In-Band Full-Duplex Communication for Cognitive Radio

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***Abstract*—In this paper, we present a new Cognitive Radio (CR) paradigm based on the Full-Duplex mechanism. In the classical Full-Duplex CR (FD-CR) system, the Secondary User (SU) can examine the availability of a channel while transmitting. This fact leads to enhance the SU transmission rate. However, in this classical secondary network, SU is assumed to adopt frequency or time division duplex. In the proposed work, we analyse the CR performance with an In-Band Full-Duplex communication, *i.e.* SU can simultaneously receive and transmit at the same band. This scenario is accompanied with a Full-Duplex sensing, *i.e.* SU performs the Spectrum Sensing while transmitting. The Spectrum Sensing performance is analysed as well as proposing an adaptable detection mechanism that can perform well under such situation. Further, a study on the SU throughputs is developed in order to show the spectral efficiency of the proposed CR paradigm.**

I. Introduction

Full-Duplex (FD) is a promising technique that can double the channel efficiency by simultaneously transmitting and receiving at the same frequency band [1], [2], [3]. FD is based on the Self Interference Cancellation (SIC) techniques. When completely cancelling the image of the transmitted signal at the receiver, the transceiver receives the Signal of Interest affected by some circuitry noises and interferences. However, SIC cannot be perfectly achieved; therefore, some Residual Self Interference (RSI) are present in the received signal.

FD has been recently exploited in Cognitive Radio (CR) context in order to enhance the data rate of the secondary network. In classical CR systems, SU should stop its transmission during the Spectrum Sensing, this kind of CR is known as Half-Duplex CR (HD-CR). The stop of transmission affects the SU throughput, hence, FD has been introduced in the Spectrum Sensing stage of the CR functioning. In Full-Duplex CR (FD-CR), SU should have two antennas: TX for the transmission and RX for receiving. At RX, SU cancels the Self Interference (SI) signal coming from TX. This cancellation process makes the received signal SI-less; therefore, a noisy PU signal (if any) is purely received. A Test Statistic (TS) is applied on this received signal after making the SIC operation in order to decide on the channel status: free (Primary User (PU) is absent) or occupied (PU is active). Due to several limitations such as the imperfect channel estimation and the circuit impairments, SIC is not perfectly achievable, so RSI is still present in the received signal. This RSI affects the TS reliability [4], [5], so it should be highly minimized to keep a robust Spectrum Sensing performance.
Several works have been proposed to deal with the FD-CR, especially the Spectrum Sensing part [6], [7], [8], [9], [10], [11]. Their performance analysis has been based on the Spectrum Sensing accuracy and the effect of the FD functioning on the SU throughput.

As said above, FD means in CR the ability to sense and transmit simultaneously. Here, Frequency Division Duplex (FDD) or Time Division Duplex (TDD) is adopted. In FDD two communicating SUs should have two available primary channels, the first one is used by the transmission of the first SU, while the second one is used by the second SU. FDD leads to a loss in the channel efficiency due to considering two frequency channels in order to establish the communication between two SUs. However, on each channel, the FD SU simultaneously performs the Spectrum Sensing with the transmission procedures. On the other hand, TDD is used when only one primary channel is detected. Therefore the data rate of SUs is affected.
In this paper, we consider a more complicated scenario: *two secondary users are simultaneously communicating using the same frequency band, and have the ability to sense and transmit at the same time*. Such a system provides the cognitive network with the ability of using one primary channel instead of two. In ideal circumstances, the channel efficiency of the unused primary channels could be doubled thanks to the simultaneous transmission of the communicating SUs at the same band.
The main contribution of this manuscript is to propose a new FD-CR paradigm, where the FD is exploited for both:

