Network-Level Cooperation for a Multiple-Access Channel via Dynamic Decode-and-Forward

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Abstract

In this paper, we investigate some cross-layer cooperative strategies for cognitive Time-Division Multiple-Access relay channels with bursty arrivals. The proposed schemes adopt an advanced physical (PHY) layer cooperation and an "intelligent" cognitive network-layer cooperation in order to improve the stable throughput region of the system. In contrast to previously reported work, where relaying is only enabled on periods of source silence, here, we incorporate a Dynamic Decode-and-Forward (DDF) policy which allows relaying assistance also during the source transmission. The enhancement of cognitive relaying with DDF provides more cooperative opportunities which results in faster emptying of the user queues and higher stable throughput compared to the conventional approaches. In addition to this PHY-layer relaying, the cognitive cooperation is supported by an adaptive superposition scheme which allows the relay node to simultaneously forward packets from different users. We demonstrate that adaptive superposition can further increase the transmission opportunities and significantly improve the stable throughput region. The proposed schemes are studied from a networking perspective and their advantages are shown through both theoretical results and computer simulations.

Index Terms

Cooperative diversity, bursty traffic, relay channel, Dynamic Decode-and-Forward, superposition, queueing theory.

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I. INTRODUCTION

Cooperative diversity has emerged as a promising technique to combat fading in wireless communications [1], [2]. It enables single-antenna users to "enjoy" space diversity benefits by sharing their physical resources through a virtual transmit and/or receive antenna array. In most of previous work on cooperative techniques, cooperation is implemented at the physical layer, and is based on information-theoretic considerations where users have always data to transmit. Here, we adopt a packet-based network view of cooperation with bursty sources [3].

In order to exploit the bursty nature of data transmissions, cognitive cooperation has been recently proposed in the literature for bursty wireless applications [4]. To exploit source burstiness, the cognitive relay utilizes the periods of silence of the terminals to enable cooperation without extra channel resources. More recent work relaxes the "pure" relaying assumption and assumes that the relay node has also its own transmission requirement according to the principles of cognitive radio [5], [6]. This concept of cognitive cooperation has been introduced in [7] for single user configurations and has been generalized in [8] for clustered applications. However, all the existing work deals with simple physical (PHY)-layer cooperative protocols which, despite the performance gain against non-cooperative schemes, does not utilize fully the available degrees of cooperation in the system and thus limits the potential improvement in performance. The latter is measured in terms of packet stable throughput region rather than bit rate.

In this paper, we investigate more advanced PHY-layer protocols for cognitive cooperative systems. In contrast to the previously reported work, where cognitive cooperation is enabled only during the periods of source silence, a Dynamic Decode-and-Forward (DDF) is elaborated as a PHY relaying strategy [9]-[11]. The proposed method allows the relay node to provide diversity benefits simultaneously with the source transmission, if the relay node is able to decode the source message based on partial reception. In addition to this dynamic cooperation, the conventional cognitive cooperation (cooperation during periods of source silence) is enhanced via an adaptive superposition coding approach. The proposed scheme allows the relay node to switch between a single-queue service and a simultaneous service of several relaying queues by using a 1-bit feedback channel. The combination of DDF with superimposed cognitive relaying improves significantly the stable throughput region compared to previous techniques and introduces a new concept for protocol-level cooperation in a network. The proposed schemes are analyzed from a networking perspective and the stable throughput region for a two-user configuration is obtained using queueing theoretic ideas and methods. The impact of advanced PHY cooperative techniques on the stable throughput region has not yet been investigated in the literature. The contribution of this paper is twofold:

1) A novel cooperative scheme is introduced, which exploits (1) advanced PHY-layer cooperation via a DDF scheme, and (2) network (NET)-layer cooperation via cognitive relaying.
2) The cognitive cooperation is enhanced by an adaptive superposition approach which enables several relaying queues to be served simultaneously, based on simpe side-information at the transmitter.

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 stable throughput region. The integration of the superposition coding approach to the proposed protocols is presented in Section IV. Numerical results are shown and discussed in Section V, followed by concluding remarks in Section VI.

II. System model

We assume a simple multiple-access relay channel (MARC) configuration consisting of two primary users A, B, one common cognitive relay S and one common destination D as shown in Fig. 1. Both primary users (A, B) have a buffer of infinite capacity to store incoming packets and Q_i denotes the queue length in packets of the i-th user ($i \in \{A, B\}$). Time is considered to be slotted with a normalized slot duration ($T = 1$) and both users share the channel through Time-Division Multiple-Access (TDMA) scheduling which allows the users A and B to access the channel over disjoint fractions of time ω_A and ω_B, respectively, where $0 \leqslant \omega_A \leqslant 1$, $0 \leqslant \omega_B \leqslant 1$ and $\omega_A + \omega_B = 1$. The packet length for the i-th user is fixed, and contains R_i bits which are transmitted during one slot, thus resulting in a spectral efficiency of R_i bits/slot. The packet arrivals at the users are independent and stationary Bernoulli processes with mean λ_i (packets per slot) for the i-th user.

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 over a separate narrow-band channel in order to inform the network of that packet's reception status. When supporting the cognitive cooperation, the relay node is equipped with two relaying queues Q_{RA}, Q_{RB}, to relay some packets from the source users A and B respectively. The relaying queues Q_{Ri} ($i \in \{A, B\}$) are formed in the following way: when the i-th user transmits a packet, if the destination D decodes the packet successfully, it sends back an ACK and the packet exits the system; otherwise, if D cannot decode the packet but S decodes the packet, S sends back an ACK and keeps the packet in its Q_{Ri} queue for retransmission, while the i-th source drops the packet; if neither S nor D decodes the packet, the packet remains at Q_i for retransmission in the next TDMA frame.

