# Performance Analysis of Energy Constrained Cognitive Full-Duplex Generalized Network Coding Scheme

Samuel B. Mafra, Evelio M. G. Fernandez, Samuel Montejo-Sánchez and Hebert Douglas Pereira

*Abstract*— **We evaluate the performance of an energy constrained cognitive full-duplex network coding based scheme. The secondary cooperative network is composed of two energy-constrained full-duplex users that cooperate to transmit their independent information to a common destination. The secondary users do not have sources of energy and they harvest energy from the signals transmitted by the primary user. We show through theoretical and numerical results that the proposed energy harvesting cognitive full-duplex scheme has the best performance in terms of outage probability, when compared with energy constrained half-duplex network coding scheme as well as to the direct non-cooperative transmission.**

*Keywords*— **Energy Harvesting, Cognitive Radio, Network Coding, Full-Duplex.**

## I. INTRODUCTION

In the last years, several protocols have been proposed with the goal of obtaining a more efficient use of the radio frequency spectrum and energy. Among these schemes, we can cite the energy harvesting and cognitive radio as promising techniques for energy and spectrum constrained networks [1].

In a wireless sensor network nodes are operated by batteries, which are difficult or even impossible, to be replaced or recharged by direct human intervention. An alternative for these networks is energy harvesting (EH), which can be described as the process of extracting energy from the surrounding environment in order to supply energy and to prolong the lifetime of energy-constrained communication networks. The nodes can harvest energy from different sources such as heat, light, wave, wind and radio frequency (RF) signals. The main advantage of energy harvesting from RF signals is that it does not depend on weather conditions, so this technique has gained great attention in the last years [1], [2]. Two commonly used EH architectures are power splitting (PS) and time switching (TS) [2]. In the PS protocol, a fraction of the received signal power is used to harvest energy and the remainder is used to send information to the destination, while in the TS protocol, a fraction of time is used to harvest energy from the received signal and the rest of the time is used to send the information to the destination [2].

In a cognitive radio network, unlicensed or secondary users (SUs) utilize the same frequency band allocated to the licensed or primary users (PUs). The SUs are usually subject to interference caused by the RF transmissions of PUs. However, under an energy harvesting point-of-view, this interference can be seen as a free energy source for the SUs [1].

Recently, cooperative communications have emerged as a promising technique to boost the performance of communication systems [3]. In a cooperative network, one or more nodes, known as relays, help the communication between source and destination. For the Decode-and-Forward (DF) protocol, 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 [3]. 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, inherent to the full-duplex approach. This self-interference cannot be completely removed, but it can be considerably attenuated by using interference cancellation techniques [4]. Nevertheless, the full-duplex relays can still achieve high performance, even in the presence of strong interference levels.

Recent works have applied the concept of network coding to cooperative networks [5], [6]. 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 [5], the dynamic network coding scheme (DNC) is proposed, where the linear combinations transmitted during the CP are formed from a non-binary Galois Field GF($q$). In [6] a generalization to the DNC scheme is proposed, namely generalized dynamic network coding (GNC). In the GNC 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 [7], the authors analyzed a cognitive wireless network with two energy-constrained SUs and a common secondary destination, where the SUs harvest energy from the transmitted signals of primary user. The authors consider that the secondary users are able to send linear combinations of their

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own information and those of other nodes by adopting the GNC scheme. The proposed scheme outperforms the non-cooperative transmission and the DF cooperative protocol.

In [8], we evaluate the use of network coding in cognitive underlay networks with multiple secondary users, where the transmit power is limited by a primary interference threshold. 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. Such performance can be improved even further with a proper power allocation between the nodes, as demonstrated in [9].

Motivated by the great benefits of full-duplex radios, we extend the analysis to a scenario with two full-duplex secondary users and subject to Rayleigh fading in [10]. The transmit power of the secondary users is limited by the maximum interference accepted by the primary destination. The proposed scheme outperforms previous methods even in the presence of self-interference.