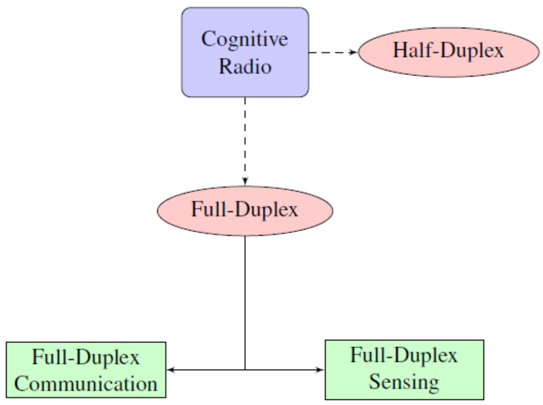

Fig. 1. Cognitive Radio paradigms

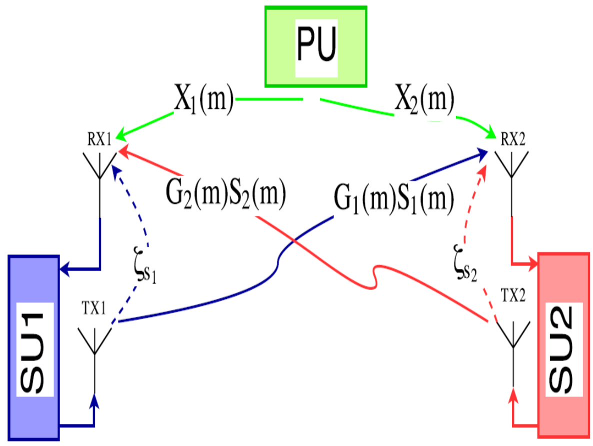

Fig. 2. The FDC-CR paradigm model: Two SUs are simultaneously transmitting and receiving at the same primary channel when detected as available

Transmission and Sensing:

1) SU can transmit and sense at the same time by using the SIC techniques.
2) Two SUs can communicate using the same band, where each SU can simultaneously transmit and receive on the same band. This new capacity should be accompanied with the capability to monitor PU activity in order to protect him as possible from the SU interference.

We refer to this paradigm by Full-Duplex Communication CR (FDC-CR), whereas the classical FD-CR is called Full-Duplex Sensing CR (FDS-CR).

Due to the transmission of both cognitive secondary users at the same band, the main challenge of FDC-CR becomes how to keep an efficient Spectrum Sensing performance in order to protect PU from the interference and to efficiently use the available primary channel. In other words, after performing the SIC operation, SU should be able to differentiate between the only-secondary transmission (PU is absent) and the secondary-plus-primary transmission (PU exists). Here the secondary transmission may negatively affect the PU signal detection reliability.
In order to keep a reliable Spectrum Sensing performance, a Spectrum Sensing mechanism is proposed in this paper. This mechanism is based on sharing the detection parameters between the communicating SUs, the calculated test statistics and the decisions on the channel status.

II. System Model

Let the two Secondary Users, SU1 and SU2 communicate with each other using the same frequency band, each of them has the capability to apply the SIC and to sense the presence of PU. Let us consider the received base-band frequency signal at SUi's, ($i \in \{1, 2\}$), receiving antenna after applying the SIC operation as follows:

$$Y_i(m) = \zeta_{s_i}(m) + G_j(m)S_j(m) + \eta X_i(m) + W(m) \quad (1)$$

where the symbols in equation (1) are defined as follows:
$Y_i(m)$: the received signal at RX_i of SUi after applying the SIC in base-band,
$\zeta_{s_i}(m)$: the Residual Self Interference at SUi,
$S_j(m)$: the signal transmitted from the SUj transmitting antenna ($j \in \{1, 2\},\ i \neq j$),
η: channel indicator, $\eta = 1$ if the PU is active, $\eta = 0$ if PU is idle,
$G_j(m)$: the channel effect between the SUj transmitting antenna and RXi
$X_i(m)$: The PU signal including the channel effect between the PU base station and RXi.
$W_i(m)$: Additive White Gaussian Noise (AWGN) at SUi, with a zero mean and a variance σ_w^2.

