On The Performance of Cognitive Full-Duplex Generalized Dynamic Network Coding

Samuel B. Mafra, Evelio M. G. Fernandez, Richard D. Souza, João L. Rebelatto and Samuel M. Sánchez

Abstract— **We propose a cognitive full-duplex network coding based scheme. The secondary cooperative network is composed of two secondary full-duplex users that cooperate to transmit their independent information to a common secondary destination. The transmit power is constrained by the maximum interference threshold accepted by the primary destination. We show through theoretical and numerical results that the proposed cognitive full-duplex scheme has the best performance in terms of outage probability, when compared with half-duplex network coding schemes, traditional cooperative techniques as well as to the direct non-cooperative transmission.**

Keywords— **Cognitive radio, Network coding, Full-duplex.**

I. INTRODUCTION

In the last years, several cognitive radio protocols have been proposed with the goal of obtaining a more efficient use of the radio frequency spectrum. In a cognitive radio network, the unlicensed (secondary) network may transmit concurrently with the licensed (primary) network as long as the primary communication is not compromised. For such an operation, a maximum allowable interference level at the primary receiver is defined, and secondary users (SUs) should take into account this threshold during the transmission in order to adjust their transmit powers [1].

Recently, cooperative communications have emerged as a promising technique to boost the performance of communication systems [2]. In a cooperative network, one or more nodes, known as relays, help the communication between source and destination. The transmission occurs in two phases: first, in the broadcast phase (BP), the source broadcasts its information; then, in the cooperative phase (CP), if the relay correctly decoded the source message it retransmits such message to the destination. In cooperative systems, the relay can operate on either half-duplex (HD) or full-duplex (FD) modes [2]. In half-duplex mode, the relay transmits and receives in orthogonal channels, while in full-duplex mode the transmission and reception are performed at the same time and at the same frequency band. Owing to this fact, half-duplex relays require the use of additional system resources, while full-duplex relays arise as a viable option to alleviate this problem. However, the simultaneous transmission and reception introduce self-interference that is inherent to the full-duplex approach [3]. The works in [3], [4] show that self-interference cannot be completely removed but considerably attenuated, even though employing sophisticated schemes of interference cancellation. As a consequence, there remains residual self-interference, that can be modeled as a fading channel which, by its turn, allows the emulation of various (non) line-of-sight configurations arising from antenna isolation and interference cancellation techniques [3], [4]. Nevertheless, the full-duplex relays can still achieve high performance, even in the presence of strong interference levels.

Several works have analyzed the performance of cooperative cognitive networks under spectrum sharing constraints. In [5], the authors consider a cognitive scenario with a full-duplex relay subject to self-interference. The outage probability is analyzed for a full-duplex dual-hop (DH) relaying scheme, in which the self-interference at the relay was taken into account and the direct link was seen as interference at the secondary destination. In [6], the authors propose a new full-duplex relaying scheme for a cooperative underlay network, where the direct link can be seen as useful information at the secondary destination rather than interference. Moreover, an optimal power allocation (OPA) is proposed, where the secondary network can operate with the help of a relay or through the direct transmission (DT). The OPA scheme has a better performance in comparison with HD and non-cooperative schemes even in the presence of self-interference.

Recent works have applied the concept of network coding to cooperative networks [7]–[9]. In a network-coded cooperative network each user broadcast its information in the BP, then transmits a linear combination in the CP composed of its own message and the message(s) from its partner(s). In [7], a network-coded cooperative scheme is proposed where the users send a binary sum (XOR) in the CP. However, the scheme does not increase the diversity gain. An alternative is proposed in [8], called dynamic network coding (DNC), where the linear combinations transmitted during the CP are formed from a non-binary Galois Field GF(q). For a scenario with M cooperative users the DNC scheme can achieve a diversity gain of $2M-1$, which is higher than that of binary coding schemes. In [9] a generalization to the DNC scheme is proposed, namely generalized dynamic network coding (GDNC). In the GDNC scheme the users are allowed to transmit several packets in the BP as well as to transmit an arbitrary number of non-binary linear combinations in the CP, resulting in a larger achievable diversity order than DNC.