All wireless links exhibit fading and additive white Gaussian noise (AWGN). The fading is assumed to be stationary, with frequency non-selective Rayleigh block fading. This means that the fading coefficients $h_{i,j}$ (for the $i \rightarrow j$ link) remain constant during one slot, but change independently from one slot to another according to a circularly symmetric complex Gaussian distribution with zero mean and variance $\sigma_{i,j}$ for the link $i \rightarrow j$. Furthermore, the variance of the AWGN is assumed normalized with zero mean and unit variance which corresponds to an average signal-to-noise ratio (SNR) equal to $\rho_{i,j} = P_0 \sigma_{i,j}^2$, where P_0 denotes the transmitted power common to all nodes. Each link $i \rightarrow j$ is characterized by the success probability $f_{i,j}(R) \triangleq \mathbb{P}\{\log(1 + \rho_{i,j}|h_{i,j}|^2) > R\} = \exp(-\frac{2^R - 1}{\rho_{i,j}})$ which denotes the probability that the link $i \rightarrow j$ is not in outage ($\overline{f_{i,j}}(R) = 1 - f_{i,j}(R)$ denotes the outage probability). An outage occurs when the instantaneous capacity of the link $i \rightarrow j$ is lower than the transmitted spectral efficiency rate R_i. The channel is assumed to be known only at the receivers (not at the transmitters) and perfect radio sensing is assumed for the cognitive relay which allows the node S to access the channel only when the latter is unutilized [4], [8].

As the arrival processes are assumed to be stationary, and since the departure processes are also stationary due to the stationary channel fading model described above, we can apply Loynes' Theorem [12] to check the stability of the queues which requires the average service rate be higher than the average arrival rate. The assumed TDMA structure decouples the queueus of the terminals and, hence, bypasses the thorny aspects of stability that arise when the queues interact.

III. Relaying cooperation and stability region

A. Non-cooperation (NC)

The non-cooperative (NC) option refers to the case in which the cognitive relay S does not relay data for the users and thus users A, B deliver their data via their direct links to the destination. Since both the arrival processes and the service processes are stationary and since the queues operate without interdependence (because of the time-division between the two users), the stability analysis of the two users' queues can be carried out separately for each queue; and by applying the Loynes' Theorem, for a fixed (ω_A, ω_B), the stability condition is defined by

$$\lambda_i < \mu_i^{(max)} = \omega_i f_{i,D}(R_i) \qquad \text{with } i \in \{A, B\}, \tag{1}$$

where $\mu_i^{(max)}$ denotes the maximum service rate for the i-th queue. If we take the union over all (ω_A, ω_B) such that $\omega_A + \omega_B \leq 1$, we obtain the stable throughput region which is

$$L_{\text{NC}} = \left\{ (\lambda_A, \lambda_B) : \frac{\lambda_A}{f_{A,D}(R_A)} + \frac{\lambda_B}{f_{B,D}(R_B)} < 1 \right\}. \tag{2}$$

B. Conventional cooperation (CC)

Conventional cooperation (CC) enables the common relay to deliver data for both users when users are sensed to be idle. In contrast to the non-cooperative case where a user only removes a packet from its queue when it is successfully received at the destination, here, a user will also drop a packet when it is successfully received by the cognitive relay node (modified ACK/NACK). More specifically, if a packet transmitted by the i-th user is not decoded correctly at the destination but is decoded at the cognitive relay, it is removed from the user's queue Q_i and is stored at the relaying queue Q_{Ri} for cognitive retransmission. Again, we adopt a TDMA relaying policy, in which the relaying queue Q_{Ri} is served only when the time slot is assigned to the i-th user and the i-th user's queue Q_i is empty. The slight inefficiency that arises from this restriction is tolerated in order to avoid the complexity of analysis of interacting queues.

In order to study the stability of the CC scheme, we first consider the stability condition for the sources' queues. By using Loynes' theorem, we have

$$\lambda_i < \mu_i^{(\max)} = \omega_i \left[f_{i,D}(R_i) + \underbrace{[1 - f_{i,D}(R_i)] f_{i,S}(R_i)}_{\triangleq g_{i,S}(R_i)} \right]. \tag{3}$$

Similarly to the NC case, by taking the union over all (ω_A, ω_B) such that $\omega_A + \omega_B \leq 1$, the stability region for the two primary users is solved to be

$$L_{\mathrm{CC}^1} = \left\{ (\lambda_A, \lambda_B) : \frac{\lambda_A}{f_{A,D}(R_A) + g_{A,S}(R_A)} + \frac{\lambda_B}{f_{B,D}(R_B) + g_{B,S}(R_B)} < 1 \right\}. \tag{4}$$

Then we analyze the stability of the cognitive relay S. Relay S serves its relaying queues when the corresponding time slot becomes idle. The average arrival rate (λ_{Ri}) and average service rate ($\mu_{Ri}^{(\max)}$) of the relaying queues Q_{Ri} with $i \in \{A, B\}$ can be obtained by

$$\lambda_{Ri} = \omega_i \mathbb{P}\{Q_i \neq 0\} g_{i,S}(R_i) = \omega_i \frac{\lambda_i}{\mu_i^{(\max)}} g_{i,S}(R_i), \tag{5}$$

$$\mu_{Ri}^{(\max)} = \omega_i \mathbb{P}\{Q_i = 0\} f_{S,D}(R_i) = \omega_i \left[1 - \frac{\lambda_i}{\mu_i^{(\max)}} \right] f_{S,D}(R_i). \tag{6}$$