Unlike FDC-CR, the term $G_j(m)S_j(m)$ is not present in the received signal of FDS-CR model since the SUs are communicating using FDD (separated channels) or FDD (different transmission time slots). Regarding HD-CR, both $G_j(m)S_j(m)$ and $\zeta_{s_i}(m)$ are not present in the received signal since HD communication is adopted beside the fact that SU stops the transmission during the Spectrum Sensing period. Thus, compared to FDS-CR and HD-CR, the term $G_j(m)S_j(m)$ represents a main limiting detection performance factor, which may prevent SUs from truly detecting the correct status of PU. This paper deals with this challenge by proposing a new detection mechanism that is adaptable to FDC-CR as seen in the next section.

III. Proposed Mechanism for Spectrum Sensing

The proposed mechanism is based on the fact that the two communicating SUs in the cognitive network are cooperative. Any Test Statistic applied on the received signal $Y_i(m)$ might be a function of $\zeta_{s_i}(m)$, $G_j(m)S_j(m)$, $X_i(m)$ in addition to $W_i(m)$. Despite a very limited cooperation made among SUs and PU (by sharing the cyclic frequency, the length of the Cyclic-Prefix, the knowledge of a pilot signal, *etc.*), SUs can be fully cooperating. In this context, assuming that an energy detector is applied on $Y_i(m)$, by assuming the independence among $\zeta_{s_i}(m)$, $G_j(m)S_j(m)$, $X_i(m)$ and $W_i(m)$:

$$E[|Y_i(m)|^2] = E[|\zeta_{s_i}(m)|^2] + E[|G_j(m)S_j(m)|^2] + \eta E[|X_i(m)|^2] + E[|W_i(m)|^2] \quad (2)$$

where $E[\cdot]$ stands for the expected value. The main objective of the energy detector is to differentiate between the SU-transmission-only case ($\eta = 0$) or the PU-plus-SU-transmission case ($\eta = 1$). Due to the presence of the SUj signal in the received mixture at RXi, the reliability of the energy detector will be strongly affected.

In order to overcome this limitation, we propose to eliminate the SUj energy term prior to make a decision on the channel state at SUi. Due to the statistical independence between $G_j(m)$ and $S_j(m)$, we can obtain the SUj energy term $E[|G_j(m)S_j(m)|^2]$ as follows:

$$E[|G_j(m)S_j(m)|^2] = E[|G_j(m)|^2]E[|S_j(m)|^2] \quad (3)$$

Eq. (3) can be estimated as follows:

$$E[|G_j(m)|^2]E[|S_j(m)|^2] \simeq \left[\frac{1}{N}\sum_{m=0}^{N-1}|G_j(m)|^2\right]\left[\frac{1}{N}\sum_{m=0}^{N-1}|S_j(m)|^2\right] \quad (4)$$

The term $\gamma_j = \frac{1}{N}\sum_{m=0}^{N-1}|S_j(m)|^2$ can be calculated at SUj when transmitting the N corresponding symbols. The value of this term is communicated with SUi via a reporting channel [12]. In contrast, the term $\phi_j = \frac{1}{N}\sum_{m=0}^{N-1}|G_j(m)|^2$ can be estimated based on the estimation of the channel between SUj and SUi.

Regarding the term γ_j, we assume that the SUj is transmitting with a constant power *i.e.* $E[|S_j(m)|^2] = \bar{\gamma}_j$. Assuming that $S_j(m)$ is *i.i.d* and a large number of samples N, the distribution of γ_j will follow a normal distribution with a mean μ and a variance V:

$$\mu = E[\gamma_j] = \bar{\gamma}_j \quad (5)$$

$$V = E[\gamma_j^2] - E^2[\gamma_j] = \frac{1}{N}\bar{\gamma}_j^2 \quad (6)$$

The distribution of γ_j is essential to quantize the transmit value of the energy of the transmitted signal from SUj to SUi through the reporting channel [12].

On the other hand, since the two communicating SUs adopt the same primary channel, so they can cooperate to monitor the PU status. As each SU performs the Spectrum Sensing at its part based on the provided term of energy γ_j, as explained above, the decision on the PU status can be made based on a soft or a hard combining scheme [13].

For the soft scheme, the two test statistics evaluated by the two SUs are linearly combined to obtain a final measure and compare it to a threshold in order to make the final decision on the PU status.