In this paper we extend the cognitive full-duplex GNC (C-FD-GNC) scheme proposed in [10], for a scenario with energy constrained secondary users. The transmit powers of the secondary users are provided by the energy harvested from the PU transmission, being a function of the fading realization between the PU and the SUs. Moreover, we consider Nakagami-$m$ fading in order to evaluate the effect of the line-of-sight. The performance in terms of outage probability of the proposed energy constrained cognitive full-duplex GNC (EC-FD-GNC) is compared with the energy constrained half-duplex network coding scheme proposed in [7] and with the direct transmission.

The remainder of this paper is organized as follows: Section II introduces the system model and some related work. In Section III the proposed EC-FD-GNC 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 $D_s$ and a primary transmitter $T_p$[1], as illustrated in Fig. 1. The quasi-static fading channel between transmitter $i$ and receiver $j$ is denoted by $h_{ij}$, $i \in \{1,2,p\}$, $j \in \{1,2,s\}$, where $\{1,2\}$ represent the users, $s$ the secondary destination and $p$ the primary transmitter. $h_{ij}$ follows a Nakagami-$m$ distribution[2] with fading parameter $m_{ij}$ and average power $\lambda_{ij}$. 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 distance between users $i$ and $j$ and $\nu$ is the path-loss exponent ($\nu \geq 2$). We also consider a symmetric scenario in the secondary network and that the secondary users are approximately at the same distance from the primary transmitter. Moreover, we consider that $T_p$ is very close to the SUs, characterizing an interference-limited scenario.

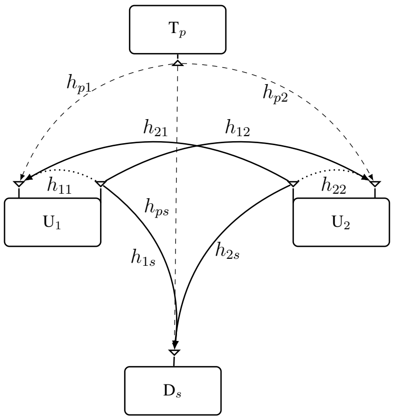

Fig. 1. System model composed by a primary transmitter $T_p$ and two SUs, denoted by $U_1$ and $U_2$, which transmit to a common secondary destination $D_s$.

In this article, we consider a TS energy harvesting protocol, where the nodes first devote a fraction $0 \leq \alpha \leq 1$ of each time-slot for harvesting energy from $T_p$. The remainder of the time slot is used by $U_1$ and $U_2$ for information (new or parity packets) transmission. We consider that each user transmits during a fraction $\beta$ of the $(1-\alpha)T$. For instance, each user transmits during a fraction $\beta = 0.5$ in half-duplex scheme, while, we consider $\beta = 1$ for the full-duplex scheme and the direct transmission, since each user transmits during all remainder of the time slot. The energy harvested at source node $U_k$ ($k \in \{1,2\}$) during the first fraction $\alpha$ of the time slot is

$$E_k = \eta P_p |h_{pk}|^2\, \alpha T, \tag{1}$$

where $\eta$ represents the energy transfer efficiency, with $0 \leq \eta \leq 1$, $T$ is the duration of the time-slot and $P_p$ is the primary transmit power. Consequently, the available transmit power is

$$P_k = \frac{E_k}{\beta(1-\alpha)\,T} = \frac{\alpha\eta P_p}{\beta(1-\alpha)}|h_{pk}|^2 = \mathcal{K} P_p |h_{pk}|^2. \tag{2}$$

Outage is the event that the mutual information between nodes $i$ and $j$ is less than an attempted information rate $\mathcal{R}_{\text{sch}}$. The outage probability of the link $k$–$j$, with $k \neq j$, is obtained as

$$\mathcal{O}_{kj} = \Pr\left\{\log_2\left(1 + \frac{\mathcal{K}|h_{kj}|^2|h_{pk}|^2}{|h_{pj}|^2}\right) < \frac{\mathcal{R}_{\text{sch}}}{1-\alpha}\right\}, \tag{3}$$

where $\Pr\{a\}$ is the probability of event $a$ and $\mathcal{R}_{\text{sch}} = \frac{\mathcal{R}_s}{\text{R}_{\text{sch}}}$ is the transmission rate in bits per channel use (bpcu) of the scheme sch $\in$\{EC-DT, EC-HD-GNC, EH-FD-GNC\}. Also, $\mathcal{R}_s$ is the attempted information rate in the case of non-cooperative direct transmission and $\text{R}_{\text{sch}}$ 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 $\text{R}_{\text{EC-DT}} = 1$.

