Performance and Energy Efficiency of Cognitive Full-Duplex under Spectrum Sharing Constraints

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I. Introduction

In a cognitive radio context under spectrum sharing constraints, a secondary network may transmit concurrently with the primary one as long as the communication of this latter 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 to not damage the reception of the primary receiver [1], [2]. This will allow a more efficient use of the frequency spectrum. On the other hand, cooperative communications [3], [4] have emerged as an alternative technique to boost the performance of communication systems. The idea behind this strategy is to make use of one or more nodes (called relays) in order to emulate a physical antenna array. Thus, the same benefits obtained in multiple-input multiple-output systems can also be achieved with the use of single-antenna nodes through the distributed transmission and processing of the information. In cooperative systems, the relay behavior is governed by the so-called cooperative protocols and it can operate on either half-duplex or full-duplex modes [3], [5]. Specifically, in half-duplex mode, the relay transmits and receives in orthogonal channels, whereas 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, although ideal full-duplex relaying can achieve higher capacity than half-duplex relaying [5], its use introduces self-interference that is inherent to the full-duplex approach (please, see [6]–[8] and references therein). Nevertheless, the works in [6]–[8] showed that full-duplex relays can still achieve high performance, even in the presence of strong interference levels.

Motivated by the important benefits acquired with cognitive radio and cooperative diversity techniques, several recent works have analyzed the performance of cooperative cognitive networks under spectrum sharing constraints [9].Common to these works is that they assumed that all nodes operate on a half-duplex mode. However, in [14] the authors considered a scenario with a full-duplex relay subject to self-interference. In that work, through the use of a whitening filter, the interference from the primary network was assumed to be approximately Gaussian. With this assumption in mind, [14] performed a closed-form outage analysis 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.

Recently, energy efficient schemes have become the focus of academia and industry. The objective of power consumption analysis is to propose alternatives to prolongate the battery lifetime of mobile devices as well as to reduce carbon emissions, and reduce energy consumption of the network as a whole [10]. In [11] power consumption was analyzed for non-cooperative and cooperative networks. Moreover, by defining an end-to-end throughput requirement, it is shown that incremental cooperation is more energy efficient than direct transmission and than multi-hop transmission, even at small transmission ranges. Moreover, in [12] an energy efficient analysis is carried out considering multi-hop HD and FD schemes in the AWGN relay channel. The results show that the multi-hop HD relay requires more bandwidth than multi-hop FD relay with the same rate and power constraints.

Differently from all previous works, in this paper we consider a cooperative cognitive network operating on a spectrum sharing scenario with a full-duplex relay subject to self-interference. In particular, this paper differs from [14] because the secondary destination applies joint decoding with the signals received from the relay and from the secondary source such that the direct link can be seen as useful information rather than interference. Closed-form expressions for the outage probability and throughput are derived and insightful discussions are provided. The proposed scheme, termed as full-duplex joint-decoding (JD) relaying, is compared with the full-duplex DH scheme presented in [14] as well as with the standard half-duplex (HD) relaying scheme. Our results demonstrate that the proposed cognitive cooperative full-duplex relaying scheme can considerably outperform the full-duplex relaying method proposed in [14] for the whole signal-to-noise ratio (SNR) range. Moreover, our results show that the proposed JD method performs better than the half-duplex HD scheme in terms of throughput even in the presence of self-interference.

II. System model and Discussions

Consider a cooperative cognitive network composed by one secondary source s, one full-duplex secondary relay r, one secondary destination d, and one primary receiver p. Since our analysis focused on the secondary communication, we assume that the primary transmitter is far from the secondary network such that the interference can be seen as noise [15]. Such network operates on a spectrum sharing environment and under transmit power constraints. The quasi-static fading channel between transmitter i and receiver j is denoted by h_{ij}, $i \in \{s, r\}$ and $j \in \{r, d, p\}$. All channels undergo independent identically distributed (i.i.d.) Rayleigh fading, thus $|h_{ij}|^2$ follows an exponential distribution with mean power λ_{ij}. The received signals at the relay and at the destination can be expressed, respectively, as

$$y_r = \sqrt{P_s}\, h_{sr}\, x_s + \sqrt{P_r} h_{rr}\, x_r + n_r, \tag{1}$$

$$y_d = \sqrt{P_r}\, h_{rd}\ x_r + \sqrt{P_s}\, h_{sd}\, x_s + n_d, \tag{2}$$

where P_i is the transmit power of the node i, x_i is the message sent by the node i, h_{rr} denotes the fading coefficient of the self-interference at the full-duplex relay, $n_j \sim \mathcal{CN}(0, \sigma_n^2)$ stands for the additive white Gaussian noise at node j with variance $\sigma_n^2 = N_0$, where N_0 is the one-sided noise power spectral density. Moreover, $\lambda_{ij} = \frac{1}{(d_{ij})^{\alpha}}$, with d_{ij} being the distance between nodes i and j, and α represents the path loss exponent. Note that the self-interference may represent the residual interference after the application of some interference cancellation technique at the relay [8], [16]. We recall that the self-interference is dominated by the scattering component once the line-of-sight component is considerably reduced by antenna isolation [8], which leads to in general very small values of λ_{rr} [6].

Due to the spectrum sharing environment, the primary receiver tolerates a maximum interference level given by I. In a spectrum sharing scenario with a full duplex relay, the secondary transmitter and the secondary relay transmit their messages at the same time. Thus, the primary destination receives interference from both transmitters simultaneously. For this case, the transmission powers of the secondary transmitter and secondary relay must be constrained as [14], thus $|h_{sp}|^2 P_s + |h_{rp}|^2 P_r \leq I$. As in [14], we consider an equal power allocation scheme such that the secondary transmitter and the secondary relay have their respective transmit powers limited by $P_s = \frac{I}{2|h_{sp}|^2}$, $P_r = \frac{I}{2|h_{rp}|^2}$.

Next, we analyse in close-form the outage probability and throughput of the proposed JD scheme. Additionally, we also include the outage and throughput formulations for the cases of full-duplex DH and HD schemes, which are used as benchmarks for the proposed scheme. Our results show that in terms of outage probability, the HD scheme mat outperform the DH and JD schemes. Moreover, with the increment of the primary interference threshold, the outage of the full-duplex JD and DH methods saturates because of the effect of the self-interference. Therefore, for sufficiently large I, the outage probability of the JD and DH schemes becomes independent of I due to a performance floor caused by the self-interference at the full-duplex relay. On the other hand, when we account for the throughput, the JD scheme considerably outperforms the HD and the DH schemes in the whole SNR range. Applying joint decoding at the destination in the case of a full-duplex relaying scheme considerably enhances performance, otherwise the multiplexing gain expected from full-duplex schemes may not be realized. We also analysed how energy efficient is the proposed scheme compared to conventional HD relaying schemes.

All in all, we investigate the performance of a FD cooperative cognitive network with self-interference and subject to spectrum sharing constraints. Our results show that, even though the half-duplex cooperative cognitive network presents the best performance in terms of outage probability, the proposed full-duplex cooperative secondary network is superior in terms of throughput.

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