This is because, a packet departing from the i-th source queue is stored in the relaying queue Q_{Ri} if the following events happen together: (1) the i-th source queue is not empty, which happens with probability $\lambda_i/\mu_i^{(\max)}$, (2) the slot is assigned to the i-th source, (3) the i-th source-destination channel is in outage and the i-th source-relay channel is not in outage which corresponds to a probability equal to $g_{i,S}(R_i)$. Therefore, the arrival rate to the relaying queue Q_{Ri} is as written in Eq. (5). Accordingly, the service process of Q_{Ri} depends by definition on the empty slots available from the corresponding sources, and the channel from the relay to the destination not being in outage; as a result, the average service rate is given by Eq. (6).

By applying Loynes' Theorem ($\lambda_{R_i} < \mu_{R_i}^{(\max)}$), and taking the union over all (ω_A, ω_B), the stability region for the cognitive relay is given by

$$L_{\mathrm{CC}^2} = \left\{ (\lambda_A, \lambda_B) : \frac{\lambda_A [g_{A,S}(R_A) + f_{S,D}(R_A)]}{f_{S,D}(R_A)[f_{A,D}(R_A) + g_{A,S}(R_A)]} + \frac{\lambda_B [g_{B,S}(R_B) + f_{S,D}(R_B)]}{f_{S,D}(R_B)[f_{B,D}(R_B) + g_{B,S}(R_B)]} < 1 \right\}, \tag{7}$$

The system is stable if and only if both the users' queues and the relay's queues are stable. Therefore, the resulting stability region for the conventional CC protocol is given by the intersection of the two regions $L_{\mathrm{CC}^1} \bigcap L_{\mathrm{CC}^2}$, which is easily shown to be equal to L_{CC^2} as written in Eq. (7).

C. Non-cognitive DDF (NC-DDF)

The NC-DDF scheme introduces a more advanced PHY-layer relaying to the considered MARC configuration. In this protocol, we assume that cognitive (NET-layer) cooperation is not available and a DDF scheme enables a partial relaying during a source transmission [9], [10]. The DDF scheme has been well-studied from an information theoretic standpoint, but here, we use it to access its impact on improving the stable throughput region. According to the DDF protocol, the source codeword is divided into M blocks which are delivered to the destination in two dependent phases during the time of one slot. More specifically, in the first phase of the protocol which is called listening phase, the source broadcasts the source message towards the relay and the destination. During this phase, the destination receives the source message via the direct link without diversity. At a certain instant, referred to as the decision time m, if the relay is able to decode the source information message (based on the received m blocks) before receiving the whole codeword, it starts to assist the source transmission by providing cooperative diversity. More specifically, after successful decoding, the relay can correctly anticipate the future transmissions from the source since it knows the source codebook by using an Alamouti constellation.

The duration of the second phase is from the decision time to the end of the codeword and is a random variable which depends on the instantaneous quality of the $i \rightarrow S$ link. If we restrict the decision time to coincide with the end of a block, the decision time can be presented by a random variable $m \in [1, 2 \ldots, M]$ ($m = M$ corresponds to the case where the relay does not help the destination). If the destination cannot decode the packet successfully, the source packet remains in the source queue and will be retransmited by the source at the next assigned time slot using the same DDF policy. Furthermore, the relay node will drop the packet, even if it achieved to decode it, and will treat the retransmission as a new packet. Again, the reduction in efficiency from this restriction is accepted for simplifying the analysis. The system model for the DDF case can be written as

$$y_k^{(i)} = \begin{cases} h_{i,D} x_{i,k} + w_k & k = 1 \ldots m, \\ \sqrt{|h_{i,D}|^2 + |h_{S,D}|^2} x_{i,k} + v_k & k = m+1 \ldots M \end{cases} \tag{8}$$

where $y_k^{(i)}$ denotes the received signal at the destination for the k-th block and the i-th user

($i \in \{A, B\}$), $x_{i,k}$ denotes the transmitted k-th bock for the i-th user, $n_k, v_k \sim \mathcal{CN}(0,1)$ denote the normalized AWGN noise for the two phases of the protocol with a zero mean and a variance equal to one, respectively, and $m = \min\left\{M, \left\lceil \frac{MR_i}{\log(1+P_0|h_{i,S}|^2)} \right\rceil \right\}$ denotes the decision time where the relay node starts to assist the transmission [9] (practical issues concerning the decision time are beyond the scope of this paper [11]). It is worth noting that the orthogonality during the second phase of the DDF protocol is achieved by using an Alamouti scheme [10], [11]. In this case, the achievable rate for $m = k$ and i.i.d. Gaussian inputs is given by [11], which is

$$C_k^{(i)} = \underbrace{\frac{k}{M}\log(1+P_0|h_{i,D}|^2)}_{\text{non-cooperation}} + \underbrace{\frac{M-k}{M}\log(1+P_0|h_{i,D}|^2+P_0|h_{S,D}|^2)}_{\text{cooperation}} \tag{9}$$