The outage probability of the EC-DT scheme in (3) has

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[1] We assume that the SUs are far enough from $D_p$ so that the interference imposed by the SUs in $D_p$ is negligible. Moreover, the primary and secondary networks operate under very different transmission ranges. Thus, we can neglect the interference from the SUs on $D_p$ assuming that the SUs are outside the guard zone of $D_p$.

[2] The Nakagami-$m$ distribution is a general distribution, that fits several types of fading. The Rayleigh distribution, for example, corresponds to $m = 1$. For $m > 1$ there is some line-of-sight between the transmitter and receiver.

$$\mathcal{O}_{kj} = \int_0^\infty \int_0^\infty \int_0^{\frac{z_{pl}(2^{\frac{\mathcal{R}_{\text{sch}}}{(1-\alpha)}}-1)}{\mathcal{K} z_{pk}}} \frac{e^{-\frac{m_{kj} z_{kj}}{\lambda_{kj}}} \left(\frac{m_{kj} z_{kj}}{\lambda_{kj}}\right)^{m_{kj}}}{z_{kl}\Gamma(m_{kj})} \frac{e^{-\frac{m_{pj} z_{pj}}{\lambda_{pj}}} \left(\frac{m_{pj} z_{pj}}{\lambda_{pj}}\right)^{m_{pj}}}{z_{pj}\Gamma(m_{pj})} \frac{e^{-\frac{m_{pk} z_{pk}}{\lambda_{pk}}} \left(\frac{m_{pk} z_{pk}}{\lambda_{pk}}\right)^{m_{pk}}}{z_{pk}\Gamma(m_{pk})} \mathrm{d}z_{kj}\mathrm{d}z_{pj}\mathrm{d}z_{pk}$$

$$= \begin{cases} \mathcal{Z}\, e^{\mathcal{Z}}\, \mathrm{E}_n(m_{kj}, \mathcal{Z}), & \text{for } m_{kj} \geq 1 \text{ and } m_{pk} = m_{pj} = 1 \\ 1 - \frac{\Gamma(m_{pk}+m_{pj}) U(m_{pj}, 1-m_{pk}, \frac{\mathcal{Z} m_{pk}}{m_{pj}})}{\Gamma(m_{pk})}, & \text{for } m_{kj} = 1, m_{pk} \geq 1 \text{ and } m_{pj} \geq 1. \end{cases} \tag{4}$$

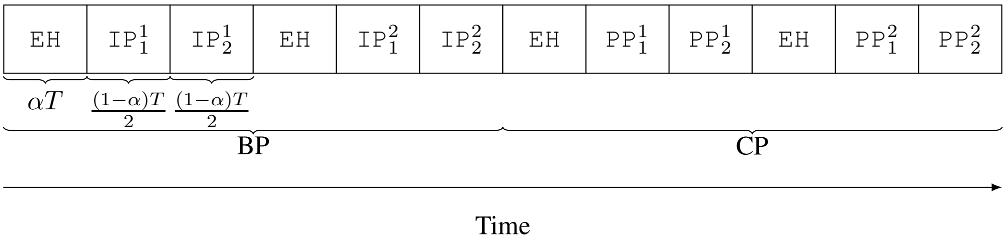

Fig. 2. Packets received by the destination in the EC-HD-GNC scheme,where two users harvest energy in the EH phase and broadcast two information packets ($\mathrm{IP}_k^1$,$\mathrm{IP}_k^2$) in the BP ($w_1 = 2$) as well as transmit two linear combinations ($\mathrm{PP}_k^1$,$\mathrm{PP}_k^2$), with $k \in \{1, 2\}$, in the CP ($w_2 = 2$).

not a general closed-form expression. In order to evaluate the performance of the proposed scheme, we derive closed-form expressions for two scenarios of interest with some particular fading parameters.

