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Simultaneous Transmitting-Receiving-Sensing for OFDM-based Full-Duplex Cognitive Radio

A. Nasser, A. Mansour, K. C. Yao

Abstract

In this paper, a Transmitting-Receiving-Sensing (TRS) mode of OFDM-based Full-Duplex Cognitive Radio (FD-CR) is proposed. The new mode aims at monitoring the Primary User (PU) activities on the operating channel while establishing an in-band full-duplex communication between two communicating Secondary Users (SUs), $i.e.$ SUs transmit and receive simultaneously on the same frequency band. Assuming that the primary activity covers all the operating band when PU is active, Spectrum Sensing is performed on some Sub-Carriers (SCs) which are neutralized by the two communicating SUs. Letting some SCs null by both SUs helps to accurately performing the spectrum sensing on these SCs since no residual self-interference neither secondary transmission are present. When PU is detected on these SCs, then we consider that he becomes active again; Then SUs should vacate the channel. For the proposed mode, false alarm, detection and collision probabilities are derived in addition to the throughput rate. An optimal selection of the sensing SCs per OFDM symbol is derived with respect to a maximal tolerable rate of collision between PU and SU transmission. Numerical results corroborate the effectiveness of our proposed mode in terms of the PU awareness and the secondary throughput rate.

Keywords

Cognitive Radio, Simultaneous Transmitting-Sensing-Receiving, In-Band Full-Duplex, Collision-Throughput Optimization, OFDM.

I. INTRODUCTION

Cognitive Radio (CR) is a key technology in the upcoming new telecommunication generations [1]–[4]. CR aims to an efficient use of the spectrum by sharing it between two kinds of users:

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Primary User (PU) and Secondary User (SU). SU can access the channel as long as PU is absent. However, when PU returns active SU must vacate the channel. Monitoring of PU activity is performed by the spectrum sensing part of CR.

In the classical mechanism of the spectrum sensing, namely known as the Half-Duplex CR (HD-CR), the activity period is divided into two parts: the first one is reserved for the spectrum sensing and the second one for the transmission [5]. SU should stop its transmission during the sensing operation time, in which a test statistic such as the energy of the received signal is compared to a threshold in order to detect the PU status. If PU is idle, then SU transmits its data.

Dedicating a part of SU's activity period for only sensing the channel affects its throughput and may increase the collision time with PU, as PU can return active during the transmission period where no sensing is performed. To avoid this shortcoming, Transmitting-Sensing (TS) CR paradigm has been recently proposed to simultaneously perform transmitting and sensing [6]. TS requires Self-Interference Cancellation (SIC) techniques; SIC let two communicating peers establish an In-Band Full-Duplex (IBFD) communication [7]. By adopting SIC, the receiver circuit can highly suppress the known Self-Interference (SI) generated by the transmitter in order to purely obtain the signal of interest. SIC is generally adopted in CR during the TS mode to minimize the effect of the SI on the received signal. This technique helps SU to be able to detect the noisy PU signal without stopping the SU's transmission. However, due to the imperfect SIC, the minimization of the residual self-interference remains a challenge to obtain a reliable decision on the channel status [8]–[10].

Besides TS, Transmitting-Receiving (TR) paradigm is proposed to establish an IBFD communication between two communicating SUs. This paradigm is based on the interference sensing, when SUs become unable to decode their messages because of the PU interference, then they should vacate the channel. The main advantage of this paradigm is its ability to establish the IBFD communication between two SUs using only one channel unlike TS, which needs two available primary channels. In contrast to TS, TR has poor sensing capabilities, which leads to increase the collision probability with PU [11], [12].

In this paper, a new paradigm for the OFDM-based CR is presented. This paradigm provides the cognitive system with the ability of Transmitting, Receiving, and Sensing (TRS) simultaneously. Thus, our system allows IBFD communications between two SUs using only one channel while keeping sensing the PU on that channel. By assuming that the primary signalling covers all the channel bandwidth, this bandwidth is divided into K Sub-Carriers (SCs), K_d among them are dedicated for the data transmission and they are called Data SCs, while the remaining $(K_s = K - K_d)$ SCs are for the spectrum sensing and they are called Sensing SCs (SSCs)[1], where both SUs should avoid them to perform the spectrum sensing continuously over time. When PU returns active, it will appear on these K_s SCs, then SUs could detect its activity on the overall channel bandwidth.

The main contributions of our study can be summarized as follows:

- New TRS mechanism is proposed for OFDM-based CR allowing the SUs to carry out an efficient spectrum sensing while establishing an IBFD communication.
- The false alarm and detection probabilities are derived at each SU side and for the secondary system due to the cooperation between the two communicating SUs in carrying out a final decision on the PU status.
- Given a maximum collision rate, an optimization of the number of SSCs per OFDM symbol is evaluated.
- The mean capacity of the CR system is derived under two strategies optimizing the secondary throughput while keeping the sensing. These strategies lead to compensate the transmission rate loss due to the dedication of some SCs for spectrum sensing.

The rest of this paper is organized as follows: section II presents a brief literature review on the CR paradigms recently proposed based on the IBFD techniques. Our system model is detailed in section III. In section IV, the sensing mechanism with its parameters are discussed and the optimal number of SSCs is derived. To set the number of SSCs per OFDM symbol given a tolerable probability of collision, a mathematical study is carried out in section V. Strategies on selecting the SSCs are discussed in section VI, where the associated data throughputs are analytically derived. Numerical results presented in section VII corroborate the efficiency of our proposed paradigm compared to existing ones. Section VIII concludes our work.

[1]Throughout the paper Sensing SCs and Null SCs are synonym

TABLE I: Table of Abbreviations and Acronyms

Notation	Description
AWGN	Additive White Gaussian Noise
CR	Cognitive Radio
CS	Channel Switching
FD	Full-Duplex
HD	Half-Duplex
IBFD	In-Band Full-Duplex
OFDM	Orthogonal Frequency Division Multiplexing
PU	Primary User
SC	Sub-Carrier
SI	Self-Interference
SIC	Self-Interference Cancellation
SO	Sensing Only
SNR	Signal to Noise Ratio
SSC	Sensing Sub-Carrier
SU	Secondary User
TRS	Tranmitting-Receiving-Sensing mode
TR	Tranmitting-Receiving mode
TS	Tranmitting-Sensing mode
B	Bandwidth of one sub-carrier
C_0	Channel capacity under H_0
C_1	Channel capacity under H_1
D	Binary decision $\in [0; 1]$ on the PU status of the secondary network
D_i	Binary decision $\in [0; 1]$ on the PU status at the SUi, $i \in \{1, 2\}$
$E[x]$	Expected value of x
$Ei(\cdot)$	Exponential integral
$f_x(x)$	Probability density function of x
H_0	Hypothesis that PU is absent