The probability that the DDF link is not in outage can be written as

$$\begin{aligned} f_{i,S,D}(R_i) &= \sum_{k=1}^{M} \mathbb{P}\{m=k\}\mathbb{P}\{C_k^{(i)} > R_i\} \\ &\simeq \sum_{k=1}^{M} \mathbb{P}\{m=k\} f_{i,S,D}^{(k)}(R_i), \end{aligned} \tag{10}$$

$$\begin{aligned} \mathbb{P}\{m=k\} &= \mathbb{P}\Big\{k\log(1+P_0|h_{i,S}|^2) > MR_i > (k-1)\log(1+P_0|h_{i,S}|^2)\Big\} \\ &= \exp\left(-\frac{2^{\frac{MR_i}{k-1}}-1}{\rho_{i,S}}\right) - \exp\left(-\frac{2^{\frac{MR_i}{k}}-1}{\rho_{i,S}}\right), \end{aligned} \tag{11}$$

where $\log(\cdot)$ denotes the base 2 logarithm and the closed form for the probability $f_{i,R,D}^{(k)}(R_i)$ is approximated in Appendix I; in the numerical results section, we plot both the approximated results using the closed-form expression, as well as the exact stability region; the approximated result is shown to be very close to the true result. We note that the probability $f_{i,S,D}^{(k)}(R_i)$ is computable precisely but at great computational cost. Thus we prefer to use a simple approximation for it that has negligible impact on the end result. The stability region follows the formulation of the NC protocol (Eq. (2)) and thus can be written as

$$L_{\text{NC-DDF}} = \left\{(\lambda_A, \lambda_B) : \frac{\lambda_A}{f_{A,S,D}(R_A)} + \frac{\lambda_B}{f_{B,S,D}(R_B)} < 1\right\}. \tag{12}$$

D. Cognitive DDF (C-DDF)

In the NC-DDF scheme just discussed, relaying cooperation is performed for each source transmission only when a source is active. Therefore, a packet is removed from a user's queue only when it is decoded correctly at the destination. In the protocol proposed here, a packet is dropped from the user queues also when it is decoded correctly at the relay node, following the principles of the CC scheme. The C-DDF relaying strategy is described as follows: during the source transmission, if the relay node can decode the packet of the i-source with a decision time equal to m (with $1 \leq m \leq M$), it assists the source transmission for the rest of the codeword; by the end of the whole codeword, if the packet is still not successfully decoded at the destination, the relay node transmits an ACK signal and the source packet is dropped from the user, while the relay node will take the responsibility to retransmit this packet later on. The service of Q_{Ri} follows the rules of the CC protocol and therefore it is activated when an i-th slot is sensed to be idle. The C-DDF scheme provides two different types of relaying collaboration: (1) a dynamic cooperation when the source is active based on the DDF protocol, and (2) a cognitive cooperation when the source is idle. By inserting the DDF outage probabilities in Eq. (7), the stability region of the C-DDF protocol becomes

$$L_{\text{C-DDF}} = \Bigg\{(\lambda_A, \lambda_B) : \frac{\lambda_A\big[v_{A,S}(R_A) + f_{S,D}(R_A)\big]}{f_{S,D}(R_A)\big[f_{A,S,D}(R_A) + v_{A,S}(R_A)\big]} + \frac{\lambda_B\big[v_{B,D}(R_B) + f_{S,D}(R_B)\big]}{f_{S,D}(R_B)\big[f_{B,S,D}(R_B) + v_{B,D}(R_B)\big]} < 1\Bigg\}, \tag{13}$$

where $v_{i,S}(R_i) \triangleq [1 - f_{i,S,D}(R_i)]f_{i,S}(R_i)$.

Comparison between NC-DDF and C-DDF: The C-DDF scheme utilizes a dynamic and cognitive relaying cooperation. More specifically, in addition to dynamic cooperation, a cognitive cooperation is enabled. In this subsection, we determine when this alternative type of cooperation is favorable to the non-cognitive DDF in terms of stable throughput region.

Due to the adopted TDMA transmission policy, the stability region of both DDF schemes is bounded by a straight line. Therefore, to compare the two stability regions, it is enough to compare the intersection of these lines with the axes. The intersection points for NC-DDF and C-DDF are given as

$$\lambda_i^*(\text{NC-DDF}) = f_{i,S,D}(R_i), \tag{14}$$

$$\lambda_i^*(\text{C-DDF}) = \frac{f_{S,D}(R_i)[f_{i,S,D}(R_i) + v_{i,S}(R_i)]}{v_{i,S}(R_i) + f_{S,D}(R_i)}. \tag{15}$$

It is clear that the stability region of NC-DDF is completely contained inside the stability region of C-DDF, if $\lambda_i^*(\text{C-DDF}) > \lambda_i^*(\text{NC-DDF})$ for $i \in \{A, B\}$. After a little algebra, this condition reduces to

$$f_{S,D}(R_i) > f_{i,S,D}(R_i). \tag{16}$$

The above condition reveals that the integration of the "cognitive" relaying to the NC-DDF scheme is beneficial only when the relay-destination link is better than the combined DDF links ($i \to D$, $i \to S \to D$).

IV. Superposition relaying for cognitive cooperation

In this section, we deal with the cognitive (NET) cooperation and we investigate a more efficient relaying technique for the periods of source silence. The protocols discussed so far, assume that the relay node serves only one non-empty queue at a time when the source becomes silent. In order to boost cooperation, we investigate an adaptive superposition coding technique which allows the relay node to serve simultaneously both relaying queues via a power split technique [13, Ch. 6]. More specifically, when the relay node senses an i-th time slot to be idle, it either serves the corresponding relaying queue Q_{Ri} or it superimposes packets from both relaying queues and transmits to the destination with a total power equal to P_0.

