Sensing and Utilization of Spectrum with Cooperation Interference for Full-Duplex Cognitive Radio Networks

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***Abstract*—Full duplex (FD) radios in cognitive radio (CR) networks enable secondary users (SUs) to perform sensing and transmission simultaneously, and improve the utilization of spectrum. In general, cooperation between the nodes enhances the detection performance through spatial diversity. However, secondary transmission co-exists with the cooperation procedure for FD-SUs, and degrades the sensing performance when secondary transmit power is high. In this paper, we propose the sensing framework for FD-SUs in a cooperative environment, and present the analytical formulation of sensing and utilization of spectrum (UoS) performance for FD-SUs. It is demonstrated that the self-interference, secondary transmit power, PU activity, number of cooperative users, and the sensing outcomes have a significant influence on the sensing and UoS performance.**

***Index Terms*—Cognitive radio, full duplex, utilization of spectrum, cooperative sensing.**

I. Introduction

Cognitive radio (CR) networks exploit the dynamic spectrum allocation (DSA) and spectrum diversity, and enhance the spectrum utilization efficiency. In CR networks, sum rate and the utilization of spectrum by users can be improved by choosing the optimal sensing operating points [1]. The full-duplex (FD)-enabled nodes can perform sensing and transmission simultaneously (in a given time-slot), and can use the spectral opportunity uninterruptedly and continuously [2]. Thus, FD-CR networks have a great potential to further enhance the efficiency of spectrum utilization and increase the overall network capacity. However, FD-CR networks are achieved with increased energy consumption and hardware complexity. The major limitation of FD mode is the self-interference (SI). The SI suppression (SIS) and SI cancellation (SIC) techniques help to implement the radical FD-CR systems. The performance of FD-radios highly depends on the SI mitigation capabilities. Excessive SI can lead to the reduced capacity even below that of half-duplex (HD) systems.

In this paper, we consider the cooperation-based sensing framework for FD-SU TXs. Unlike HD mode (which has TDMA based separation between the sensing and transmission procedures), sensing duration for FD-SU TXs is no longer limited, and can be extended to the entire frame duration. In such case, secondary transmission interferes the cooperation procedure, and degrades the sensing performance when secondary transmit power is high. We then formulate the utilization of spectrum (UoS) performance for different interference levels of secondary transmissions.

II. System Model

We assume that the activity of PU is modeled by a two-state (semi-) Markov process. The random variables representing the duration of OFF and ON states follow exponential distribution. Moreover, FD-SU TXs consist of imperfect SIS enabled two narrow-band antennas, i.e., receiving antenna ($Ant-1$) to perform the sensing, and transmitting antenna ($Ant-2$) to transmit when spectral opportunity is available [3]. The considered time-slotted frame structure for FD-SU TXs is shown in Fig. 1, in which sensing duration (in each frame) is divided into g consecutive short same-length sensing slots ($T_{S.0}$, $T_{S.1}$,... and $T_{S.g-1}$). The PU state is assumed to be consistent in each sensing slot. The number of samples in each sensing slot is N, and is expressed as M/g, where M is the number of total samples in each frame. The first sensing-slot (in each frame) is HD. If a PU is not detected, FD-SU TX initiates its transmission and sensing simultaneously. Otherwise, FD-SU TX do not transmit and continues to perform the sensing procedure until channel is available in the next frame. Similarly, if a PU is detected at the end of any FD sensing slot, FD-SU TX aborts its transmission until the next frame. The motivation behind the considered time-slotted frame structure is to account for tradeoff between the sensing efficiency and timeliness in detecting the PU [3]. The sensed signal during FD sensing slots is corrupted by a SI signal. We consider energy detection (ED) [4]–[6] method for sensing, and the sensing procedure is formulated for both (HD and FD) types of sensing slots.

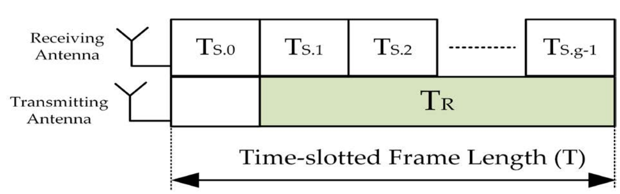

Fig. 1. Time-slotted frame structure for FD-SU TXs.