TABLE I: Table of Abbreviations and Acronyms

Notation	Description
H_1	Hypothesis that PU is active
K	Number of sub-carriers per OFDM symbol
K_s	Number of sensing sub-carriers per OFDM symbol
K_s^*	Optimal number of sensing sub-carriers
K_d	Number of data sub-carriers per OFDM symbol
L	Number of received OFDM symbol per SUs' time slot
N	Total number of sensing sub-carriers
OR	Logic OR function
$p_{d,i}^s$	Probability of detection at the SUi in the stage $s \in \{0,1\}$
P_c	Probability of Collision
P_d^s	Probability of detection of the secondary network in the stage $s \in \{0,1\}$
$p_{fa,i}^s$	Probability of false alarm at the SUi in the stage $s \in \{0,1\}$
P_f^s	Probability of false alarm of the secondary network in the stage $s \in \{0,1\}$
$Pr\{z\}$	Probability of the event z
$Q(\cdot)$	Gaussian Q-function
R	Throughput at the secondary network
R_0	Throughput at the secondary network under H_0
R_1	Throughput at the secondary network under H_1
$R_0^{(1)}$	Expected useful throughput under the strategy (S1)
$R_0^{(2)}$	Expected useful throughput under the strategy (S2)
s	$s \in \{0,1\}$: $s=0$ for the initializing stage and $s=1$ for the communicating stage.
$S_k(m)$	Secondary received data signal at the kth SC
T	Duration of SU time slot
T^*	Optimal duration of SU time slot
T_{min}	Minimal sensing duration
t_{sc}	Duration of one OFDM sub-carrier
$U_k(m)$	Residual Self-Interference at the SC k

TABLE I: Table of Abbreviations and Acronyms

Notation	Description
$W_k(m)$	Additive White Gaussian Noise at the kth SC
$X_k(m)$	PU signal at the kth SC
$Y_k(m)$	Received signal at the kth SC
α	Average holding time of PU absence
β	Average holding time of PU presence
$\bar{\gamma}$	Average SNR of the sub-carriers
γ_k	SNR at the sub-carrier k
λ	Decision threshold
μ	Probability that PU appears in a given time slot
ν	Probability that PU disappears in a given time slot
Ω_d	The set of data SC
Ω_s	The set of sensing SCs
Υ	Measured Energy of the received signal
ζ	Channel indicator: $\zeta = 0$ when PU is idle and $\zeta = 1$ elsewhere

II. Full-Duplex Cognitive Radio: Literature Review

IBFD is a promising candidate for 5G and beyond and it has been applied in several upcoming communication techniques such as Massive MIMO, Device-to-Device and CR [6], [13]–[18]. IBFD, which is mainly based on SIC, has been recently proposed in order to double the throughput over a frequency band due to the capability of the transceiver to send and receive simultaneously over the same frequency band [2], [7], [18]–[20]. SIC techniques have been recently extended to the CR applications and adopted at the spectrum sensing stage. In fact, SIC can be performed for exploiting the TS paradigm in which the SU can establish the sensing of PU while transmitting over the same band [6], [21]–[25]. In classical cognitive radio paradigm, the spectrum sensing is performed periodically [5], [21]. Subsequently, during the sensing period SU becomes idle in order to do not corrupt the spectrum sensing decision.

Consequently, adopting SIC in CR leads to two main advantages:

1) Enhance the SU throughput since no silence period is required.
2) Decrease the collision time between an active PU and SUs due to the continuity of the spectrum sensing period.

However, the SIC has been used by CR mainly to make a TS paradigm and not to make an IBFD communication between the communicating SUs. Therefore, to establish a bidirectional communication between two SUs, two available channels should be sensed to ensure a channel for the transmission of each SU.

The TS mode performance is studied in [26]. The false alarm, detection and collision probabilities are derived when adopting TS mode. In addition, a power-throughput trade-off under TS mode is developed where the optimal transmitting power is found in order to meet a satisfying sensing accuracy and a high throughput.

In [12], [22], [27], the authors derive the optimal functioning mode of the secondary network among several modes such as: Sensing only (SO), TS, TR and channel switching (CS). SO stands for the case where SU seeks for an available primary channel while CS is the mode of handoff when the adopted channel is affected by the primary interference and SU is forced to switch to another channel. In addition, the authors proposed a strategy in order to switch from a mode to another one, especially from TS to TR.

In [28], the TR mode is studied under the scenario of an imperfect SIC. Once the SUs starts communicating, PU is monitored based on the capability of SUs to decode their messages. When a PU reappears and collides with SUs transmission leading to corrupt the received signals resulting in undecoded messages.

TR mode proposed in [12] and [28] may fail in detecting the signal of the PU if its Signal to Noise Ratio (SNR) is relatively low since the SUs remains capable to decode their messages.

In [11], the authors extended the work of [28], where the SUs operates adaptively in three modes: TR, TS or SO. The switching from TR to TS and *vice versa* is based on the SNR of the PU measured at SUs. If the SNR of an active PU is high then SUs should operate in TR mode. In this case, the PU activity can be detected since SUs become unable to decode their messages due to the PU interference. However, a weak PU SNR incites the SUs to switch to TS mode in order to avoid a harm collision with the PU. Nevertheless, this strategy depends on a good estimation of the PU's SNR, which may be affected by the channel condition such as shadowing or fading.

In [29], a new Transmitting-Receiving-Sensing mode is proposed in order to maintain the TR mode with an efficient capability to monitor PU activity. This mode is based on exchanging the measure of the energy of transmitted signals between two communicating SUs. Each SU subtracts the known energy of the signal of its peer from the overall energy of the received signal to obtain the noise energy when PU is absent, or the PU signal plus the noise energies when PU becomes active. However, this proposed mechanism suffers from an unreliable sensing results for a high SNR of SU signal.

The IBFD communication remains a challenging issue in CR due to the need of the spectrum sensing, which is affected in IBFD case by the received signals of the peer SU. The techniques of SIC become useless due to the fact that the received signal of the peer SU is unknown. In TR mode, there is a lack in the PU monitoring mechanism; And in TRS mode as in [29], the sensing becomes highly corrupted by the received secondary signal.

In a related work dealing with the energy harvesting in CR, the authors of [30] proposed a win-win strategy of cooperation among SUs and PU; Where a PU, using OFDM standard, lets SUs transmit on the channel at the cost of harvesting their energies. In addition, when PU re-transmits on the channel it keeps some SCs null allowing SU to remain active over them.
In our work, it is the SUs who make some null SCs in order to sense the PU activity over them. This strategy results in TRS mode for the CR leading to IBFD for OFDM-based SUs. TRS mode provides the CR with the ability of using one available channel instead of two to make a bidirectional communication between two SUs. This fact may positively impact the secondary throughput. In turn, PU is sensed using the null SCs, since the primary transmission might cover the operating band.