In [10], the authors evaluate the use of network coding in cognitive underlay networks with limits of maximum transmit power and primary interference threshold. The performance in terms of outage probability of the DNC and GDNC schemes in cognitive scenarios are compared with the direct transmission

S. B. Mafra and E. M. G. Fernandez, Universidade Federal do Paraná (UFPR), Curitiba, Paraná, Brasil. E-mails: (mafrasamuel@gmail.com, evelio@ufpr.br), R. D. Souza and J. L. Rebelatto, Universidade Tecnológica Federal do Paraná (UTFPR), Curitiba, Paraná, Brasil. E-mails: (richard,jlrebelatto)@utfpr.edu.br, S. M. Sánchez is with Central University of Las Villas (UCLV), 54830 Santa Clara, Cuba (e-mail:montejo@uclv.edu.cu).
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and traditional cooperative protocols. The analysis of [10] is extended for a scenario with multiple secondary users in [11]. Furthermore, the optimum number of parity packets that maximizes the ϵ-outage capacity is obtained through the use of the Dinkelbach algorithm. The results show that the use of cooperative communications with network coding can provide significant gains in terms of outage probability and diversity order, when compared to non-cooperative or traditional cooperative techniques.

Motivated by the great benefits of full-duplex radios, in this paper we extend the analysis of [10], [11] to a scenario with two full-duplex secondary users. The transmit power of the secondary users is limited by the maximum interference accepted by the primary destination. As the users transmit their messages simultaneously, the limit of interference must be shared among the users. The performance in terms of outage probability of the proposed cognitive full-duplex GDNC (C-FD-GDNC) is compared with the half-duplex network coding schemes analyzed in [11]. The proposed scheme outperforms previous methods even in the presence of self-interference.

The remainder of this paper is organized as follows: Section II introduces the system model and some related work. In Section III the proposed C-FD-GDNC scheme is analyzed. In Section IV representative numerical results are provided and insightful discussions are drawn. Finally, Section V concludes the paper.

II. PRELIMINARIES

A. System Model

We consider a cognitive network composed of two SUs U_1 and U_2, a common secondary destination D_s, a primary destination D_p[1], as illustrated in Fig. 1. The quasi-static fading channel between transmitter i and the receiver j is denoted by h_{ij}, $i \in \{1,2\}$, $j \in \{1,2,s,p\}$, where $\{1,2\}$ represent the users, s the destination and p the primary destination. We assume that all channels undergo independent Rayleigh fading, thus $|h_{ij}|^2$ follows an exponential distribution with mean power λ_{ij}. The average fading power is $\lambda_{ij} \triangleq \mathbb{E}\left[|h_{ij}|^2\right] \triangleq d_{ij}^{-\nu}\,\sigma_{ij}$, where d_{ij} represents the normalized distance between users i and j with respect to d_{1p}, which is assumed equal to one, and ν is the path-loss exponent ($\nu \geq 2$). We also consider a symmetric scenario in the secondary network and that all the secondary nodes are approximately at the same distance from the primary nodes.

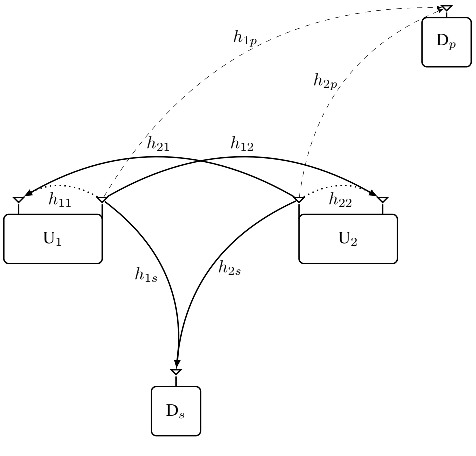

Fig. 1. System model composed by a primary destination D_p and two SUs, denoted by U_1 and U_2, which transmit to a secondary destination D_s.