1) In the first scenario, we evaluate the effect of some line-of-sight in a link of the secondary network. We consider Rayleigh fading for the link between the primary and secondary networks ($m_{pk} = m_{pj} = 1$) and a generic value for the fading parameter $m_{kj} \geq 1$ for the link $k - j$;
2) In the second scenario, we are interested in evaluate the effect of some line-of-sight in the harvesting and interference links. We consider Rayleigh fading for the link $k - j$ ($m_{kj} = 1$) and generic values of fading parameter for the link among the primary network and the secondary network ($m_{pk} \geq 1$ and $m_{pj} \geq 1$).

Considering the two scenarios described above, we can write the outage probability of the link $k - j$ as in (4), where $\mathrm{E}_n(n, z) = \int_1^\infty \frac{e^{-zt}}{t^n} dt$ corresponds to the exponential integral [11, Eq. (5.1.4)], $U(a, b, c)$ corresponds to the confluent hypergeometric function [12, Eq. (9.211.4)] and $\mathcal{Z}$ is a constant given by:

$$\mathcal{Z} = \frac{\left(2^{\frac{\mathcal{R}_{\text{sch}}}{1-\alpha}} - 1\right) m_{kj} \lambda_{pj}}{\mathcal{K} \lambda_{kj}\, \lambda_{pk}}. \tag{5}$$

### B. Energy Constrained Cognitive HD-GNC Scheme

In [7], an energy constrained cognitive half-duplex GNC (EC-HD-GNC) scheme is proposed where first, each user devotes $\alpha$ of each time-slot for harvesting energy from the signal of $T_p$, then each user sends a new information or parity packet in a half of the remaining of the time slot. The authors adopt the GNC scheme that was proposed in [6]. The GNC scheme considers that each user is able to broadcast $w_1$ information packets during the BP and an arbitrary number $w_2$ of linear combinations of its own information and the information of the other $M - 1$ users in the CP, if correctly decoded during the BP. The operation of the EC-HD-GNC scheme is illustrated in Fig. 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 $\mathrm{IP}_1^1$ if the direct transmission fails and at least $w_1$ out of the $w_1 + w_2 - 1$ remaining packets containing $\mathrm{IP}_1^1$ cannot be decoded. On the other hand, if the inter-user channel is not in outage ($U_2$ correctly decoded $\mathrm{IP}_1^1$), an outage occurs when the direct transmission fails and at least $2w_1$ of the $2(w_1 + w_2) - 1$ remaining packets received by the destination cannot be decoded.

The high SNR approximation for the outage probability of the energy constrained cognitive two-user GNC (EC-HD-GNC) scheme with $\beta = 0.5$, $w_1 = w_2 = 2$ and code rate $\mathrm{R}_{\text{EC-HD-GNC}} = \frac{w_1}{(w_1+w_2)} = \frac{1}{2}$, can be written as [6], [8]

$$\mathcal{O}_{\text{EC-HD-GNC}} \approx C_2^3\, \mathcal{O}_{12} {\mathcal{O}_{1s}}^3, \tag{6}$$

where $\mathcal{O}_{12}$ and $\mathcal{O}_{1s}$ are given by (4), and $C_m^n = \frac{n!}{m!(n-m)!}$ is the binomial coefficient.

## III. ENERGY CONSTRAINED COGNITIVE FD-GNC SCHEME

In this section, we propose an energy constrained cognitive full-duplex GNC (EC-FD-GNC) scheme, where the secondary users harvest energy from the primary transmission in a fraction $\alpha$ of the time-slot and transmit a new information or parity packet simultaneously in the remainder of the time-slot. 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 $h_{kk} \sim \mathcal{CN}(0\,, \sigma_{kk})$, with average fading power $\lambda_{kk} \triangleq \delta\, \sigma_{kk}$, where $\delta$ represents the interference cancellation factor which arises from the association of antenna cancellation and interference cancellation techniques [4].