III. System Model

Hereinafter, the adopted model of cognitive radio network considers SUs seeking to establish a communication between each other using the frequency band of PU. We consider that the SU should communicate using OFDM modulated signal having a total of K SCs per OFDM symbol: K_d among them are allocated for the data transmission and K_s are dedicated to perform the spectrum sensing. On those K_s SCs, there is no secondary transmission, $i.e.$ the two communicating SUs avoid those SCs[2]. The transmission of an active PU is assumed to cover all the K SCs. Consequently, the frequency-domain received signal $Y_k(m)$ at the secondary receiving antenna in the kth SC can be modelled as follows:

$$Y_k(m) = \begin{cases} \zeta X_k(m) + W_k(m); & k \in \Omega_s \\ \zeta X_k(m) + S_k(m) + U_k(m) + W_k(m); & k \in \Omega_d \end{cases} \tag{1}$$

where $X_k(m)$ stands for the PU received signal at the kth SC, $U_k(m)$ represents the residual SI and $W_k(m)$ is an Additive White Gaussian Noise (AWGN) at the kth SC. ζ is the channel indicator, $i.e.$ $\zeta = 0$ (hypothesis H_0) when PU is idle and $\zeta = 1$ (hypothesis H_1) elsewhere. $S_k(m)$ is the secondary received data at the kth SC. Ω_d and Ω_s are two sets of SCs dedicated for transmission and sensing respectively, where:

$$\Omega_s \cap \Omega_d = \emptyset \text{ and } K_s + K_d = K \tag{2}$$

where $K_s = card\{\Omega_s\}$ and $K_d = card\{\Omega_d\}$, and $card\{\cdot\}$ stands for the cardinality. As shown in equation (1), the SU transmission is not present along with the residual SI, since no secondary transmission is performed at the SC $k \in \Omega_s$ which is reserved for the sensing operation. In addition, equation (2) implies that there is no SC allocated for both sensing and transmitting.

A. *Initializing stage*

Initialized at a mode where no transmission is made neither a detection of an available band, the secondary network starts by sensing the primary channel. Both SU1 and SU2 cooperate to make a decision on the channel status. A test statistic is carried out by each of them based on the observations of the channel. Each of SUs makes a decision by comparing its test statistic to

[2]In case more than two SUs are communicating, they should be cooperative so that they avoid transmitting on the SSCs to monitor the PU's activity.

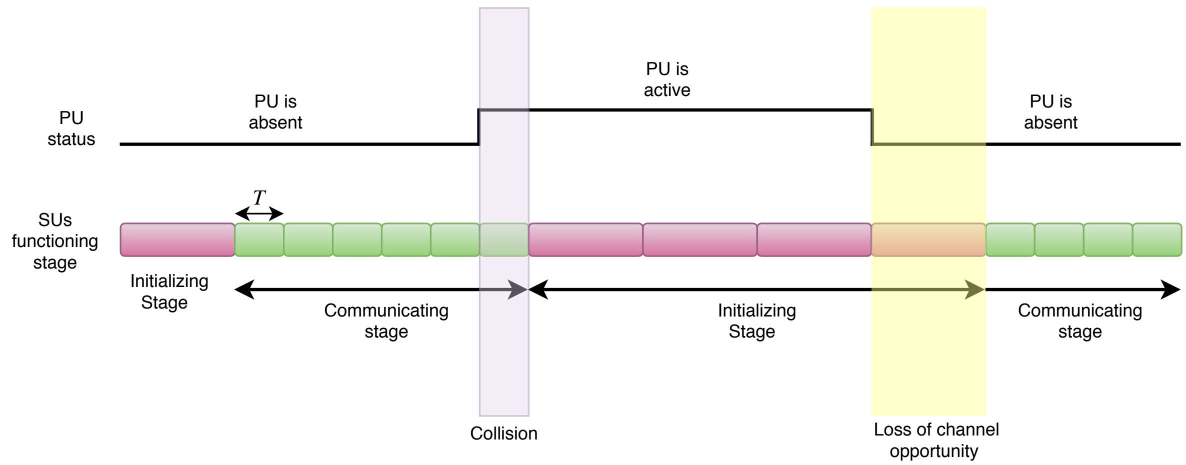


Fig. 1. SUs functioning stages under the proposed scheme: Initializing stage when SUs are seeking for an available channel and communicating stage when SUs are active. The figure also depicts both the unavoidable collision and channel opportunity loss.

a threshold. Then, the SUs exchange their data by combining them using the logic OR decision rule:

$$D = OR(D_1, D_2), \tag{3}$$

where D_i is the binary decisions made by the ith SU and D is the secondary decision. Therefore, in our system, the PU is assumed active ($i.e.$ $D = 1$) when one or two of the communicating SUs output '1' in the sensing decision. At the initial stage, all the SCs ($i.e.$ $K_s + K_d$) are used to evaluate the test statistic in order to make a fast and reliable detection of an idle channel.

B. Communicating stage

Once an idle primary channel is detected, the two SUs transmit their data under an IBFD. At this stage, the spectrum sensing is performed over only K_s SCs out of K in order to monitor the return of PU. At the end of each time slot T which holds L OFDM symbols, SUs exchange their detection decisions in order to make a final decision on the PU status by Oring their decisions as presented in equation (3).

Figure 1 describes the functioning mechanism of the proposed scheme. An IBFD communication with a simultaneous spectrum sensing is started once the primary channel is detected as idle. At the end of each operation slot T, SU1 and SU2 exchange their decisions in order to reach a final decision on the opportunity of the channel. If PU becomes again active, then SUs returns to an initialization stage. Even if the detection performance evaluation indexes ($i.e.$ the false alarm and the detection) are perfect, the collision between the secondary and the primary transmissions, and the loss in the opportunity of the channel are unavoidable due to the unpredicted return or departure of PU.

IV. Sensing Mechanism

As addressed earlier, the IBFD communication is started once a free channel is detected. Therefore, some SCs have to be nulls at the two communicating SUs. As shown in figure 2, a set of SCs has to be free of secondary transmissions. Avoiding these SCs helps the SUs to detect the PU activity on these SCs. On the other side, since the two communicating SUs use the same frequency band, then they can share their detection information in order to enhance the spectrum sensing reliability. The cooperation between SUs enhances the detection accuracy and leads to decrease the number of samples needed to make a decision on the channel status. Consequently, this allows the reduction of the number of null SCs booked for spectrum sensing.

In this paper, the Energy Detector is deployed to perform the spectrum sensing. The estimated energy Υ of the received signal at the sensing $N = LK_s$ SCs is evaluated as follows:

$$\Upsilon = \frac{1}{N}\sum_{l=1}^{L}\sum_{k\in\Omega_s}|Y_k(m)|^2, \tag{4}$$

where L is the number of OFDM symbols within a spectrum sensing period. If Υ is higher than a threshold λ then PU is assumed to be active.

