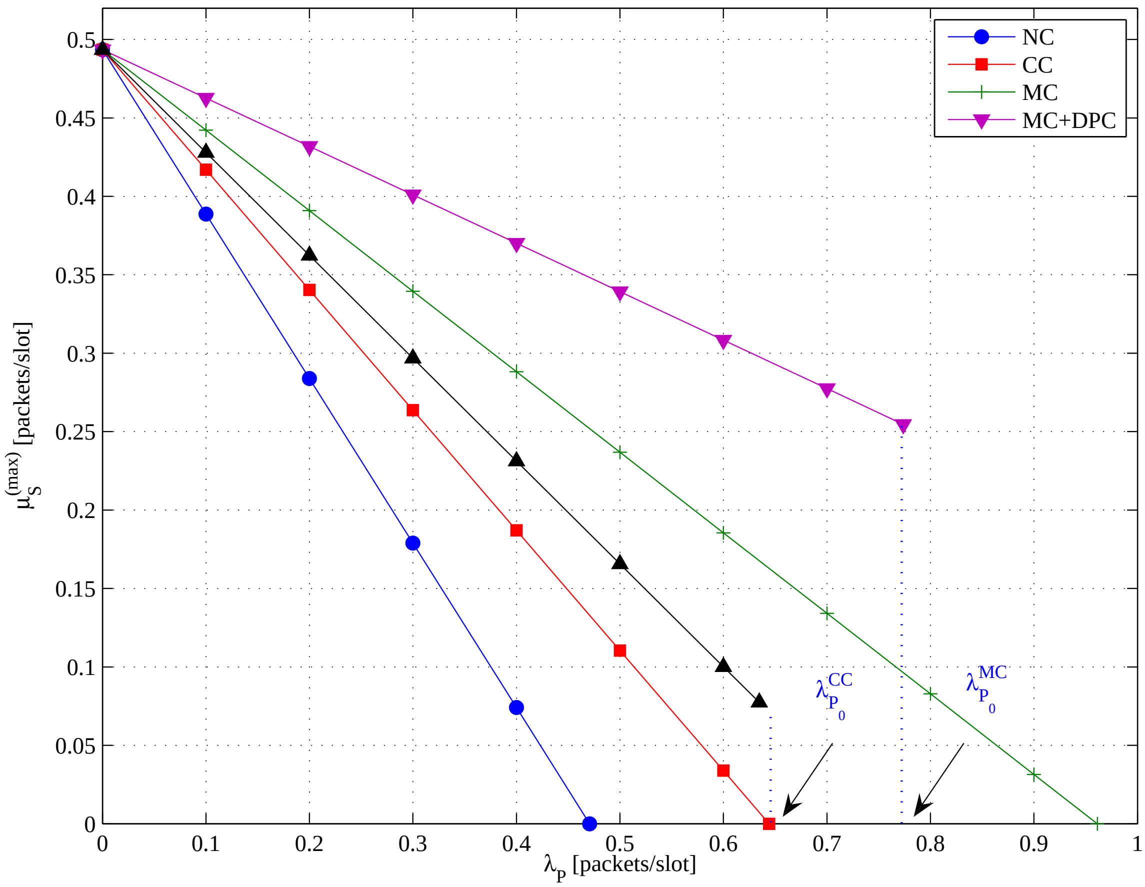

Fig. 3. Maximum throughput μ_S versus λ_P for NC, CC, CC+DPC, MC, and MC+DPC; $R_0 = 2$ BPCU, $K = 2$ cognitive users, $d = 0.6$, $P_0 = 6$ dB, $\alpha^{\text{CC}} = 0.7$, $\alpha^{\text{MC}} = 0.8$.