Regarding the hard combining scheme, each SU makes its own decision, then the two decisions are combined according to a logic rule.

The algorithm III summarizes the steps of our Spectrum Sensing mechanism at SUi.

Algorithm 1 Spectrum Sensing mechanism for FDC-CR

1. SUi estimate the channel between the transmitting antenna of SUj TXj and its receiving antenna RXi, and calculate the term ϕ_j.
2. SUj calculates the energy term $\gamma_j$and communicate it to SUi.
3. SUi calculates the energy of the received signal after applying the SIC
4. SUi should subtract the term $\phi_j\gamma_j$ from the calculated TS at SUi

Hard Scheme

5. Compare the calculated TSs to a appropriate threshold: if TS is greater than this threshold, then PU is active, otherwise PU is idle
6. The two decisions of the two communicating SUs is hardly combined using "And" or "Or"

Soft Scheme

5. Combine the calculated TSs at the two communicating SUs
6. Compare the combined TS to a appropriate threshold: if TS is greater than this threshold then PU is active, otherwise PU is idle

IV. Performance evaluation

To show the spectral efficiency of the proposed scheme, we evaluate the channel throughput in the secondary network, which is given as the sum of the throughputs of the two communicating SUs as they use the same channel to communicate:

$$R = R_{SU1} + R_{SU2} \quad (7)$$

Due to a missed detection, the ith SU ($i \in \{1, 2\}$) becomes active when PU is operating on the channel. The corresponding throughput is denoted by R_1^i and related to the interference caused by PU. On the other hand, SU can operate on the channel when a rejection[1] decision is made. In this case the throughput is denoted by R_0^i, which represents the gainful throughput of the secondary transmissions. Consequently, the throughput of each SU can be presented as follows:

$$R_{SU_i} = R_0^i + R_1^i \quad (8)$$

The two throughputs, R_1^i and R_0^i are given by [14]:

$$R_0^i = C_0^i\left(1 - p_{fa}\right)p_0 \quad (9)$$

$$R_1^i = C_1^i\left(1 - p_d\right)p_1 \quad (10)$$

where p_d and p_{fa} are the detection and false alarm probabilities respectively, p_0 and p_1 stand for the probabilities of absence and presence of PU in the channel respectively, and

[1]SU correctly detects the absence of PU.

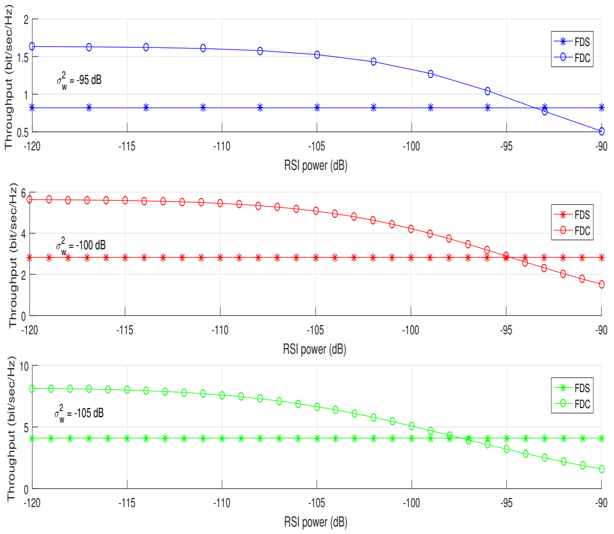

Fig. 3. Throughput of FDC-CR Vs. FDS-CR in terms of RSI power for several values of the noise power