Due to the spectrum sharing environment, the primary receiver tolerates a maximum interference level given by β. Supposing half-duplex operation, since only one transmission per time slot, the transmit power of the user U_i is limited as

$$P_i = \frac{\beta}{|h_{ip}|^2}. \tag{1}$$

Outage is the event that the mutual information between nodes i and j is less than an attempted information rate $\mathcal{R}_{\text{sch}}$. Thus, the outage probability is defined as [12]

$$\mathcal{P}_{out}^{ij} = \Pr\left\{\log_2\left(1 + \frac{|h_{ij}|^2 P_i}{N_0}\right) < \mathcal{R}_{\text{sch}}\right\}, \tag{2}$$

where $\Pr\{a\}$ is the probability of event a, N_0 is the one-sided noise power spectral density, $\mathcal{R}_{\text{sch}} = \frac{\mathcal{R}_s}{\text{R}_{\text{sch}}}$ is the transmission rate in bits per channel use (bpcu) of the scheme sch $\in$\{DT, C-SDF, C-DNC, C-GDNC, C-FD-GDNC\}. Also, $\mathcal{R}_s$ is the attempted information rate in the case of non-cooperative direct transmission and R_{sch} corresponds to the code rate (the ratio between the number of information packets and the total number of packets) of a given scheme sch. For instance, for the non-cooperative scheme $\text{R}_{\text{DT}} = 1$.

As we consider a symmetric scenario in the secondary network, we have that $\left(\mathcal{P}_{out}^{12} = \mathcal{P}_{out}^{1s} = \mathcal{P}_{out}^{21} = \mathcal{P}_{out}^{2s} = \mathcal{O}\right)$, where $\mathcal{O}$ is the outage probability of an individual link [6],

$$\mathcal{P}_{out}^{ij} = \frac{\lambda_{ip}\,\varepsilon}{\lambda_{ip}\,\varepsilon + \lambda_{ij}\,\mu_{HD}}, \tag{3}$$

where $\varepsilon = 2^{\mathcal{R}_{\text{sch}}} - 1$ and $\mu_{HD} = \frac{\beta}{N_0}$.

B. C-SDF Scheme

Let us consider that the secondary network operates according to the selective decode-and-forward (SDF) protocol [2], where each user first broadcasts its own message in the BP. In the CP, the users retransmit the messages from their partners, if correctly decoded. Otherwise, the users remain in silence. The destination applies Maximal Ratio Combining (MRC) between the messages if the user has successfully decoded the message from its partner. Finally, the outage probability of cognitive SDF (C-SDF) can be approximated at a high signal-to-noise ratio (SNR) as [2], [11]

$$\mathcal{O}_{\text{C-SDF}} \approx 1.5\,\mathcal{O}^2, \tag{4}$$

where $\mathcal{O}$ is obtained from (3), with $\text{R}_{\text{C-SDF}} = 1/2$.

C. C-DNC Scheme

The dynamic network coding (DNC) scheme proposed in [8] is a non-binary network coded cooperative scheme that allows the nodes to transmit linear combinations from a non-binary Galois Field GF(q) during the CP, as depicted in Fig. 2

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[1] We assume that the primary transmitter is far from the secondary network.

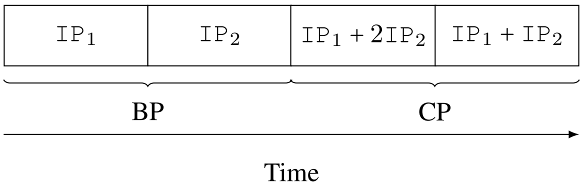

Fig. 2. Transmitted packets in the C-DNC scheme, where IP_1 and IP_2 are the original information packets from U_1 and U_2, respectively.

for a particular case of $M = 2$ cooperative nodes and linear combinations formed from GF(4).

In order to evaluate the outage probability of the two-user network presented in Fig. 2, consider that the channel between the cooperative nodes is outage-free, such that the destination receives four messages: IP_1, IP_2, $\mathrm{IP}_1+2\mathrm{IP}_2$ and $\mathrm{IP}_1+\mathrm{IP}_2$. With this set of received messages, the destination is able to decode IP_1 and IP_2 from any two of the four received messages. Therefore, an outage occurs for the message of U_1 whenever IP_1 and at least two out of the three remainder messages (IP_2, $\mathrm{IP}_1 + 2\mathrm{IP}_2$ and $\mathrm{IP}_1 + \mathrm{IP}_2$) cannot be decoded.

When the inter-user channel fails and U_2 cannot decode the message from its partner, U_1 retransmits its own message. In this scenario, upon receiving two copies of the same message, the destination performs selection combining (SC) between the messages. Finally, it can be shown that the outage probability of the two-user cognitive DNC (C-DNC) scheme, with $\mathrm{R}_{\text{C-DNC}} = \frac{1}{2}$, can be approximated as [11]

$$\mathcal{O}_{\text{C-DNC}} \approx 4\,\mathcal{O}^3. \tag{5}$$

D. C-GDNC Scheme

A generalization of the DNC scheme of [8] is proposed in [9] which considers that each user is able to broadcast k_1 information packets during the BP. Then, in the CP, each user transmits an arbitrary number k_2 of linear combinations of its own information and the information of the other $M-1$ users, if correctly decoded during the BP. The operation of the GDNC scheme is illustrated in Fig. 3.