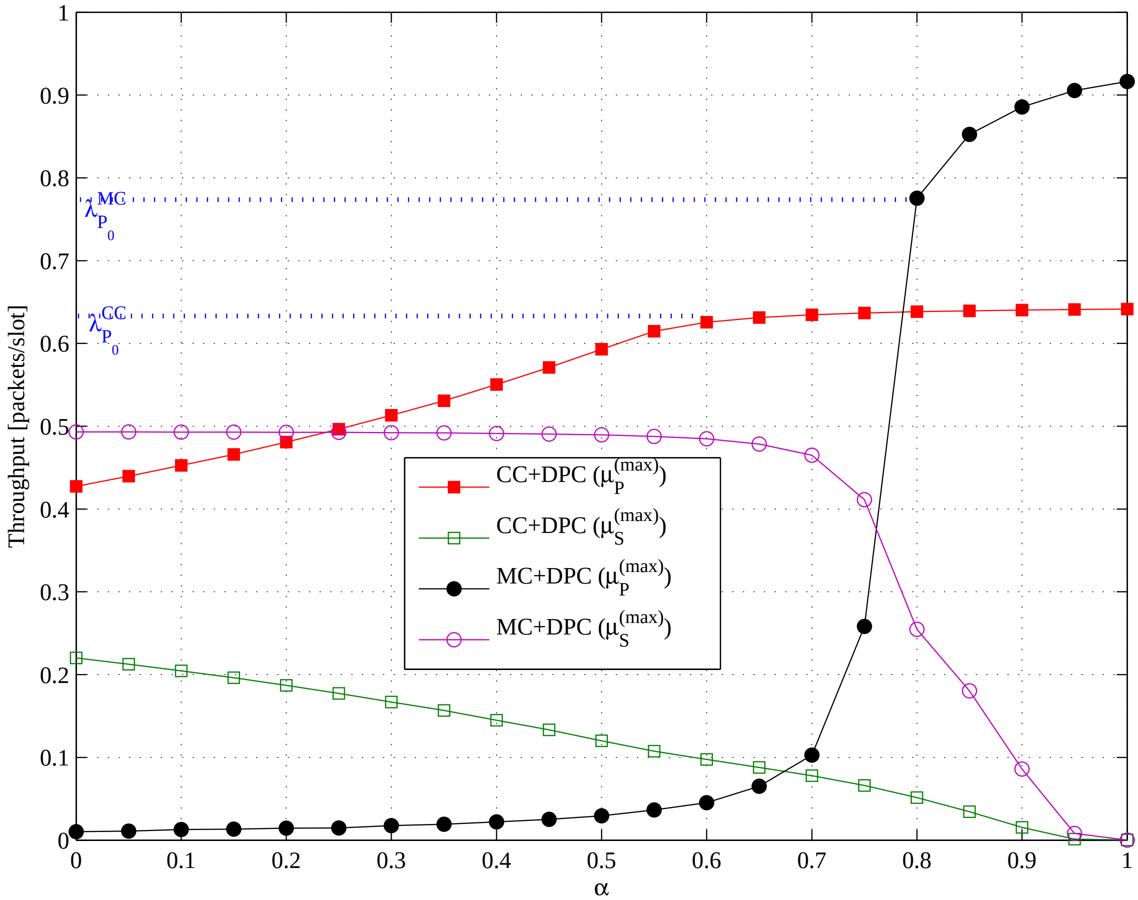

Fig. 4. Maximum throughput for primary and cognitive user versus α for CC+DPC and MC+DPC; $R_0 = 2$ BPCU, $K = 2$ cognitive users, $d = 0.6$, $P_0 = 6$ dB.