To support both data flows when the instantaneous channel capacity is higher than the total spectral efficiency, multiuser detection schemes like interference cancelation (IC) can be implemented at the destination [13, Ch. 9] so that both data flows can be decoded. Alternatively, scenarios where only one data flow can be decoded from the superimposed relaying signal, depend on the specific power allocation and yield an interaction between the two relaying queues. In order to simplify the analysis, in this paper, a feedback channel that informs the relay node about the instantaneous condition of the relay-destination link, is introduced. The feedback message consists of one bit, informing the relay node whether the relay-destination link can support the superimposed spectral efficiency $R_A + R_B$ or not. It is assumed to be error-free and always available at the relay node. Therefore, in the case that the relay-destination channel cannot support the total spectral efficiency, all the power is allocated to the corresponding relaying data flow (which corresponds to the spare source time slot), and the schemes reduces to the conventional single-user cognitive relaying. The transmission schemes are summarized as follows:

1) If the feedback informs that the relay-destination link can support the total spectral efficiency $R_A + R_B$ (feedback is equal to 1):
   - a) If $Q_{RA} \neq 0, Q_{RB} \neq 0$, the relay serves both relaying queues, one packet from Q_{RA}, and one packet from Q_{RB}.
   - b) If $Q_{RA} \neq 0, Q_{RB} = 0$, the relay serves a packet from the relaying queue Q_{RA}.
   - c) If $Q_{RA} = 0, Q_{RB} \neq 0$, the relay serves a packet from the relaying queue Q_{RB}.
2) Otherwise, if the feedback informs that the relay-destination link *cannot* support the superimposed spectral efficiency $R_A + R_B$ (feedback is equal to 0), then if the i-th slot is sensed to be idle, the relay serves a packet from the Q_{Ri} relaying queue without superposition coding (conventional transmission).

It is worth noting that the feedback is a form of strongly compressed side-information that concerns the relay-destination link only and consists of 1 bit; therefore the related complexity overhead is negligible. Furthermore, a feedback equal to 1, guarantees that a packet can be correctly decoded at the destination at the sum rate. The above adaptive superposition mechanism can be integrated in the cognitive protocols (CC, C-DDF) proposed in Section III as follows.

A. *Conventional Cooperation with Superposition (S-CC)*

The stability analysis of the user queues under the S-CC protocol is similar to that of the CC protocol, and the stability condition of the user queues can be obtained as

$$\left.\begin{array}{c} \lambda_i < \omega_i \big[\underbrace{f_{i,D}(R_i) + g_{i,S}(R_i)}_{\triangleq \Gamma_i} \big] \\ \omega_A + \omega_B \leq 1 \end{array}\right\} \Rightarrow L_{\text{S-CC}^1} = \left\{ (\lambda_A, \lambda_B) : \frac{\lambda_A}{\Gamma_A} + \frac{\lambda_B}{\Gamma_B} < 1 \right\} \tag{17}$$

Similarly, we establish the stationarity of the service process from the relay's queue. When the sources' queues are stable, they offer a stationary pattern of empty slots (hence, a stationary service process) to the relay; also since the channel processes are stationary, the relay's service process is stationary. The stability condition for the relaying queue Q_{Ri} ($i \in \{A, B\}$) is defined by

$$\lambda_{Ri} = \frac{\lambda_i}{\Gamma_i} g_{i,D}(R_i) < \mu_{Ri}^{(\max)} = \omega_i \underbrace{\left[1 - \frac{\lambda_i}{\omega_i \Gamma_i}\right]}_{\mathbb{P}\{Q_i=0\}} \underbrace{\left[\underbrace{f_{S,D}(R_A+R_B)}_{\text{feedback equal to 1}} \cdot 1 + \underbrace{\left[1 - f_{S,D}(R_A+R_B)\right]}_{\text{feedback equal to 0}} f_{S,D}(R_i) \right]}_{\triangleq \delta_i}$$
$$+ \omega_{\bar{i}} \underbrace{\left[1 - \frac{\lambda_{\bar{i}}}{\omega_{\bar{i}} \Gamma_{\bar{i}}}\right]}_{\mathbb{P}\{Q_{\bar{i}}=0\}} \underbrace{f_{S,D}(R_A+R_B)}_{\text{feedback equal to 1}} \cdot 1, \tag{18}$$

$$\omega_A + \omega_B < 1, \tag{19}$$

$$\Rightarrow L_{\text{S-CC}^2} = \Bigg\{ (\lambda_A, \lambda_B) : \frac{\lambda_A}{\Gamma_A} \left[\frac{g_{A,S}(R_A) + \delta_A}{\delta_A - \theta} + \frac{\theta}{\delta_B - \theta} \right] + \frac{\lambda_B}{\Gamma_B} \left[\frac{g_{B,S}(R_B) + \delta_B}{\delta_B - \theta} + \frac{\theta}{\delta_A - \theta} \right] - \theta \left[\frac{1}{\delta_A - \theta} + \frac{1}{\delta_B - \theta} \right] < 1 \Bigg\}, \tag{20}$$

where $\theta \triangleq \mathbb{P}\{\text{feedback equal to } 1\} = f_{S,D}(R_A + R_B)$ denotes the success probability for the sum rate and $\bar{i}$ denotes the complementary of $i \in \{A, B\}$. The arrival rate to Q_{Ri} is the same as that in CC scheme; regarding the service process of the Q_{Ri} relaying queue, a packet will depart from Q_{Ri} if any of the following events happens: (1) the slot is assigned to the i-th source and the feedback is equal to 1, in which case the packet departs with probability 1, (2) the slot is assigned to the i-th source and the feedback is equal to 0, in which case the packet departs with probability $f_{S,D}(R_i)$, (3) the slot is assigned to the $\bar{i}$-th source and the feedback is equal to 1, the packet departs with probability 1. These events are disjoint and the service rate of Q_{Ri} can be obtained as in Eq. (18). The total stability region for the system S-CC is given by the intersection of the two regions $L_{\text{S-CC}^1} \bigcap L_{\text{S-CC}^2}$, which is easily shown to be equal to $L_{\text{S-CC}^2}$.