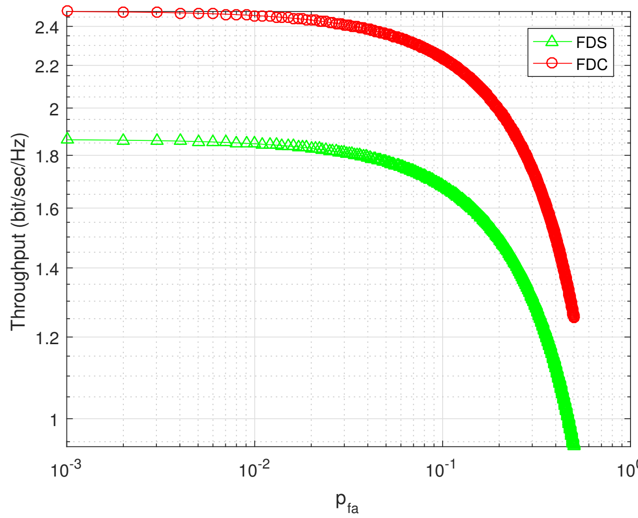

Fig. 4. The evolution of the channel throughput in terms of p_{fa} for $p_d = 0.9$ and $\sigma_w^2 = -100$ dB. SCS is adopted. σ_r^2 and σ_p^2 are fixed so that $\Delta_{PU} = \Delta_{RSI} = 0$ dB. The power of the received SU signal is considered as: $\Delta_{SU1} = \Delta_{SU2} = 5$ dB

C_0^i (resp. C_1^i) is the throughput of SUi operating under a rejection (resp. missed detection) decision.

A. Throughput Analysis

By assuming that SUs and PU signals are statistically independent and Gaussian, C_0^i and C_1^i are given by:

$$C_0^i = log_2(1 + \rho_r^i) \tag{11}$$

$$C_1^i = log_2(1 + \delta_r^i) \tag{12}$$

Where ρ_r^i is the signal to noise and RSI ratio at SUi, and it is given by:

$$\rho_r^i = \frac{E[|G_j(m)|^2]\bar{\gamma}}{\sigma_w^2 + \sigma_r^2} \tag{13}$$

where σ_r^2 is the RSI power.
δ_r^i is the signal to noise, RSI and the PU interference ratio:

$$\delta_r^i = \frac{E[|G_j(m)|^2]\bar{\gamma}}{\sigma_w^2 + \sigma_r^2 + \sigma_p^2} \tag{14}$$

where σ_p^2 is the power of the received PU signal at SUi.
As shown in equations (11) and (12), in FDC-CR the throughput is related to the power of RSI in addition to the noise and the interference, unlike FDS-CR, in which the throughput depends only on the noise and RSI power. Hereinafter, we show the impact of the RSI power on the throughput of the secondary network in FDC context.

Let us suppose that SU1 and SU2 receive the same power of PU signal, and have the same SIC capabilities. In other words, the same parameters are considered at the receiving antenna of SU1 and SU2, so that $R_0^1 = R_0^2$ and $R_1^1 = R_1^2$. The PU and the SU signal power values at the receiving antenna are fixed to -100 dB and -90 dB respectively. The detection and false alarm probabilities are fixed to 0.9 and 0.1 respectively, whereas $p_0 = 0.9$ and $p_1 = 0.1$ are considered.

Figure 3 shows the evolution of the channel throughput for the two schemes, FDC-CR and FDS-CR. As shown in this figure, the channel efficiency is doubled when adopting FDC compared to FDS for considered values of $\sigma_w^2 = -95$ dB, -100 dB and -105 dB when the RSI is at very low power ($\sigma_r^2 < -112$ dB). For a certain value of the RSI power, FDS becomes more efficient; as its throughput exceeds that of FDC (-93 dB for $\sigma_w^2 = -95$, -95 dB for $\sigma_w^2 = -100$ dB and -97 for $\sigma_w^2 = -105$ dB). Thus, RSI is considered as the main limiting performance factor of the secondary network throughputs. For that reason, the SIC capabilities at both communicating SUs should be efficient.

In order to show the impact of p_{fa} on the gain of the throughput in the channel, figure 4 shows the evolution of the channel throughput in terms of p_{fa} for a constant $p_d = 0.9$ for both FDS and FDC. The fixed value of p_d means that the interference induced by SUs on the PU due to a missed detection is the same for the two considered schemes FDC and FDS. The noise power is fixed at $\sigma_w^2 = -100$ dB as -100 dB is a typical value for that noise, and the RSI power is set equal to the noise floor as this level of RSI power is needed in the FD systems.
As expected, as p_{fa} increases the throughput decreases for FDC and FDS. However, the channel throughput of FDC remains higher than the one of FDS for all considered values of p_{fa}. This can be explained by the same probabilities of detection and false alarm considered for both FDC and FDS and the low power of RSI, which is at the noise floor. Thus the impact of RSI at this power level is reduced. On the other hand, despite the low power of RSI, it prevents the channel throughput related to FDC is not the double of that of FDS.