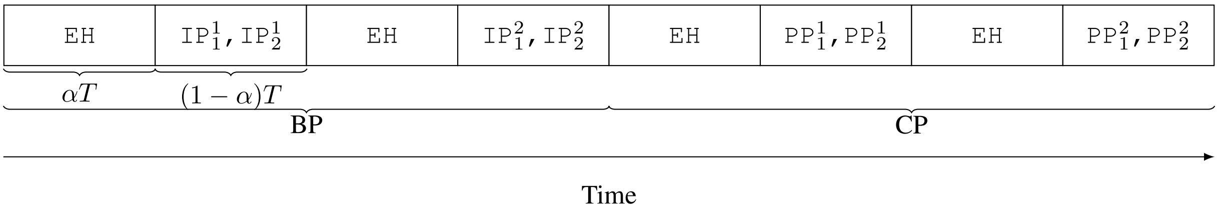

Fig. 3. Packets received by the secondary destination in a energy constrained full-duplex network coding protocol, where two users harvest energy in the EH phase and broadcast two information frames (IP$_k^1$ and IP$_k^2$) in the BP ($w_1 = 2$) as well as transmit two linear combinations (PP$_k^1$ and PP$_k^2$),with $k \in \{1, 2\}$ in the CP ($w_2 = 2$).

The operation of the EH-FD-GNC scheme is illustrated in Fig. 3. Considering a two-user scenario, as in the EC-HD-GNC 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 $w_1$ out of the $w_1 + w_2 - 1$ 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 $2w_1$ of the $2(w_1 + w_2) - 1$ remaining packets received by the destination cannot be decoded.

The code rate of the EC-FD-GNC scheme is

$$\mathrm{R}_{\text{EC-FD-GNC}} = \frac{2w_1}{\frac{2(w_1+w_2)}{2}} = \frac{2w_1}{w_1 + w_2}. \tag{7}$$

One can see from (7) that, when $w_1 = w_2$, the EC-FD-GNC scheme transmits with the same code rate $\mathrm{R}_{\text{EC-FD-GNC}} = \mathrm{R}_{\text{EH-DT}} = 1$ of the direct transmission.

The mutual information between $U_1$ and $U_2$, considering that each users communicate with transmit power $P_l$, is

$$\begin{aligned}\mathcal{I}_{12} &= \log_2\left(1 + \frac{|h_{12}|^2 P_1}{|h_{p2}|^2 P_p + |h_{22}|^2 P_2}\right)\\ &= \log_2\left(1 + \frac{\mathcal{K}|h_{p1}|^2 P_p |h_{12}|^2}{|h_{p2}|^2 P_p + \mathcal{K} P_p |h_{p2}|^2 |h_{22}|^2}\right)\\ &= \log_2\left(1 + \frac{\mathcal{K}|h_{p1}|^2 |h_{12}|^2}{|h_{p2}|^2 (1 + \mathcal{K}|h_{22}|^2)}\right). \end{aligned} \tag{8}$$

Note that the self-interference at user $U_2$ is taken into account in (8). As demonstrated in [4], the self interference can be attenuated to levels in the order of $\delta < 10^{-3}$. Thus, we can consider the value of self-interference term negligible ($\mathcal{K}|h_{22}|^2 << 1$) in (8) and write the outage probability of the inter-user channel between the users $U_1$ and $U_2$ as:

$$\mathcal{O}_{12} \approx \Pr\left\{\log_2\left(1 + \frac{\mathcal{K}|h_{12}|^2 |h_{p1}|^2}{|h_{p2}|^2}\right) < \frac{\mathcal{R}_{\text{EC-FD-GNC}}}{1-\alpha}\right\}. \tag{9}$$