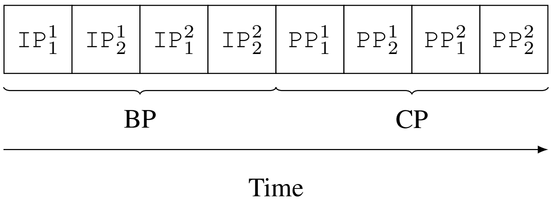

Fig. 3. Packets received by the destination in the C-GDNC scheme, where two users broadcast two information packets (IP_i^1,IP_i^2) in the BP ($k_1 = 2$) as well as transmit two linear combinations (PP_i^1,PP_i^2), with $i \in \{1,2\}$, in the CP ($k_2 = 2$).

In a two-user scenario, if the inter-user channel fails (*e.g.*, U_2 cannot decode the information from U_1), then an outage occurs for the information packet IP_1^1 if the direct transmission fails and at least k_1 out of the $k_1 + k_2 - 1$ remaining packets containing IP_1^1 cannot be decoded. On the other hand, if the inter-user channel is not in outage (U_2 correctly decoded IP_1^1), an outage occurs when the direct transmission fails and at least $2k_1$ of the $2(k_1 + k_2) - 1$ remaining packets received by the destination cannot be decoded.

The high SNR approximation for the outage probability of the cognitive two-user GDNC (C-GDNC) scheme with $k_1 = k_2 = 2$ and code rate $\mathrm{R}_{\text{C-GDNC}} = \frac{k_1}{(k_1+k_2)} = \frac{1}{2}$, can be written as [9], [11]

$$\mathcal{O}_{\text{C-GDNC}} \approx C_2^3\,\mathcal{O}^4, \tag{6}$$

where $C_m^n = \frac{n!}{m!(n-m)!}$ is the binomial coefficient.

III. Full Duplex Cognitive GDNC Scheme

In this section, we propose a cognitive full-duplex GDNC scheme, where the secondary users transmit their messages simultaneously. Since, in the proposed FD scheme each user sends its own message and receives the message of the partner at the same time, there exist self-interference at the receiver antenna, caused by the transmission of the transmitter antenna. The residual self-interference is modeled as a fading channel such that $h_{ii} \sim \mathcal{CN}(0\,,\,\sigma_{ii})$, with average fading power $\lambda_{ii} \triangleq \delta\,\sigma_{ii}$, where δ represents the interference cancellation factor which arises from the association of antenna cancellation and interference cancellation techniques. Another consequence of the full-duplex transmission is that primary destination receives interference from both secondary transmitters at the same time. Thus, the transmit power of U_1 and U_2 must be constrained as [5], [6]:

$$|h_{1p}|^2\,P_1 + |h_{2p}|^2\,P_2 \leq I_{th}. \tag{7}$$

As in [5], [6], we consider an equal power allocation (EPA) strategy, where the maximum interference threshold β is divided equally among the two users. Thus, the users U_1 and U_2 have their transmit powers limited, respectively, by [5], [6]:

$$P_1 = \frac{\beta}{2|h_{1p}|^2}, \qquad\qquad P_2 = \frac{\beta}{2|h_{2p}|^2}. \tag{8}$$

The operation of the cognitive full duplex GDNC scheme is illustrated in Fig. 4.

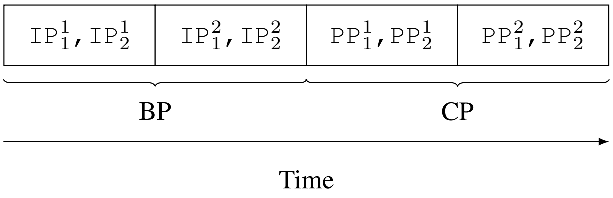

Fig. 4. Packets received by the secondary destination in a full-duplex network coding protocol, where two users broadcast two information frames (IP_i^1 and IP_i^2) in the BP ($k_1 = 2$) as well as transmit two linear combinations (PP_i^1 and PP_i^2),with $i \in \{1,2\}$ in the CP ($k_2 = 2$) .