B. Cognitive DDF with superposition (SC-DDF)

The C-DDF protocol can also be enhanced by the superposition approach. In a manner similar to the CC scheme, it can be shown that the stability region is given by Eq. (20) by replacing $g_{i,S}(R_i)$, Γ_i with $u_{i,S}(R_i)$ and $\gamma_i \triangleq f_{i,S,D}(R_i) + u_{i,S}(R_i)$, respectively.

V. Numerical results

Computer simulations were carried-out in order to validate the performance of the proposed schemes. For clarity of presentation, a symmetric configuration is considered with $R_A = R_B = 2$ bits per channel per use (BPCU), $\rho_{A,D} = \rho_{B,D} = 5$ dB, $\rho_{A,S} = \rho_{B,S} = 12$ dB, $\rho_{S,D} = 30$ dB, and $M = 3$ for the DDF-based schemes. Fig. 2 plots the stable throughput region for the investigated protocols. As expected, cooperation increases the stable throughput region as it overcomes deep-fading of the direct links, resulting in faster emptying of the users' queues. Regarding the cooperative methods, it can be seen that the NC-DDF scheme provides a superior stable throughput region than the CC scheme ($L_{\text{NC-DDF}} \supset L_{\text{CC}}$). The NC-DDF scheme allows the relay node to assist the source transmission each time when the source is active but not during the periods of source silence which create more relaying opportunities than the CC scheme (most of the time the source slots are not idle unless the traffic is light). Furthermore, the integration of the cognitive relaying (relaying when the source is sensed to be idle) to the NC-DDF scheme, improves further the stable throughput region (C-DDF). As far as the superposition coding approach is concerned, it is shown that it outperforms all other cooperative protocols in terms of the stable throughput region, as a result of the opportunity of simultaneous service of both relaying queues. However, the combination of DDF with superposition cognitive relaying (CS-DDF) provides the largest stable throughput region and is introduced as an efficient cross-layer technique for bursty cooperative applications. Fig. 2 shows the stable throughput region which corresponds to the approximated expressions given in Appendix I. The approximated stable throughput region is seen to be close to the true one, and thus this observation validates the approximation.

Fig. 3 shows the maximum stable throughput (MST) for the above symmetric configuration. MST is defined as the maximum common arrival rate (the arrival processes are the same across source users) that stabilizes the system, rather than the full two-dimensional region. The first important observation is that the "cognitive" cooperation becomes more important as the rate (in bits/packet) is increased, and hence, the MST for the NC and NC-DDF protocols decays to zero faster than in the cognitive cooperative schemes as the bit rate per packet increases. The fundamental reason for this property is that the cognitive protocols convey a major part of the traffic from the primary users to the relay-destination link, which has a better successful delivery probability than the direct links. Furthermore, it can be seen that the superposition coding approach significantly increases the MST for all protocols, which is expected as the superposition coding technique uses more efficiently the relay-destination link.

It should be noted here that cooperation for cognitive systems is a beneficial solution only when the direct links are in deep-fading and the relay-destination link is strong enough in order to establish communication [4], which motivated our particular choice of simulation parameters.

VI. Conclusion

In this paper, we designed and analyzed cooperation methods for cognitive multiple-access relay channels (CR MARCs) that combine physical layer and network layer ideas. The proposed schemes use a DDF cooperative protocol in order to increase relaying opportunities by allowing the relay node to access the channel also when the sources are active. Furthermore, an adaptive superposition coding approach, which enables the simultaneous service of several relaying queues when the source becomes idle, was investigated. The combination of DDF with superposition coding substantially increases the stability region by exploiting the cross-layer nature of network cooperation. Future work includes the generalization of our analysis to a larger network, the integration of a random (ALOHA) MAC scheme and the elaboration of alternative physical layer approaches.

Appendix A
On approximating the outage probability for DDF

The derivation of the stable throughput region for the DDF case requires the computation of the outage probability $\overline{f_{i,S,D}}(R_i) = \mathbb{P}\{C_k^{(i)} < R_i\}$. Although this probability can be computed numerically, in order to simplify the analysis, here, we approximate the achievable rate of the DDF protocol, that has a decision time equal to k, as follows [11]

$$
\begin{aligned}
C_k^{(i)} &= \frac{k}{M}\log(1+P_0|h_{i,D}|^2) + \frac{M-k}{M}\log(1+P_0|h_{i,D}|^2+P_0|h_{S,D}|^2), \\
&\text{(Since } X+Y \leq \max[X,Y] \text{ where } X,Y \in \mathcal{R}^+ \text{ we have)} \\
&\geqslant \max\Bigg[\underbrace{\frac{k}{M}\log(1+P_0|h'_{i,D}|^2)}_{\triangleq\zeta}, \underbrace{\frac{M-k}{M}\log(1+P_0|h_{i,D}|^2+P_0|h_{S,D}|^2)}_{\triangleq\psi}\Bigg], \qquad (21)
\end{aligned}
$$