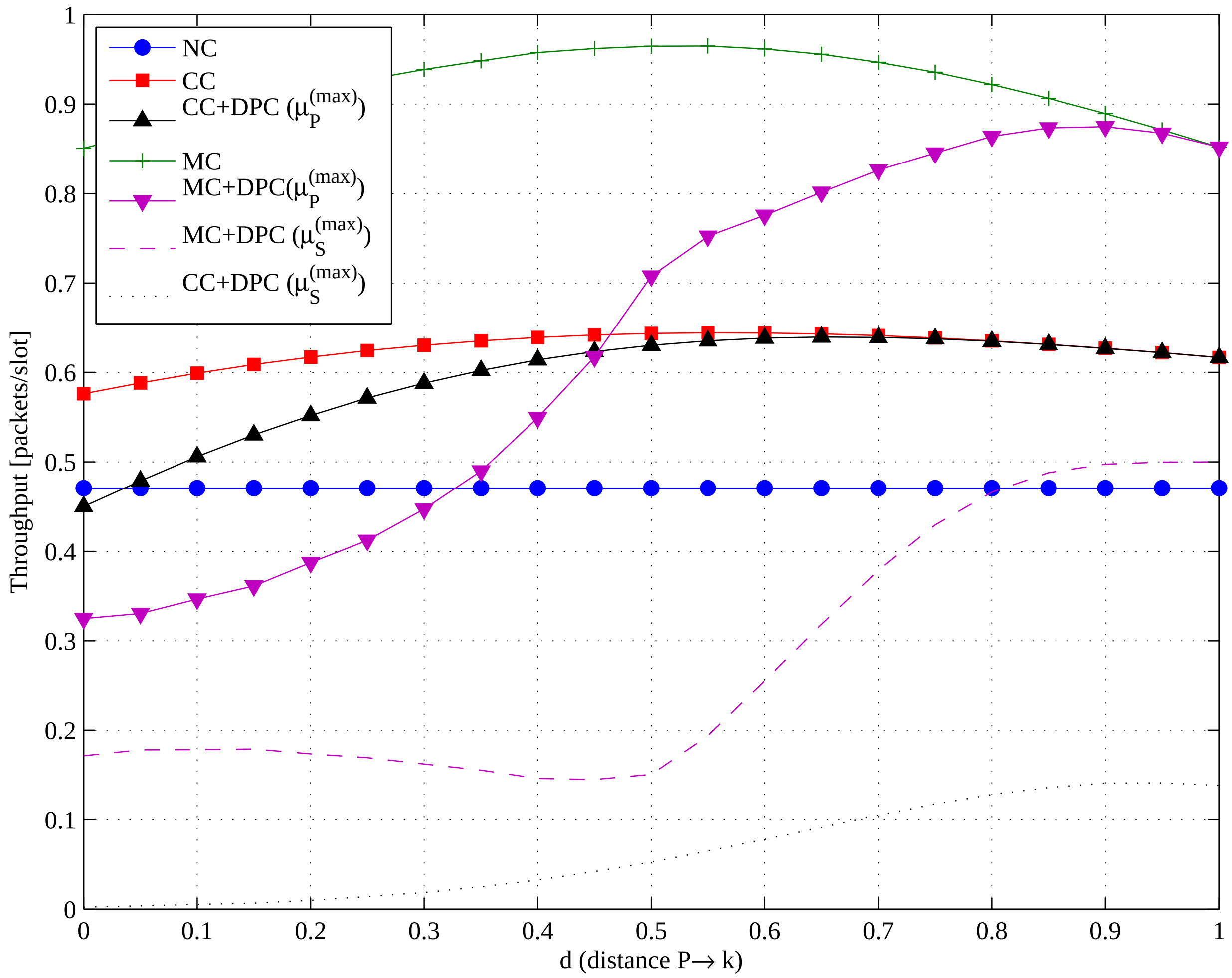

Fig. 5. Maximum throughput for primary and cognitive user versus the distance between primary user and cluster; $R_0 = 2$ BPCU, $K = 2$ cognitive users, $P_0 = 6$ dB, $\alpha^{\text{CC}} = 0.7$ and $\alpha^{\text{MC}} = 0.8$.