A. False Alarm and Detection probabilities

A False Alarm happens at SU1 or SU2 when PU is absent but the measured energy Υ is greater than a certain threshold λ:

$$p^s_{fa,i} = Pr\{D_i = 1|\text{PU is absent at the stage } s\}, \tag{5}$$

where $p^s_{fa,i}$ is the false alarm probability at SUi, $i \in \{1, 2\}$, and the upper-script s refers to the operating stage: $s = 0$ at the initializing stage or $s = 1$ for the communicating stage.

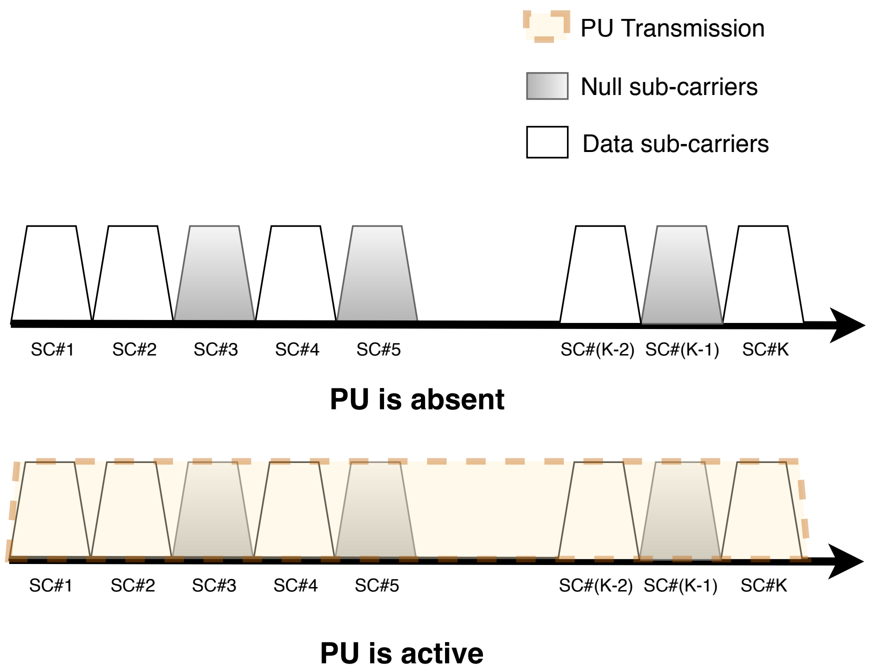


Fig. 2. The SCs partitioning of secondary transmissions. The null SCs are dedicated for the spectrum sensing.

Given that the detection decisions of SUs are independent on SUs, the overall false alarm P_f^s of the system becomes [31]:

$$P_f^s = 1 - \left(1 - p_{fa,i}^s\right)^2. \tag{6}$$

Similarly, the overall detection probability P_d^s of the system at the stage s can be derived as follows [31]:

$$P_d^s = 1 - \left(1 - p_{d,i}^s\right)^2, \tag{7}$$

where $p_{d,i}^s$ is the detection probability at SUi, $i \in \{1, 2\}$ at the stage s, $s \in \{0, 1\}$ Assuming that $Y_k(m)$ symbols are independent over the index k, then Υ becomes asymptotically Gaussian distributed for a large N according to the central limit theorem [32]. Consequently, $p_{fa,i}^s$ and $p_{d,i}^s$ can be presented as follows [33]:

$$p_{fa,i}^s = Q\left(\sqrt{N}\left(\frac{\lambda}{\sigma_W^2} - 1\right)\right), \tag{8}$$

$$p_{d,i}^s = Q\left(\sqrt{N}\left(\frac{\lambda}{\sigma_X^2 + \sigma_W^2} - 1\right)\right), \tag{9}$$

where σ_W^2 and σ_X^2 stand for the variances of the noise and the PU signal respectively.

B. Optimal Number of Sensing Sub-Carriers and Minimal Sensing Duration

As our proposed strategy mainly concerns the communicating stage ($i.e.\ s = 1$), for a target (P_f^1, P_d^1) of the secondary system, one can find the target $(p_{fa,i}^1, p_{d,i}^1) = (\rho, \theta)$ at each SU based on equations (6) and (7) assuming that $p_{d,1}^1 = p_{d,2}^1$ and $p_{fa,1}^1 = p_{fa,2}^1$. These target probabilities lead to set the optimal number of samples N used in the sensing process using equations (8) and (9) as follows [34]:

$$N = \left(\frac{(\sigma_X^2 + \sigma_W^2) Q^{-1}(\rho) - \sigma_W^2 Q^{-1}(\theta)}{\sigma_X^2} \right)^2. \tag{10}$$

Finding N leads to determine the number of null SCs per OFDM symbol. This number is related to the throughput and the collision probability between secondary and primary transmissions. As the number of null SCs per OFDM symbol decreases the throughput increases, but this may lead to increase the collision duration.

Subsequently, when fixing the optimal N, T should not be smaller than T_{min}:

$$T_{min} = \frac{t_{sc}}{K} N, \tag{11}$$

where t_{sc} is the duration of one OFDM SC. Here, all the SCs are assigned to sensing, so no transmission is performed by both SUs.

V. Collision and Throughput Analysis

In this section, we analyse the collision probability of the proposed TRS mode and the throughput of the secondary network adopting it. Such an analyse guides us to set the optimal number of SSC per OFDM symbol with respect to a tolerable collision probability and maximize the SUs throughput.

A. Collision Analysis

The collision between SUs and PU may happen in the two following cases:

1) When SUs falsely decide that PU is absent, then a missed detection occurs at a time slot i and PU remains active at $i+1$

2) When PU becomes active again during the SUs transmission at the time slot $i+1$ while it was absent at the time slot i.

Let α and β be the holding time of absence and transmission of PU respectively. Accordingly, the probabilities that PU appears or disappears in a given time slot T, are given by:

$$\mu = 1 - \exp\left(-\frac{T}{\alpha}\right) ; \nu = 1 - \exp\left(-\frac{T}{\beta}\right); \tag{12}$$