III. COOPERATION BASED SENSING FRAMEWORK FOR FD-SU TXS

We consider a PU-TX, a fusion center (FC), and k number of $FD-SUTXs$ ($FD-SUTX_1$, $FD-SUTX_2$,..., $FD-SUTX_k$), as shown in Fig. 2. In each time-slot, $FD-SUTXs$ perform sensing, and send sensing results to FC for a final decision [1]. There are two potential signal sources, i.e., PU-TX and $FD-SUTX_1$. Hence, we define four tests of hypothesis. The received signal at $FD-SUTX_1$ and at any other $FD-SUTX_i$ (i = 2,..., k) can be written as,

$$S_1(m) = \begin{cases} h_1 s_1(m) + g_1 s_2(m) + n_1(m), & H_{11} \\ g_1 s_2(m) + n_1(m), & H_{10} \\ h_1 s_1(m) + n_1(m), & H_{01} \\ n_1(m), & H_{00} \end{cases} \quad (1)$$

$$S_i(m) = \begin{cases} h_i s_1(m) + g_i s_2(m) + n_i(m), & H_{11} \\ g_i s_2(m) + n_i(m), & H_{10} \\ h_i s_1(m) + n_i(m), & H_{01} \\ n_i(m), & H_{00} \end{cases} \quad (2)$$

where $s_1(m)$, and $s_2(m)$ are m^{th} samples of PSK-modulated PU, and $FD-SUTX_1$ signals. $n_1(m)$, and $n_i(m)$ are m^{th} samples of complex Gaussian ($C.G.$) noise signals at $FD-SUTX_1$, and $FD-SUTX_i$. h_1, h_i, g_1 and g_i are $C.G.$ channel coefficients between PU-TX and $FD-SUTX_1$, PU-TX and $FD-SUTX_i$, $Ant-1$ and $Ant-2$ of $FD-SUTX_1$, and $FD-SUTX_1$ and $FD-SUTX_i$, respectively.

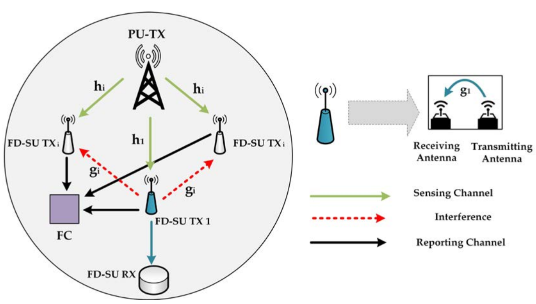

Fig. 2. System Model.

The test statistics T_i for ED scheme is expressed as,

$$T_i = \frac{1}{N} \sum_{i=1}^{N} |S_i(m)|^2 \quad (3)$$

Given $S_i(m)$, in any sensing slot, as i.i.d., and N large enough, PDF of T_i can be approximated by a Gaussian distribution using central limit theorem (CLT).

The description and statistical properties of T_1, and T_i are given in Table 1 & 2, respectively, where $\gamma_{p.1} = \frac{\sigma^2_{h_1}\sigma^2_{s_1}}{\sigma^2_{n_1}}$ is sensing SNR at $FD-SUTX_1$, $\gamma_1 = \frac{\sigma^2_{g_1}X^2\sigma^2_{s_2}}{\sigma^2_{n_1}}$ is INR at $FD-SUTX_1$ (due to its transmission). $\gamma_{p.i} = \frac{\sigma^2_{h_i}\sigma^2_{s_1}}{\sigma^2_{n_i}}$ is sensing

TABLE I
STATISTICAL PROPERTIES OF T_1

	PU-TX	$FD-SUTX_1$	Expected value	Variance
H_{00}	OFF	$Not\ Trans.$	$\sigma^2_{n_1}$	$\frac{\sigma^4_{n_1}}{N}$
H_{01}	ON	$Not\ Trans.$	$(1+\gamma_{p.1})\sigma^2_{n_1}$	$\frac{(1+\gamma_{p.1})^2\sigma^4_{n_1}}{N}$
H_{10}	OFF	$Trans.$	$(1+\gamma_1)\sigma^2_{n_1}$	$\frac{(1+\gamma_1)^2\sigma^4_{n_1}}{N}$
H_{11}	ON	$Trans.$	$(1+\gamma_1+\gamma_{p.1})\sigma^2_{n_1}$	$\frac{(1+\gamma_1+\gamma_{p.1})^2\sigma^4_{n_1}}{N}$