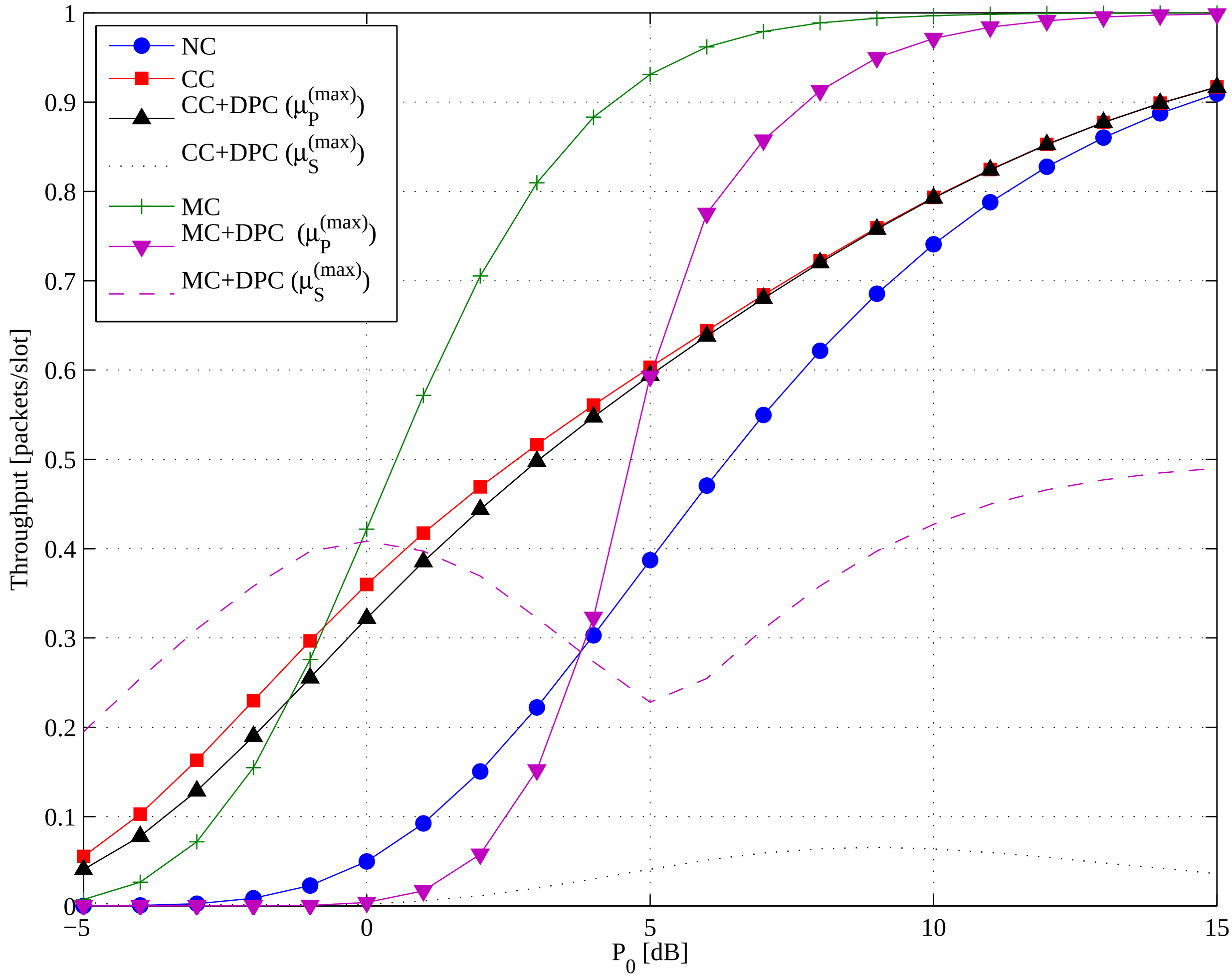

Fig. 6. Maximum throughput for primary and cognitive user versus the SNR of the direct link; $R_0 = 2$ BPCU, $K = 2$ cognitive users, $d = 0.6$ and $\alpha = 0.8$