The sensing time T is assumed to be much smaller than α and β, so we can approximate μ and ν at the first order as follows:

$$\mu \simeq \frac{T}{\alpha} ; \nu \simeq \frac{T}{\beta}; \tag{13}$$

As given in [26], the probability of collision within a time slot T during the communicating stage is presented in equation (14):

$$P_c = \frac{\nu}{2} + \frac{(1-P_d^0)(1-\xi\Delta) + (1-P_f^0)r}{(1-\xi\Delta)\omega + \xi r}, \tag{14}$$

where $r = \nu/\mu$, $\Delta = 1 + r - 1/\mu$, $\xi = 1 - P_f^0 + P_f^1$ and $\omega = 1 - P_d^0 + P_d^1$.
Note that P_d^1 and P_f^1 are evaluated with fixed N SSCs within $T \geq T_{min}$ and K_s can be obtained as follows:

$$K_s = \frac{N}{L} = \frac{N t_{sc}}{T}. \tag{15}$$

As per equation (15), the duration T affects the density of K_s per each OFDM symbol. Furthermore P_d^1 and P_f^1 becomes independent of T under the condition $T \geq T_{min}$, and P_c is an increasing function with respect to T. Using equations (13-14), the derivative of P_c under the constraint $T \geq T_{min}$ is given by:

$$\frac{\partial Pc}{\partial T} = \frac{\alpha^2\beta\xi\left(\omega(1-P_f^0) - \xi(1-P_d^0)\right)}{\Big(\beta\omega(\xi-1)T - \alpha\xi(\beta\omega - \omega T + T)\Big)^2} + \frac{1}{2\beta}. \tag{16}$$

As $\omega(1-P_f^0) - \xi(1-P_d^0) = P_d^1(1-P_f^0) - (1-P_d^0)P_f^1$ and in real CR systems $P_d^i > 0.5 > P_f^i \ \forall \ i \in \{0,1\}$, therefore $\dfrac{\partial Pc}{\partial T} > 0$ and P_c becomes an increasing function of T. Later on the optimal number of the OFDM symbols within T is derived subject to a tolerable collision probability P_c^{max}.

The collision probability, P_c, is related to three time-dependent parameters: directly to T, and indirectly to N and K_s, since P_d^1 and P_f^1 are functions of N.
For a target number of samples N as in equation (10), the density of SSC per OFDM symbol, K_s, becomes related to the number of OFDM symbols per slot and subsequently to T. The challenge becomes how to set T that abides an allowable probability of collision P_c^{max} and maximizes at the same time the throughput R of SUs.

B. Throughput Analysis

Regarding the throughput R, we analyse the situations of active SUs. In addition to the ones listed is the previous subsection when a collision happens, a third one should be highlighted: the SUs detect the absence of PU and transmit within T without any interference to PU. Given that both SU1 and SU2 are active at a time slot T: the throughput R at the secondary networks can be presented as follows:

$$R = C_0(1 - P_c) + C_1 P_c, \tag{17}$$

where C_0 and C_1 are the channel capacity of SUs under H_0 and H_1 respectively and are given respectively as follows [34]:

$$C_0 = 2B \sum_{k \in \Omega_d} \log_2 (1 + \gamma_k), \tag{18}$$

$$C_1 = 2B \sum_{k \in \Omega_d} \log_2 (1 + \Gamma_k), \tag{19}$$

where γ_k and Γ_k stand for the signal to noise and interference ratio at the SC k under H_0 and H_1 respectively, and B is the bandwidth of each SC. When SUs are active, they operate with a capacity C_1 when a collision happens with PU and with a capacity C_0 in case of no collision. The factor 2 at the beginning of equations (18) and (19) is due to the transmission of both SU1 and SU2 at the same channel. The throughputs C_0 and C_1 are related to the cardinal K_d of Ω_d. As K_d increases both C_0 and C_1 increase. In order to maximize K_d, T should be maximized as possible since $K_s = \frac{t_{sc}}{T} N$ and $K_s + K_d = K$.
In order to find the optimal number K_s^* of SSCs per OFDM symbol and the optimal SUs time slot T^*, K_s^* and T^* should satisfy the condition of maximizing the throughput of SUs subject

to do not exceed a P_c^{max}.

$$
\begin{aligned}
(K_s^*, T^*) &= \underset{K_s, T}{\text{argmax}} \; R(K_s, T) \\
\text{subject to } & P_c(T) \le P_c^{max}, \\
& K_s > 0 \\
& T \ge T_{min}.
\end{aligned} \quad (20)
$$

Since the most important issue for the secondary network is to protect the primary transmission from the secondary interference, K_s^* should be found based on the maximum duration of the allowable time slot of SUs. As P_c is an increasing function of T, T^* should satisfy:

$$P_c(T^*) \le P_c^{max}. \quad (21)$$

As the system uses N SSCs as in equation (10), then the optimal number of SSCs per OFDM symbol , K_s^*, can be derived as:

$$K_s^* = \lceil \frac{N}{L^*} \rceil = \lceil \frac{t_{sc}}{T^*} N \rceil, \quad (22)$$

where $\lceil n \rceil$ is ceiling operator, $i.e.$ the first integer greater than or equal to n.
A challenge that may face the implementation of our system is when $K_s^* > K$ or $T_{min} > T^*$. In other words, the sensing time is greater than the maximal tolerable collision time. However, this challenge is common for all cognitive radio systems based on the spectrum sensing.

VI. Null Sub-Carriers Selection

It is assumed that one of the communicating SUs plays the role of a master node while the another is a slave one. The master node decides the SSCs' positions and sends the indexes of these SCs to the slave node before establishing the communication.
Regarding the position of the SSCs of SUs, it can be done based on two strategies:
1- (S1) these SCs are randomly selected.
2- (S2) they are selected according to the channel state.
In the second strategy, the SNR at each SC is measured prior to establishing the connection between the two SUs, then the K_s^* SCs corresponding to the K_s^* worst SNRs are reserved for sensing ($i.e.$ they are not considered for transmission):

$$[k_1, k_2, ..., k_{K_s}] = \underset{\gamma_k}{\text{argmin}} \; R(\gamma_k). \quad (23)$$

Reserving the worst K_s^* SCs for spectrum sensing may compensate the bandwidth loss due to making some SCs null, unlike the strategy (S1) where the null SCs are randomly selected. Hereinafter, we will derive the expected value of the throughput under the two strategies in order to show the superiority of the second strategy (S2) over the first one (S1).

We assume that all the SCs exhibit the same Rayleigh fading as this model is widely used in the literature [35]–[38], then the distribution of SNR at each SC can be modelled by:

$$f_{\gamma}(\gamma) = \frac{1}{\bar{\gamma}} \exp\bigg(- \frac{\gamma}{\bar{\gamma}} \bigg), \tag{24}$$

where $\bar{\gamma}$ is the average SNR.

According to equation (17), $R = R_0 + R_1$, where $R_0 = C_0(1 - P_c)$ is the useful throughput when PU is absent and $R_1 = C_1 P_c$ is the throughput during the interference between SUs and PU.