Considering a two-user scenario, as in the GDNC scheme, the following outage events can occur:

- If the inter-user channel fails (*e.g.*, U_2 cannot decode the information from U_1), then an outage occurs for the information packet IP_1^1 if the direct transmission fails and at least k_1 out of the $k_1 + k_2 - 1$ remaining packets containing IP_1^1 cannot be decoded.
- On the other hand, if the inter-user channel is not in outage (U_2 correctly decoded IP_1^1), an outage occurs

when the direct transmission fails and at least $2k_1$ of the $2(k_1+k_2)-1$ remaining packets received by the destination cannot be decoded.

The code rate of the C-FD-GDNC scheme is

$$\mathrm{R}_{\text{C-FD-GDNC}} = \frac{2k_1}{\frac{2(k_1+k_2)}{2}} = \frac{2k_1}{k_1+k_2}. \tag{9}$$

One can see from (9) that, when $k_1 = k_2$, the C-FD-GDNC scheme transmits with the same code rate $\mathrm{R}_{\text{C-FD-GDNC}} = \mathrm{R}_{\text{DT}} = 1$ of the direct transmission.

The mutual information between U_1 and U_2, considering that the users communicate with the same transmit power P, is

$$\mathcal{I}_{12} = \log_2\left(1 + \frac{|h_{12}|^2 P_1}{N_0 + |h_{22}|^2 P_2}\right). \tag{10}$$

Note that the self-interference at the user U_2 is taken into account in (10).

The outage probability for the inter-user channel between the user U_1 and the user U_2 ($\mathcal{P}_{out}^{12}$) is given by (11) [5], where $\epsilon = 2^{\mathcal{R}_{\text{C-FD-GDNC}}} - 1$ and $\mu_{\text{FD}} = \beta/2N_0$.

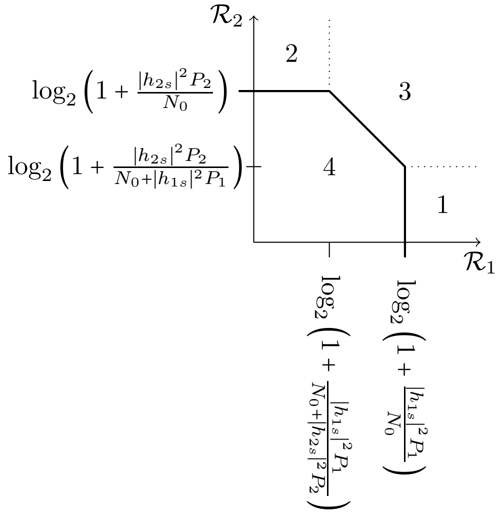

Fig. 5. Achievable region (labeled by 4) conditioned on channel state for two-user MAC.

At the secondary destination, the signals of both users arrive simultaneously. Thus, we must consider a multiple access channel (MAC) to calculate the outage probabilities of the secondary users similarly to [13]. Considering that $\mathcal{R}_1 = \mathcal{R}_2 = \mathcal{R}_{\text{C-FD-GDNC}}$, the $(\mathcal{R}_1, \mathcal{R}_2)$-plane in Fig. 5 is divided into four regions:

- Region 1 corresponds to a decoding error of the message from User 1; however, the message from User 2 can be successfully decoded,

$$\mathcal{P}_{out}^{1} = \Pr\left\{\log_2\left(1 + \frac{P_2|h_{2s}|^2}{N_0 + P_1|h_{1s}|^2}\right) > \mathcal{R}_{\text{C-FD-GDNC}} \cup \log_2\left(1 + \frac{P_1|h_{1s}|^2}{N_0}\right) < \mathcal{R}_{\text{C-FD-GDNC.}}\right\} \tag{12}$$

- Similarly, Region 2 corresponds to a decoding error of the message from User 2 and successful decoding of message of User 1,

$$\mathcal{P}_{out}^{2} = \Pr\left\{\log_2\left(1 + \frac{P_1|h_{1s}|^2}{N_0 + P_2|h_{2s}|^2}\right) > \mathcal{R}_{\text{C-FD-GDNC}} \cup \log_2\left(1 + \frac{P_2|h_{2s}|^2}{N_0}\right) < \mathcal{R}_{\text{C-FD-GDNC}}\right\} \tag{13}$$