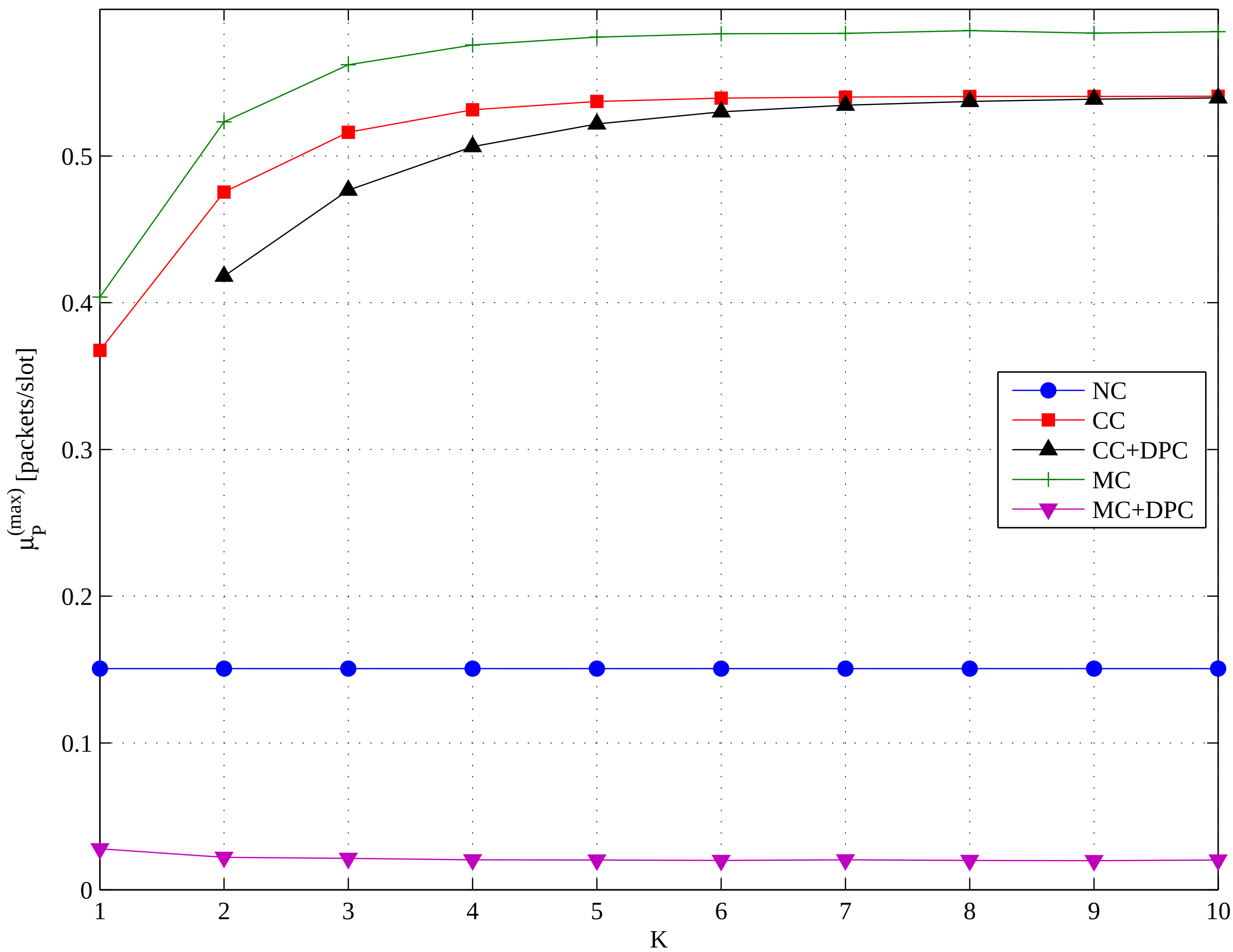

Fig. 7. Maximum throughput for primary user versus K; $R_0 = 2$ BPCU, $d = 0.5$, $P_0 = 2$ dB and $\alpha = 0.8$.