Concerning the first strategy (S1), the expected useful throughput $\bar{R_0}^{(1)}$ is found as:

$$\begin{aligned} E[R_0^{(1)}] &= 2B(1 - P_c) E\bigg[\sum_{k \in \Omega_d} \log_2 (1 + \gamma_k) \bigg] \\ &= 2B(1 - P_c) \sum_{k \in \Omega_d} E[\log_2 (1 + \gamma_k)]. \end{aligned} \tag{25}$$

Knowing that:

$$E[\log_2 (1 + \gamma_k)] = \int_0^{+\infty} \log_2 (1 + \gamma_k)\, f_{\gamma_k}(\gamma_k) d\gamma_k. \tag{26}$$

equation (25) becomes::

$$\begin{aligned} E[R_0^{(1)}] &= 2B(1 - P_c) \sum_{k=1}^{K_d} \int_0^{+\infty} \log_2 (1 + \gamma_k)\, f_{\gamma_k}(\gamma_k) d\gamma_k \\ &= 2B(1 - P_c) \sum_{k=1}^{K_d} \int_0^{+\infty} \frac{1}{\bar{\gamma}} \log_2 (1 + \gamma_k) \exp(-\frac{\gamma_k}{\bar{\gamma}}) d\gamma_k. \end{aligned} \tag{27}$$

Using the integration by parts method, equation 27 becomes:

$$E[R_0^{(1)}] = \frac{2B(1 - P_c)}{\ln 2} \sum_{k=1}^{K_d} \int_0^{\infty} \frac{1}{1 + \gamma_k} \exp\bigg(- \frac{\gamma_k}{\bar{\gamma}} \bigg) d\gamma_k. \tag{28}$$

By making the substitution $u = \frac{1+\gamma_k}{\bar{\gamma}}$, equation (29) could be presented as follows:

$$E[R_0^{(1)}] = \frac{2B(1 - P_c)}{\ln 2} \sum_{k=1}^{K_d} \bigg[\exp\bigg(\frac{1}{\bar{\gamma}}\bigg) \int_{\frac{1}{\bar{\gamma}}}^{\infty} \frac{1}{u} \exp(-u) du \bigg] \tag{29}$$

Using [39, p. 228, eq. 5.1.1 & 5.1.2], we finally obtain $E[R_0^{(1)}]$ as follows:

$$\begin{aligned} E[R_0^{(1)}] &= -\frac{2B(1-P_c)}{\ln 2}\sum_{k=1}^{K_d}\exp\left(\frac{1}{\bar{\gamma}}\right)\text{Ei}\Big(-\frac{1}{\bar{\gamma}}\Big) \\ &= -\frac{2B(1-P_c)}{\ln 2}K_d\exp\left(\frac{1}{\bar{\gamma}}\right)\text{Ei}\Big(-\frac{1}{\bar{\gamma}}\Big), \end{aligned} \tag{30}$$

where $\text{Ei}(\cdot)$ is the exponential integral [39].

On the other hand, the expected value $\bar{R}_0^{(2)}$ of the useful throughput under the strategy (2) is calculated by taking into consideration that the K_s^* weakest SCs are avoided. Accordingly, the SCs reserved for transmitting are the K_d strongest ones. Assuming that the SCs are i.i.d and exhibits Rayleigh fading, the SNR of the kth strongest SC has the following distribution [38]:

$$f_\gamma(\gamma_k) = \sum_{p=0}^{N-k}\frac{1}{\bar{\gamma}}\delta_p\exp(-\eta_p\frac{\gamma_k}{\bar{\gamma}}), \tag{31}$$

where $\delta_p = (-1)^p N \begin{pmatrix} N-1 \\ k-1 \end{pmatrix}\begin{pmatrix} N-k \\ p \end{pmatrix}$ and $\eta_p = k+p$

Using similar steps as for $E[R_0^{(1)}]$, the term $E\Bigg[\sum_{k=1}^{K_d}\log_2(1+\gamma_k)\Bigg]$ related to (S2) can be developed as follows:

$$\begin{aligned} E\Bigg[\sum_{k=1}^{K_d}\log_2(1+\gamma_k)\Bigg] &= \sum_{k\in\Omega_s}E\Bigg[\log_2(1+\gamma_k)\Bigg] \\ &= \sum_{k=1}^{K_d}\int_0^{+\infty}\log_2(1+\gamma_k)\, f_\gamma(\gamma_k)d\gamma_k \\ &= \sum_{k=1}^{K_d}\int_0^{+\infty}\log_2(1+\gamma_k)\sum_{p=0}^{k}\frac{1}{\bar{\gamma}}\delta_p\exp(-\eta_p\frac{\gamma_k}{\bar{\gamma}})d\gamma_k \\ &= \sum_{k=1}^{K_d}\sum_{p=0}^{N-k}\frac{\delta_p}{\bar{\gamma}}\int_0^{+\infty}\log_2(1+\gamma_k)\exp(-\eta_p\frac{\gamma_k}{\bar{\gamma}})d\gamma_k \\ &= -\sum_{k=1}^{K_d}\sum_{p=0}^{N-k}\frac{\delta_p}{(\ln 2)\eta_p}\exp(\eta_p/\bar{\gamma})\text{Ei}(-\eta_p/\bar{\gamma}). \end{aligned} \tag{32}$$

Subsequently, the average useful throughput under the strategy (2) is presented as follows:

$$\bar{R}_0^{(2)} = -\frac{2B(1-P_c)}{\ln 2}\sum_{k=1}^{K_d}\sum_{p=0}^{N-k}\frac{\delta_p}{\eta_p}\exp(\eta_p/\bar{\gamma})\text{Ei}(-\eta_p/\bar{\gamma}). \tag{33}$$

The strategy (2), yielding $\bar{R}_0^{(2)}$, provides the CR system with the ability of compensating the loss due to selecting some SCs to the sensing process. The numerical results shown in the next section corroborate this fact.

VII. Numerical Evaluation and Analysis

In order to show the efficiency of our proposed TRS mode, a numerical study is presented in this section. Our proposed TRS is compared to TS mode with respect to the PU detection reliability and the throughput rate. TS is chosen for comparison as it is the standard functioning mode for the FDCR [6], [21]–[25]. The average PU idle and busy times are set as $\alpha = 0.85$ msec and $\beta = 0.15$ msec respectively. The number of OFDM SCs per OFDM symbol is set to 64.

A. Analysis and discussion on the minimum time slot

Figure 3 shows the variation of the number of SSCs per time slot T in terms of P_c. We assume that the detection and false alarm probabilities are the same at the initializing and communicating stages, then $P_d^0 = P_d^1 = P_d$ and $P_f^0 = P_f^1 = P_f$. For the target pair $(P_f = 0.1; P_d = 0.9)$ and according to equations (6) and (7), $p_{fa,i} = 1 - \sqrt{0.9}$ and $p_{d,i} = 1 - \sqrt{0.1}$ for each SU.
The performance is measured for different values of PU signal SNR, which assumed to be the same at the two receiving SUs. As expected, the T increases with P_c for the different considered values of SNR. The minimal time required for sensing becomes less than T for $P_c > 0.1369$ when SNR$= -5$ dB. Then for this value of SNR; When $P_c < 0.1369$ the secondary system cannot establish any transmission activity since the sensing time is greater than the tolerable collision time. At this value of collision probability (i.e. $P_c = 0.1369$) we have $\log_2(K_s) = 6$, then $K_s = 64$ SSCs per symbol is required which means that the secondary system performs only a sensing without any transmission. However, a target null probability of collision means that there is no opportunity for SUs to access the spectrum due to the imperfect spectrum sensing. Back to figure 3, the number of SSCs per OFDM symbol decreases with P_c. For $P_c = 0.2$, the number of SSCs per OFDM symbol becomes approximately 5 for SNR$= -5$ dB, which means that $\frac{2^5}{64} = 50\%$ from the total number of SCs are reserved for the sensing. When SNR increases, this percentage decreases; for $P_c = 0.2$ and SNR$=$ 0 dB and 5 dB this percentage becomes $\frac{6}{64} = 9.3\%$ and $\frac{1}{64} = 1.5\%$ respectively.