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 $\mathcal{R}_1 = \mathcal{R}_2 = \mathcal{R}_{\text{C-FD-GNC}}$, the $(\mathcal{R}_1, \mathcal{R}_2)$-plane is divided into four regions (See [10], [13] for more details):

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

$$\begin{aligned}\mathcal{O}_{\text{R1}} = \Pr&\left\{\log_2\left(1 + \frac{P_2|h_{2s}|^2}{P_p|h_{ps}|^2 + P_1|h_{1s}|^2}\right) > \frac{\mathcal{R}_{\text{EC-FD-GNC}}}{(1-\alpha)}\right.\\ &\left.\cup \log_2\left(1 + \frac{P_1|h_{1s}|^2}{P_p|h_{ps}|^2}\right) < \frac{\mathcal{R}_{\text{EC-FD-GNC}}}{(1-\alpha)}\right\};\end{aligned} \tag{10}$$

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

$$\begin{aligned}\mathcal{O}_{\text{R2}} = \Pr&\left\{\log_2\left(1 + \frac{P_1|h_{1s}|^2}{P_p|h_{ps}|^2 + P_2|h_{2s}|^2}\right) > \frac{\mathcal{R}_{\text{EC-FD-GNC}}}{(1-\alpha)}\right.\\ &\left.\cup \log_2\left(1 + \frac{P_2|h_{2s}|^2}{P_p|h_{ps}|^2}\right) < \frac{\mathcal{R}_{\text{EC-FD-GNC}}}{(1-\alpha)}\right\};\end{aligned} \tag{11}$$

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

$$\begin{aligned}\mathcal{O}_{\text{R3}} = \Pr&\left\{\log_2\left(1 + \frac{P_1|h_{1s}|^2}{P_p|h_{ps}|^2 + P_2|h_{2s}^k|^2}\right) < \frac{\mathcal{R}_{\text{EC-FD-GNC}}}{(1-\alpha)} \cup\right.\\ &\log_2\left(1 + \frac{P_2|h_{2s}|^2}{P_p|h_{ps}|^2 + P_1|h_{1s}|^2}\right) < \frac{\mathcal{R}_{\text{EC-FD-GNC}}}{(1-\alpha)} \cup\\ &\left.\log_2\left(1 + \frac{(P_1|h_{1s}|^2 + |h_{2s}|^2 P_2)}{P_p|h_{ps}|^2}\right) < \frac{2\mathcal{R}_{\text{EC-FD-GNC}}}{(1-\alpha)}\right\};\end{aligned} \tag{12}$$

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

$$\mathcal{O}_{\text{R4}} = 1 - (\mathcal{O}_{\text{R1}} + \mathcal{O}_{\text{R2}} + \mathcal{O}_{\text{R3}}). \tag{13}$$

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]

$$\mathcal{O}_{\text{MAC}} = \mathcal{O}_{\text{R1}} + \mathcal{O}_{\text{R3}}. \tag{14}$$

The outage probability of the energy constrained two-user cognitive full duplex GNC scheme with $w_1 = w_2 = 2$, code rate $\mathrm{R}_{\text{C-FD-GNC}} = 2w_1/(w_1 + w_2) = 1$ and $\beta = 1$, can be approximated for the high SNR as [10]

$$\mathcal{O}_{\text{EC-FD-GNC}} \approx C_2^3 \mathcal{O}_{12} (\mathcal{O}_{\text{MAC}})^3, \tag{15}$$

where $\mathcal{O}_{12}$ is given by (4).

## IV. NUMERICAL RESULTS

In this section we present some numerical results in order to evaluate the performance of the proposed energy constrained cognitive full-duplex network coding scheme. We evaluate the outage probability for a two-user secondary network with

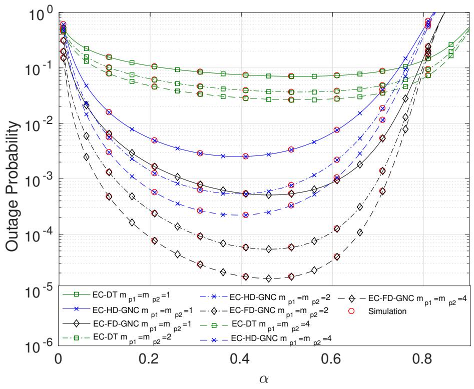

Fig. 4. Outage probability for different schemes as a function of $\alpha$.