TABLE II
STATISTICAL PROPERTIES OF $T_i (i = 2, ..., k)$

	PU-TX	$FD-SUTX_1$	Expected value	Variance
H_{00}	OFF	$Not\ Trans.$	$\sigma^2_{n_i}$	$\frac{\sigma^4_{n_i}}{N}$
H_{01}	ON	$Not\ Trans.$	$(1+\gamma_{p.i})\sigma^2_{n_i}$	$\frac{(1+\gamma_{p.i})^2\sigma^4_{n_i}}{N}$
H_{10}	OFF	$Trans.$	$(1+\gamma_{2.i})\sigma^2_{n_i}$	$\frac{(1+\gamma_{2.i})^2\sigma^4_{n_i}}{N}$
H_{11}	ON	$Trans.$	$(1+\gamma_{2.i}+\gamma_{p.i})\sigma^2_{n_i}$	$\frac{(1+\gamma_{2.i}+\gamma_{p.i})^2\sigma^4_{n_i}}{N}$

SNR at $FD-SUTX_i$, and $\gamma_{2.i} = \frac{\sigma^2_{g_i}\sigma^2_{s_2}}{\sigma^2_{n_i}}$ is INR at $FD-SUTX_i$ due to the transmission of $FD-SUTX_1$.

The sensing performance either under the QoS constraint for PU or SU can be formulated [7]. We consider the sensing performance subject to a QoS constraint for PU, i.e., probability of detection is set at a desired value, and the probability of false alarm is obtained. Substituting the statistical properties under each hypothesis given in Table 1 & 2, receiver operating characteristics (ROCs) for local sensing at $FD-SUTX_1$ and $FD-SUTX_i$ $(i = 2, ..., k)$ (during HD and FD sensing slots) are given in equations (4) – (7),

$$PF_1^{HD} = Q\left[\frac{\sqrt{N(\gamma_{p.1}+1)^2}Q^{-1}\left(Pd_1^{HD}\right)+(N\gamma_{p.1})}{\sqrt{N}}\right] \quad (4)$$

$$PF_1^{FD} = Q\left[\frac{\sqrt{N(\gamma_1+\gamma_{p.1}+1)^2}Q^{-1}\left(Pd_1^{FD}\right)+(N\gamma_{p.1})}{\sqrt{N}(\gamma_1+1)}\right] \quad (5)$$

$$PF_i^{HD} = Q\left[\frac{\sqrt{N(\gamma_{p.i}+1)^2}Q^{-1}\left(Pd_i^{HD}\right)+(N\gamma_{p.i})}{\sqrt{N}}\right] \quad (6)$$

$$PF_i^{FD} = Q\left[\frac{\sqrt{N(\gamma_{2.i}+\gamma_{p.i}+1)^2}Q^{-1}\left(Pd_i^{FD}\right)+(N\gamma_{p.i})}{\sqrt{N}(\gamma_{2.i}+1)}\right] \quad (7)$$

where $Q(.)$, and $Q(.)^{-1}$ are the complementary distribution function of standard Gaussian and its inverse, respectively.

We assume that the local sensing results at FC, and FC decisions at $FD-SUTX_i$ are available instantly and concurrently at the end of each sensing slot. A logical combining rule (OR) is considered to combine the local sensing results. The OR rule increases the protection level to PU, but also results in the lower spectrum utilization [1]. The probabilities of FC decisions during HD, and FD sensing slots are $Pd_{FC}^{HD} = 1 - \prod_{i=1}^{k}(1 - Pd_i^{HD})$, $PF_{FC}^{HD} = 1 - \prod_{i=1}^{k}(1 - PF_i^{HD})$, and $Pd_{FC}^{FD} = 1 - \prod_{i=1}^{k}(1 - Pd_i^{FD})$, $PF_{FC}^{FD} = 1 - \prod_{i=1}^{k}(1 - PF_i^{FD})$, respectively.