On the other hand, the probability of collision associated with the minimum time slot is decreased with SNR. This is due to the increase of N needed to fulfil the target (P_f, P_d). P_c is 0.1369 for the minimum time slot of 4.321×10^{-6} sec when SNR$= -5$ dB. This probability becomes 0.1029 with a minimum time slot of 3.305×10^{-7} sec for SNR=5 dB. Note that as T approaches zero, the probability of collision approaches $(1 - P_d)$, which is the miss-detection rate, when the two communicating SUs exhibit the same detection parameters as it can be shown in figure 3 and can be analytically derived from equation (14).

B. Collision and Throughputs

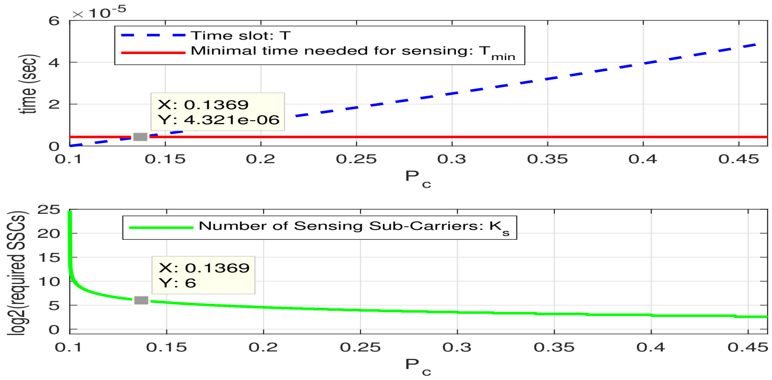
In this subsection, we compare the collision time of our TRS mode with the TS one. In the upcoming simulations, $P_f = 0.1$ and $P_d = 0.9$ are set for both TS and TRS modes. Regarding TS, it is worth to be mentioned that the collision could happen with a primary transmission at two channels since the two communicating SUs adopt two free channels to communicate, unlike TRS that needs only one channel. Thus, the overall probability of collision, $P_{c,TS}$, of TS mode, assuming that the collisions at the two adopted channels are independent, is given by $P_{c,TS} = P_c^1 + P_c^2 - P_c^1 P_c^2$, where P_c^i is the probability of collision at the channel i and $i \in \{1, 2\}$.

A strong point of TRS is that the two communicating SUs monitor the same channel which leads to reduce the number of sensing SCs comparing to TS. The last advantageous point of TRS is the free-SI sensing, where no SIC is required on the SSCs since no SU transmission is performed on them contrary to TS mode (see Table II).

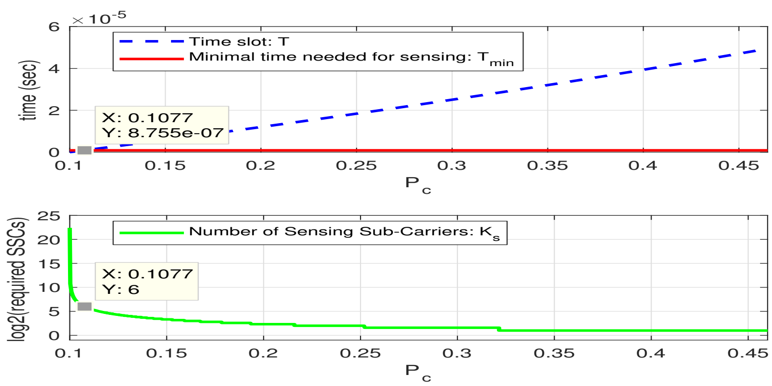
TABLE II. COMPARISON BETWEEN TS AND TRS MODES

Mode	**TRS**	**TS**
Performing SIC at the SSC	No	Yes
Cooperative Spectrum Sensing	Yes	No
IBFD Communication	Yes	No

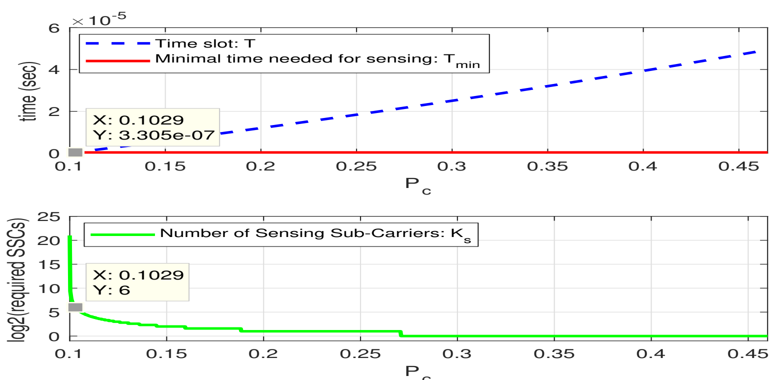
1) Same number of SSCs for both TRS and TS: The simulations associated to figure 4 are built based on the fact that both TRS and TS have the same number of the overall SSCs N. The difference here is that TRS spents a time T where $N = K_s \dfrac{T}{t_{sc}}$ before making its decision on



(a) SNR=−5 dB



(b) SNR=0 dB



(c) SNR=5 dB

Fig. 3. The number of total SCs per time slot and the number of sensing SCs in terms of the collision rate