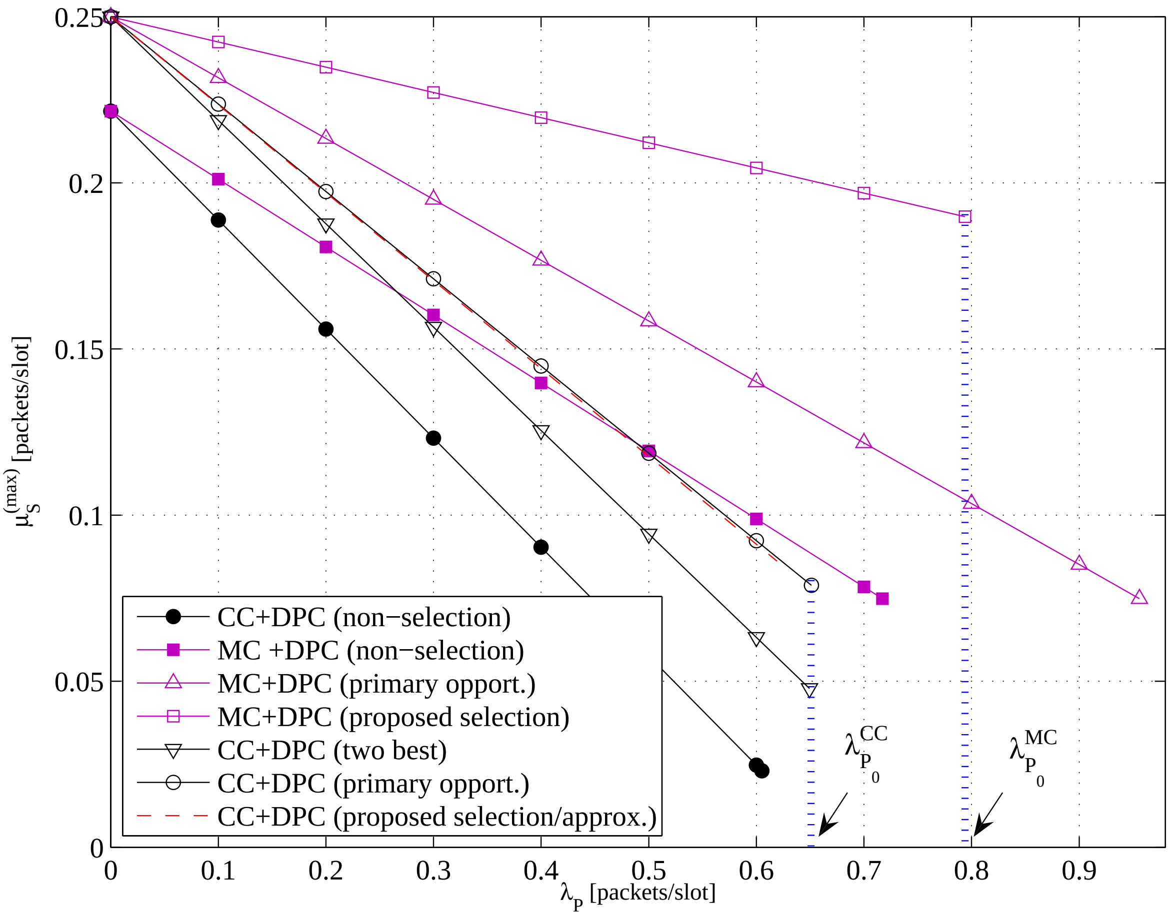

Fig. 8. Maximum throughput μ_S versus λ_P for DPC schemes for different selection criteria: non-selection, primary based selection (two best), proposed selection; $K = 4$; $R_0 = 2$ BPCU, $d = 0.6$, $P_0 = 6$ dB, $\alpha^{\text{CC}} = 0.6$ and $\alpha^{\text{MC}} = 0.8$.