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- Region 3 corresponds to decoding errors of the messages from both users,

$$\mathcal{P}_{out}^{3} = \Pr\left\{\log_2\left(1 + \frac{P_1|h_{1s}|^2}{N_0 + P_2|h_{2s}^k|^2}\right) < \mathcal{R}_{\text{C-FD-GDNC}} \cup \log_2\left(1 + \frac{P_2|h_{2s}|^2}{N_0 + P_1|h_{1s}|^2}\right) < \mathcal{R}_{\text{C-FD-GDNC}} \cup \log_2\left(1 + \frac{(P_1|h_{1s}|^2 + |h_{2s}|^2P_2)}{N_0}\right) < 2\mathcal{R}_{\text{C-FD-GDNC}}\right\} \tag{14}$$

- Region 4 corresponds to successful decoding of the messages from both users,

$$\mathcal{P}_{out}^{4} = 1 - (\mathcal{P}_{out}^{1} + \mathcal{P}_{out}^{2} + \mathcal{P}_{out}^{3}). \tag{15}$$

Finally, the individual outage probability of the User 1 at the destination is given by the sum of the outage probabilities of Regions 1 and 3. Therefore, [13]

$$\mathcal{O}_{out}^{1} = \mathcal{P}_{out}^{1} + \mathcal{P}_{out}^{3}. \tag{16}$$

Definition 1: The outage probability of the two-user cognitive full duplex GDNC scheme with $k_1 = k_2 = 2$ and code rate $\mathrm{R}_{\text{C-FD-GDNC}} = 2k_1/(k_1+k_2) = 1$ can be approximated as

$$\mathcal{O}_{\text{C-FD-GDNC}} \approx C_2^3 \mathcal{P}_{out}^{12} (\mathcal{O}_{out}^{1})^3. \tag{17}$$

Proof: In the high SNR region, the outage probability of the proposed scheme is dominated by the event that a user cannot decode the message of the partner, *e.g.*, U_2 has not decoded the information packets of U_1. In this case, an outage occurs if the direct transmission fails and at least $k_1 = 2$ out of the $k_1 + k_2 - 1 = 3$ remaining packets containing IP_1^1 cannot be decoded,

$$\mathcal{O}_{\text{C-FD-GDNC}} \approx \mathcal{P}_{out}^{12}\mathcal{O}_{out}^{1}(C_2^3(\mathcal{O}_{out}^{1})^2(1-\mathcal{O}_{out}^{1}) + C_3^3(\mathcal{O}_{out}^{1})^3) \tag{18}$$
$$\approx C_2^3 \mathcal{P}_{out}^{12}(\mathcal{O}_{out}^{1})^3.$$

■

IV. NUMERICAL RESULTS

In this section we present some numerical results in order to evaluate the performance of the proposed cognitive full-duplex network coding scheme. We evaluate the outage probability for a two-user secondary network with $d_{12} = d_{1s} = d_{2s} = 1/2$, $d_{1p} = d_{2p} = 1$, $\sigma_{ij} = \sigma_{ii} = 1$, $\nu = 4$ and attempted transmission rate of $\mathcal{R}_s = 3$ bpcu. We also consider that each user transmits $k_1 = 2$ information packets and $k_2 = 2$ parity packets in the C-GDNC and C-FD-GDNC schemes.

Fig. 6 depicts the outage probability of the FD-C-GDNC and C-GDNC schemes as a function of the interference threshold β imposed by the primary network. We also account for different levels of self-interference $\delta \in \{0, -10, -20, -60\}$ dB. Monte Carlo simulations are represented by red circles. From