TABLE I
SNR DEFINITIONS

Δ_{PU}	SNR of the PU signal
Δ_{SUi}	SNR of the received SUi signal at the SUj receiving antenna
Δ_{RSI}	SNR of the RSI

B. Performance of Spectrum Sensing

Protecting PU from the interference of the secondary transmission is a main objective of the cognitive network. In addition to RSI, in FDC-CR the received secondary signal is also affecting the detection reliability. In this case, the primary transmission may interfere with the secondary transmission, and that leads to decrease the PU throughput.

The performance of the Spectrum Sensing is evaluated in figure 5. The noise and the RSI power values are fixed at -100 dB. $\Delta_{PU} = 0$ dB is considered at the two SUs (see table I for the SNR definitions). The channel between SU1 and SU2 is assumed to be perfectly estimated and the term γ is received via the reporting channel with a high precision. In our simulation, we assume that $\Delta_{SU1} = \Delta_{SU2}$ and the target false alarm rate is $p_{fa} = 0.1$.
Figure 5 shows the evolution of p_d in terms of Δ_{SUi}, $i \in \{1{,}2\}$. As long as the SU signal power increases, the probability of detection decreases. Due to the cooperation between the communicating SUs, the detection rate of FDC system is higher than that of FDS for low Δ_{SU} which means a more efficient protection of PU against the interference of secondary transmission. In contrast, When Δ_{SU} increases the detection rate decreases, which means that the interference amount of the secondary transmission increases. Here, the challenge becomes related to the optimal power of the SU signal, as low power leads to an efficient Spectrum Sensing process but low throughput, and high transmission power deteriorates the detection process but ensures a high channel throughput.

V. CONCLUSION

In this paper, the In-Band Full-Duplex cognitive communication system is proposed. In such a system, the two communicating Secondary Users (SUs) are simultaneously sending and receiving at the same primary frequency band in addition to performing the Spectrum Sensing while transmitting. A mechanism of Spectrum Sensing has been proposed for the proposed system in order to make it efficient, where the communicating SUs share their information concerning the calculated test statistics, based on which the Spectrum Sensing is performed.

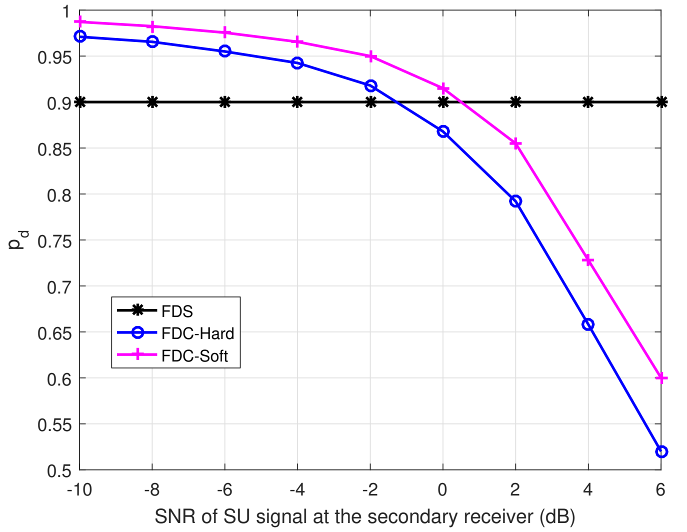

Fig. 5. The evolution of the probability of detection in terms of Δ_{SUi} for $p_{fa} = 0.1$, $\Delta_{RSI} = 0$ dB, $\Delta_{PU} = -7$ dB and N=1000 samples. The logic rule "Or" is used when hard combining scheme is adopted

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