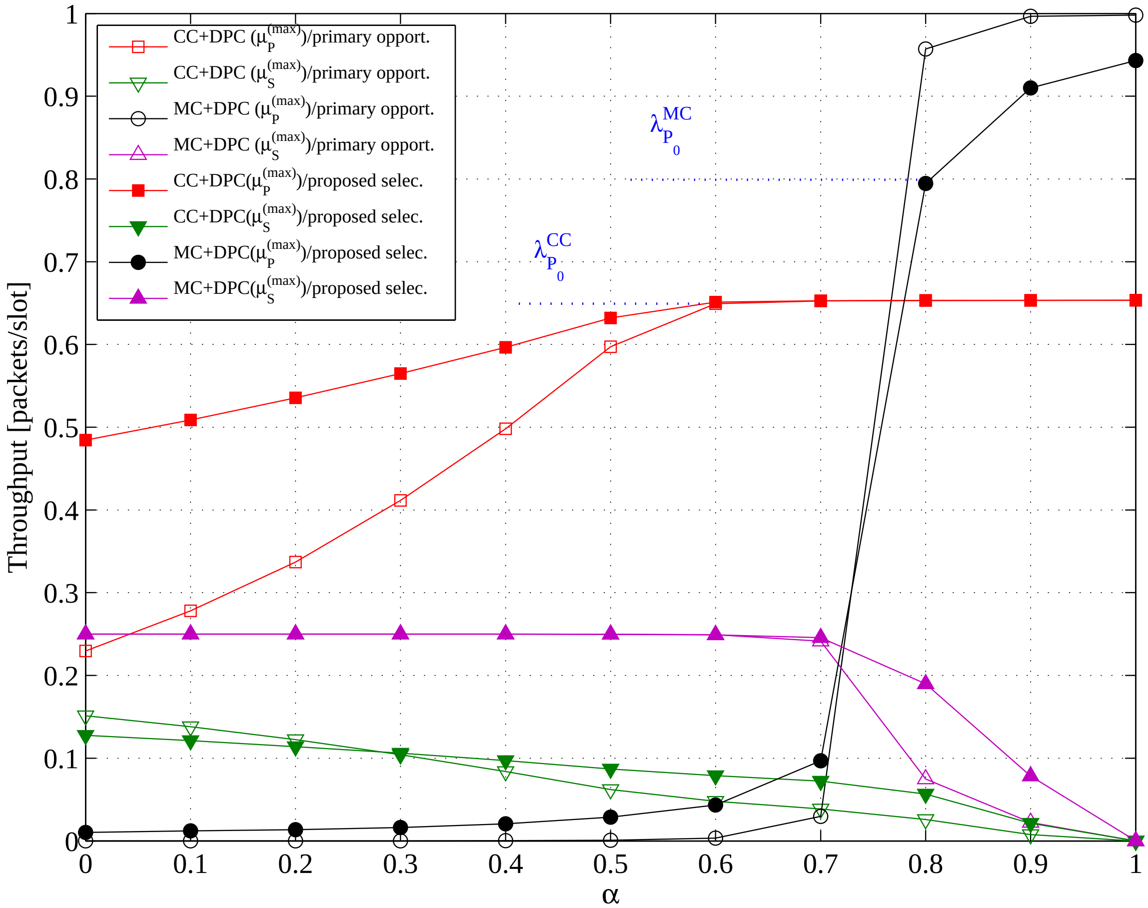

Fig. 9. Relay selection for DPC-based schemes versus the parameter α; $K = 4$; $R_0 = 2$ BPCU, $d = 0.6$, $P_0 = 6$ dB.