$$\mathcal{P}_{out}^{12} = \epsilon\,\lambda_{1p}\,\frac{\left(\lambda_{2p}-\lambda_{22}\,\mu_{\mathrm{FD}}\right)\left(\lambda_{2p}\,\lambda_{1p}\,\epsilon+\lambda_{2p}\,\lambda_{12}\,\mu_{\mathrm{FD}}-\lambda_{22}\,\lambda_{1p}\,\epsilon\,\mu_{\mathrm{FD}}\right)}{\left(\lambda_{2p}\,\lambda_{1p}\,\epsilon+\lambda_{2p}\,\lambda_{12}\,\mu_{\mathrm{FD}}-\lambda_{22}\,\lambda_{1p}\,\epsilon\,\mu_{\mathrm{FD}}\right)^{2}} + \frac{\epsilon\,\lambda_{1p}\lambda_{2p}\,\lambda_{22}\,\lambda_{12}\,\mu_{\mathrm{FD}}^{2}\,\ln\left(\frac{\lambda_{2p}\,\left(\lambda_{1p}\,\epsilon+\lambda_{12}\,\mu_{\mathrm{FD}}\right)}{\lambda_{22}\,\lambda_{1p}\,\epsilon\,\mu_{\mathrm{FD}}}\right)}{\left(\lambda_{2p}\,\lambda_{1p}\,\epsilon+\lambda_{2p}\,\lambda_{12}\,\mu_{\mathrm{FD}}-\lambda_{22}\,\lambda_{1p}\,\epsilon\,\mu_{\mathrm{FD}}\right)^{2}}. \tag{11}$$

Fig. 6, it is possible to see that the performance of the proposed scheme increases with the increment of the quality of the interference cancellation, which is reflected in low values for δ. Moreover, one can observe that for greater values of β, there is a diversity loss caused by the self-interference. This occurs because for sufficiently large β, the outage probability of the inter-user channel becomes independent of β due to a performance floor caused by the self-interference at the secondary user.

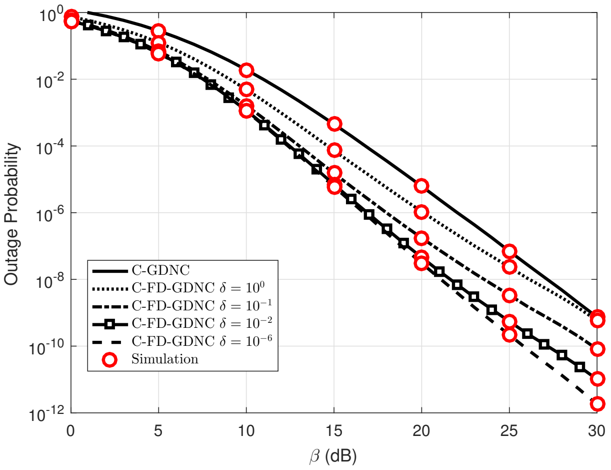

Fig. 6. Outage probability as a function of the maximum interference threshold β, for different levels of self-interference

Fig. 7 presents the outage probability as a function of the maximum interference threshold β with $\delta = -60$ dB. One can see that the proposed FD-C-GDNC scheme has the best performance for $\beta > 3$ dB. For $\beta = 10$ dB, the outage probability of the FD-C-GDNC is 10^{-3}, while the outage probability of the other schemes is greater than 2×10^{-2}.

V. CONCLUSION

We evaluated the performance of a cognitive full-duplex GDNC scheme where the two users send the messages simultaneously. We consider that the transmit powers of the secondary users are limited by the maximum interference threshold of the primary destination. The results show that the proposed scheme has the best performance in terms of outage probability, when compared with half-duplex network coding schemes, traditional cooperative techniques as well as direct non-cooperative transmission. As a future work, we intend to analyze the proposed scheme in a scenario with multiple secondary users and subject to Nakagami-m fading.

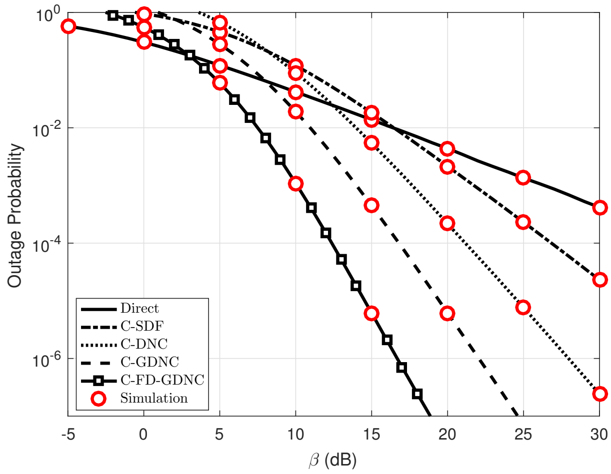

Fig. 7. Outage probability for different schemes as a function of the maximum interference threshold β.

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