where $h'_{i,D}$ denotes an independent channel coefficient with variance $\sigma^2_{i,D}$ (it is used in order to relax the dependency between the two terms). The outage probability for the random variables ζ, ψ (for $\sigma^2_{i,D} \neq \sigma^2_{S,D}$) is given as

$$P_{\zeta}(z) = \mathbb{P}\{\zeta \leqslant z\} = 1 - \exp\left(-\frac{2^{\frac{Mz}{k}} - 1}{P_0 \sigma^2_{i,D}}\right), \tag{22}$$

$$\begin{aligned} P_{\psi}(z) = \mathbb{P}\{\psi \leqslant z\} = 1 - \exp\left(-\frac{\rho}{\sigma^2_{S,D}}\right) - \frac{\sigma^2_{i,D}}{\sigma^2_{i,D} - \sigma^2_{S,D}} \exp\left(-\frac{\rho}{\sigma^2_{i,D}}\right) \\ \times \left[1 - \exp\left(-\frac{\sigma^2_{i,D} - \sigma^2_{S,D}}{\sigma^2_{i,D}\sigma^2_{S,D}}\rho\right)\right], \end{aligned} \tag{23}$$

where $\rho \triangleq \frac{2^{\frac{Mz}{M-k}} - 1}{P_0}$. By applying basic order statistics, the probability of outage for the DDF scheme is written as

$$\overline{f_{i,S,D}}(R_i) = \mathbb{P}\left\{\max[\zeta, \psi] < R_i\right\} = P_{\zeta}(R_i) P_{\psi}(R_i). \tag{24}$$

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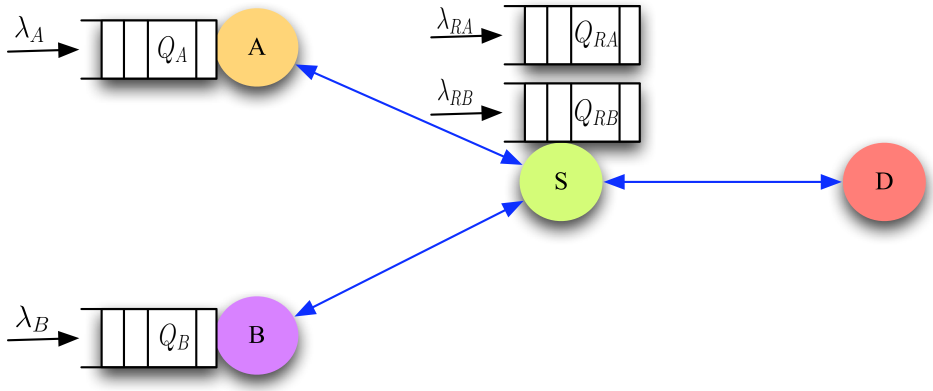

Fig. 1. The system model; Users A and B communicate with a common destination D via a TDMA policy.