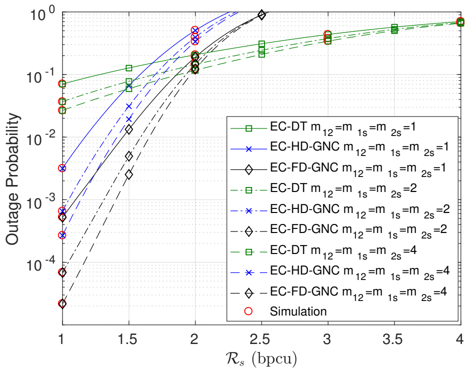

Fig. 5. Outage probability for different schemes as a function of $\mathcal{R}_s$.

$d_{12} = d_{1s} = d_{2s} = 1/2$, $d_{p1} = d_{p2} = 1/2$ and $d_{ps} = \sqrt{3}/2$, $\sigma_{ij} = \sigma_{kk} = 1, \nu = 4, \eta = 1$ [3] and attempted transmission rate of $\mathcal{R}_s = 1$ bits per channel use (bpcu). We also consider that each user transmits $w_1 = 2$ information packets and $w_2 = 2$ parity packets in the EC-HD-GNC and EC-FD-GNC schemes.

In order to evaluate the effect of the line-of-sight in the links between the primary transmitter and the secondary users, we analyze the outage probability as a function of $\alpha$ for different values of the fading parameters $m_{p1} = m_{p2} \in \{1, 2, 4\}$ in Fig. 4. With some line-of-sight, the secondary user may obtain more energy in the harvesting phase, while the line-of-sight improves the interference in the information phase. Moreover, we consider $m_{12} = m_{1s} = m_{2s} = m_{ps} = 1$. Monte Carlo simulations are represented by red circles.

From Fig. 4, it is possible to see that the performance of all schemes improves with the increment in the fading parameters. Moreover, the proposed scheme has the best performance among all schemes for $\alpha < 0.75$. For instance, with $m_{p1} = m_{p2} = 1$ and $\alpha = 0.5$, the EC-FD-GNC achieves an outage probability of $6 \times 10^{-4}$, while the outage probability of the EC-DT is greater than $10^{-2}$. Notice that Monte Carlo simulations agree very well with the theoretical results. Finally, we can observe that the optimum value of $\alpha$ does not change with variations in the fading parameters $m_{p1}$ and $m_{p2}$.

In order to investigate the effect of some line-of-sight in the secondary links, we evaluate the outage probability as a function of the attempted rate $\mathcal{R}_s$ for different values of the fading parameters $m_{12} = m_{1s} = m_{2s} \in \{1, 2, 4\}$ in Fig. 5. We consider $m_{p1} = m_{p2} = m_{ps} = 1$ and $\alpha = 0.5$.

From Fig. 5, it can be noted that the EC-FD-GNC can operate with a greater transmission rate in presence of some line-of-sight, when compared with the others schemes. For $\mathcal{R}_s > 2$, the EH-DT scheme outperforms the other schemes, however the outage probability at such region is very large.

## V. CONCLUSION

We evaluated the performance of an energy constrained cognitive full-duplex GNC network. We consider that the energy of the secondary users are provided by harvesting the RF signal from the PU transmission, being a function of the fading realization between the PU and the SUs. The results show that the proposed scheme has the best performance in terms of outage probability, when compared with energy constrained half-duplex GNC scheme and direct non-cooperative transmission.

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[3] The conclusions would not change if a different value of $\eta$ is assumed as the effect is similar, for all schemes and only their relative $y$-axis positions are changed.

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