IV. UTILIZATION OF SPECTRUM (UOS)

We present an analytical formulation of utilization of spectrum (UoS) scheme for FD-SU TXs. The UoS performance is evaluated by finding out the average number of sensing slots, (τ), used for the successful communication in each frame. The probability of detecting spectral holes in only first z number of sensing slots in each frame can be defined as,

$$P_H(z) = P_1(z) - P_2(z+1) \tag{8}$$

Here, $P_1(z)$ refers to possible scenarios where spectral opportunity is detected in greater or equal to z number of sensing slots. Similarly, $P_2(z+1)$ refers to possible scenarios where spectral opportunity is detected in greater or equal to $z+1$ number of sensing slots. Hence, $P_1(z)$ is expressed as,

$$P_1(z) = P_{OFF}\left(1 - PF_{FC}^{HD}\right)\sum_{j=1}^{z}\left(1 - PF_{FC}^{FD}\right)^j \tag{9}$$

The number of transmitted bits are adjusted as per the z number of sensing slots to consider same bit error rate (BER) in each frame. The probability of obtaining an errored secondary packet, owing to channel errors, is expressed as [3],

$$P_{error}(z) = 1 - \left[\left(1 - BER(\gamma_s)\right)^{zB}\right] \tag{10}$$

where zB is the packet size for z number of sensing-slots, γ_s is the SNR of the secondary transmission.

Thus, the average number of sensing slots (in each frame) used for the successful communication are expressed as,

$$\tau = \sum_{z=1}^{\infty} zP_H(z)\left(1 - P_{error}(z)\right) \tag{11}$$

V. RESULTS AND DISCUSSION

For numerical results, the set parameters are; zB=1000 bits for z=1, BER= 0.00025, X=.01, and secondary transmit power ($\sigma_{s_2^2}$) = [10dB, 20dB]. Fig.3 shows sensing performance during the HD (conventional) and FD sensing-slots. The sensed signals during FD sensing slots are corrupted with the SI signals. The influence of secondary transmission power over sensing performance is shown. The results illustrate that when transmit power is high, sensing performance suffers due to severe interference. Fig. 4 shows the UoS performance in term of average number of sensing slots used for successful communication (in each frame). The results validate the performance degradation in term of less number of transmitting sensing slots when transmit power (interference level) increases.

VI. CONCLUSION

In this paper, we considered the sensing framework for FD-SUs in a cooperative environment, and investigated the impact of secondary transmit power on the cooperation procedure, and hence on the sensing and UoS performance. The results validated a need to identify the optimal values of cooperative users and secondary transmit powers (subject to considered sensing parameters) for the optimal sensing and UoS performance.

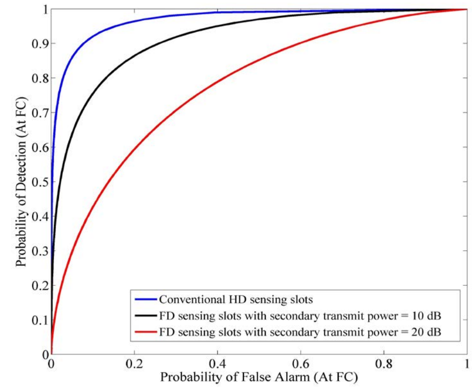

Fig. 3. Comparison of ROCs for different sensing slots, i.e., HD (conventional), and FD (with different secondary transmit powers).

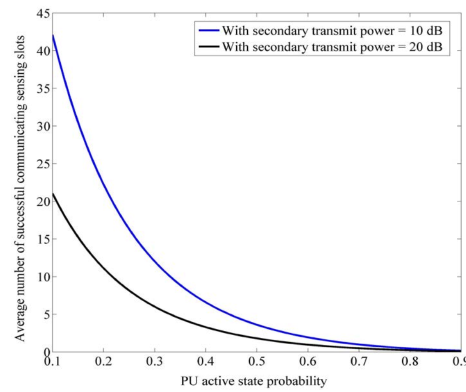

Fig. 4. Proposed UoS performance with different secondary transmit powers and PU active state probabilities.

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