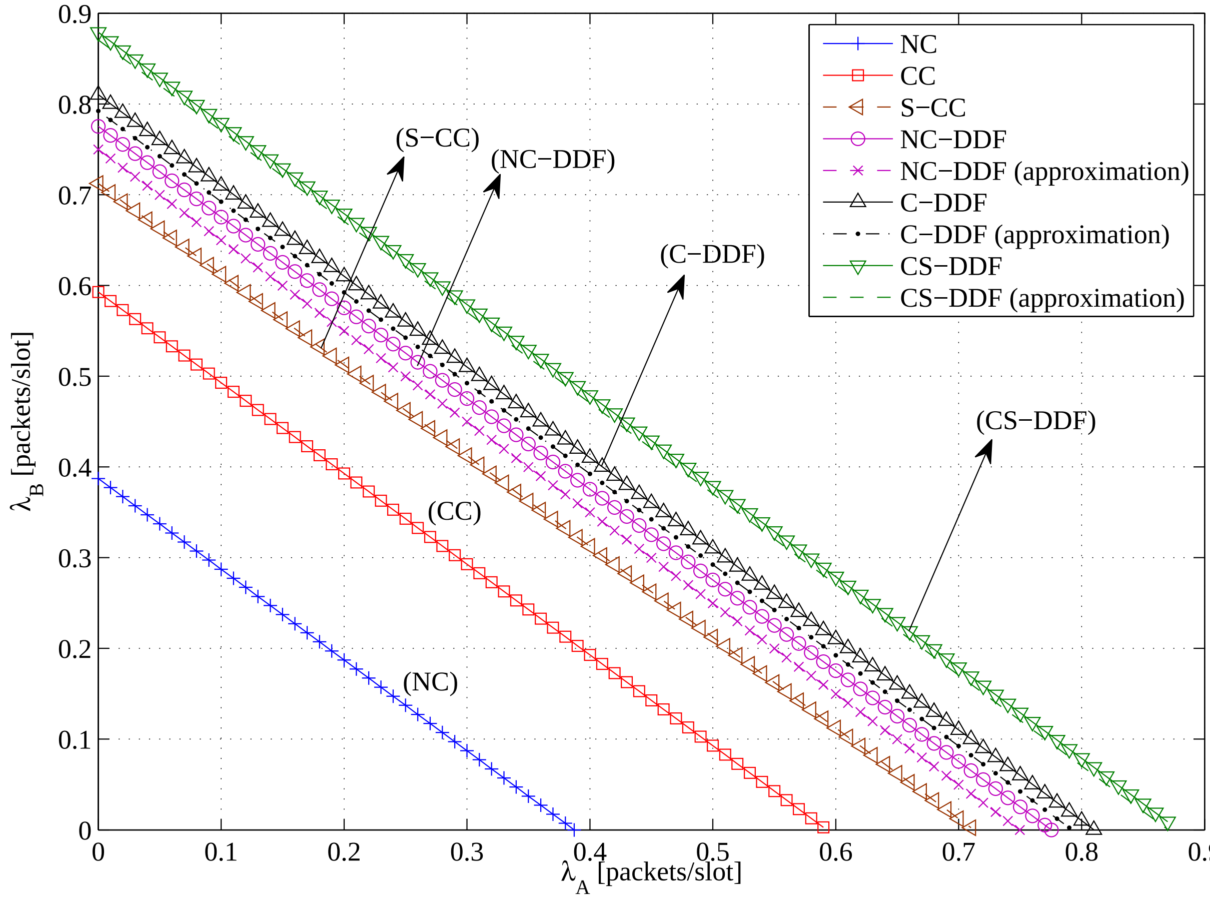

Fig. 2. Stability region for the NC, CC, S-CC, DDF, C-DDF and SC-DDF; $R_A = R_B = 2$ BPCU, $\rho_{A,D} = \rho_{B,D} = 5$ dB, $\rho_{A,S} = \rho_{B,S} = 12$ dB, $\rho_{S,D} = 30$ dB, and $M = 3$.

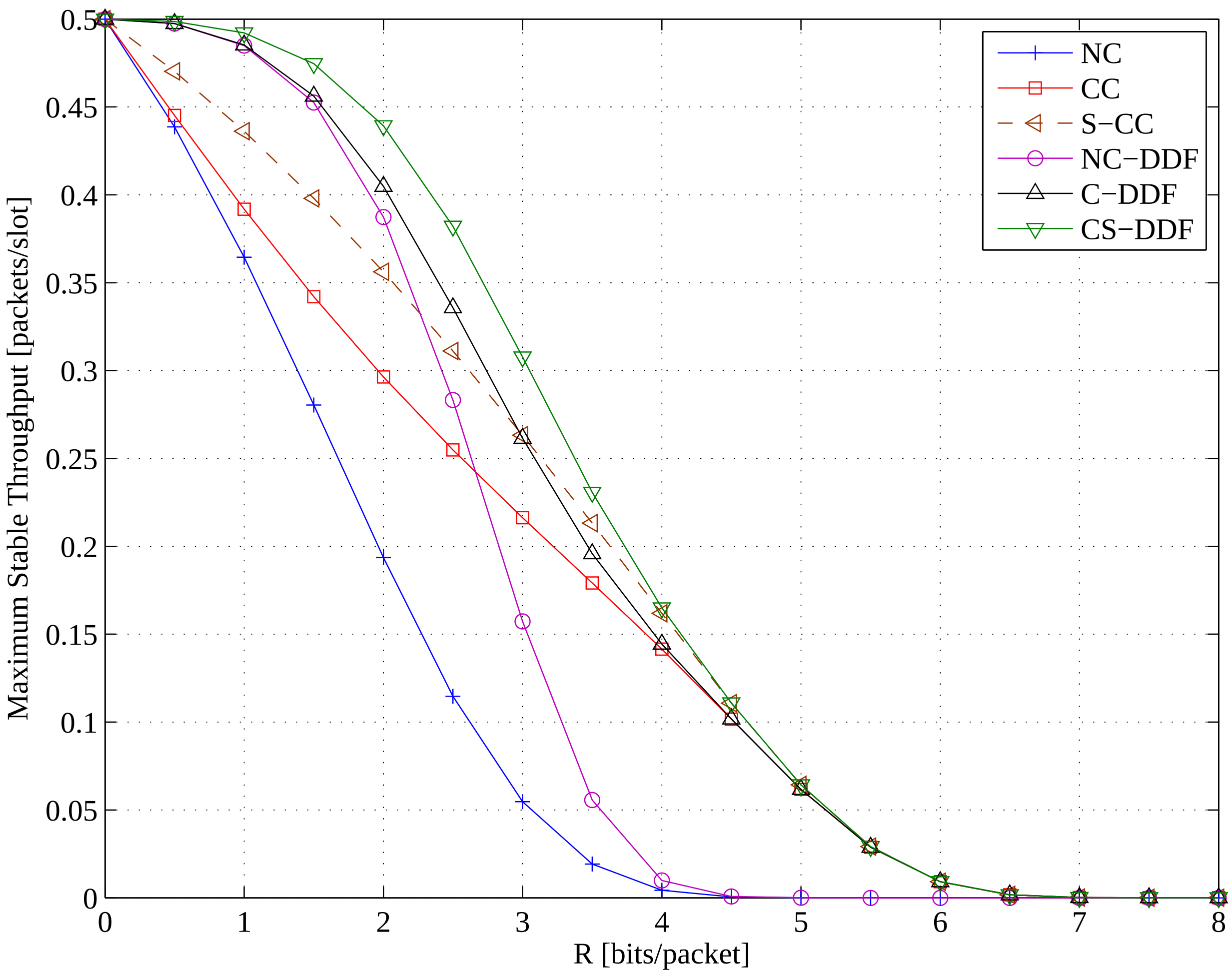

Fig. 3. Maximum stable throughput versus bits/packet for the NC, CC, S-CC, DDF, C-DDF and SC-DDF; $\lambda_A = \lambda_B$, $\rho_{A,D} = \rho_{B,D} = 5$ dB, $\rho_{A,S} = \rho_{B,S} = 12$ dB, $\rho_{S,D} = 30$ dB and $M = 3$.