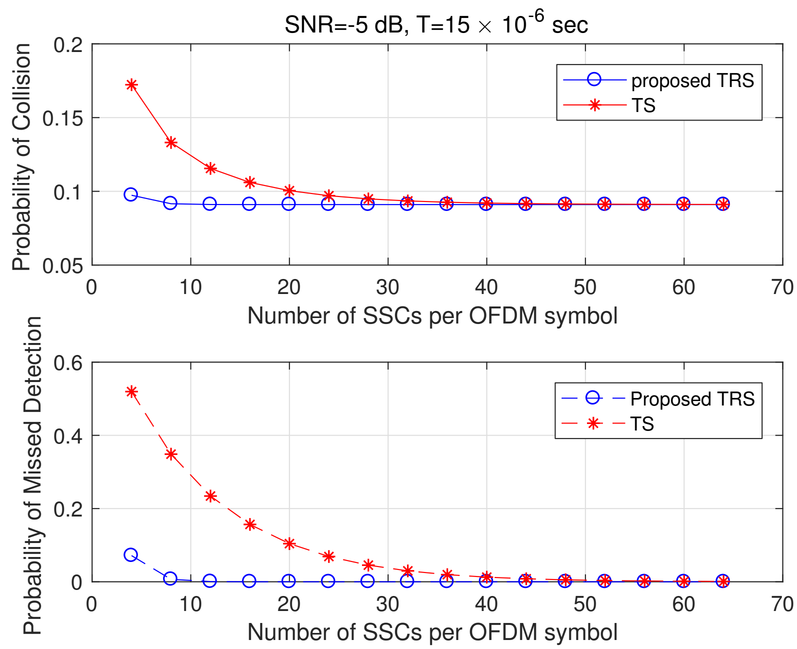
the channel. In turn, TS can make a decision after a period T_{TS} in which there are $N = K\dfrac{T_{TS}}{t_{sc}}$ since all the SCs can be used to sense the channel. T is set to 15×10^{-6} sec, PU SNR= -5 dB and K_s varies between 4 and 64. N will increase with K_s leading to decrease the missed detection probability.

Even though the overall activity time of TRS is greater than the one of TS and the total number of SSCs is the same for both modes, TRS exploits both the spatial diversity of the two communicating SUs and the fact that no residual SI occurs on the SSCs when performing the spectrum sensing. These facts lead TRS to clearly outperform TS mode by achieving lower missed detection rate and hence lower collision probability as shown in figure 4(a).

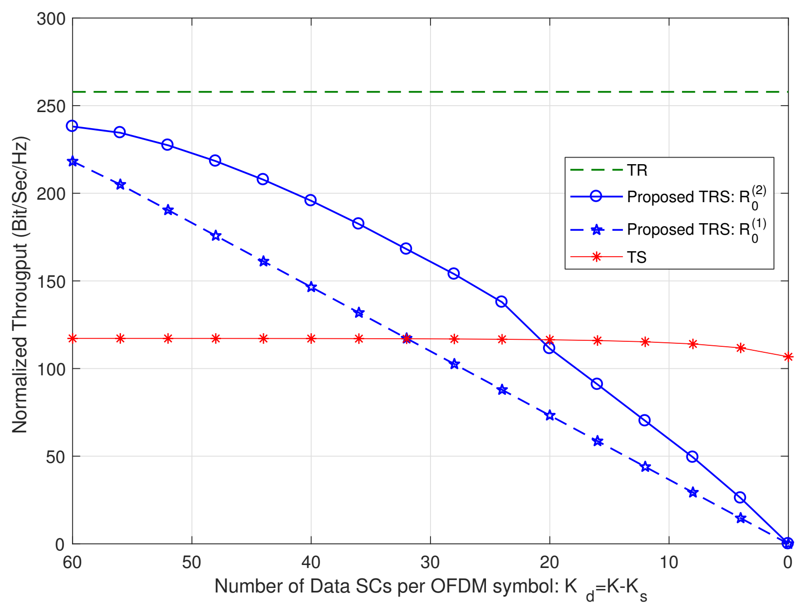
On the other hand, the throughputs $R_0^{(1)}$ and $R_0^{(2)}$ related to the proposed TRS strategies are shown in figure 4(b). $R_0^{(2)}$ highly compensates the loss of bandwidth caused by neutralizing some SCs compared to TR where all the SCs are used in the IBFD communication. Regarding the throughput $R_0^{(1)}$, it decreases linearly with the decrease of the number of data SCs. On the other hand, for $K_d = 32$ SCs (half of the overall SCs), the throughput $R_0^{(1)}$ of the strategy (S1) has the same throughput as TS whereas the throughput $R_0^{(2)}$ of (S2) outperforms TS starting $K_d > 22$ data SCs.

2) Same activity duration for both TRS and TS: In this simulation, the activity durations of both TRS and TS are the same. Both of them spent a time $T = 15 \times 10^{-6}$ sec before making a decision on the PU state. Figure (5(a)) shows the variation of P_c and P_{md} in terms of SSCs per OFDM symbol for the proposed TRS under the aforementioned condition related to T. All the OFDM symbols within T are exploited by TS in the sensing process unlike TRS which chooses only some SSCs out of $K = 64$ per each OFDM symbol. As shown in this figure, starting 8 SSCs per OFDM symbol, the performances of TS and TRS are very close each to another for both sensing and collision.

The throughputs curves of $R_0^{(2)}$ and $R_0^{(1)}$ presented in this figure are similar to those presented in the previous one since the number of the SSCs for both proposed strategies is the same at the two figures. For TS the throughput is constant since $P_{c,TS}$ keeps the same value 0.091 and the activity time is set to T. Similarly to figure 4(b), figure 5(b) shows that $R_0^{(2)}$ related to the strategy (S2) breaks the gap between throughputs of the throughput of TR and $R_0^{(1)}$ related to

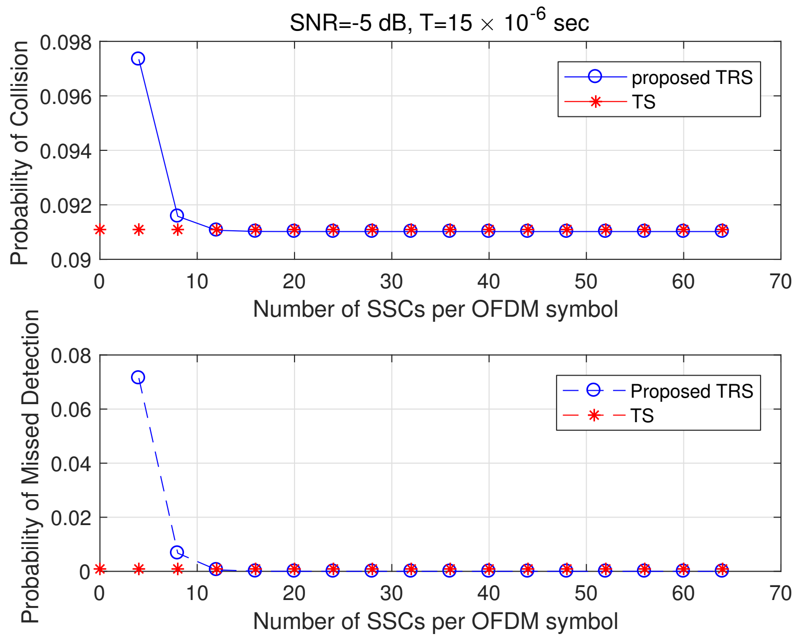


(a) P_c and P_{md} Vs. Number of SSCs

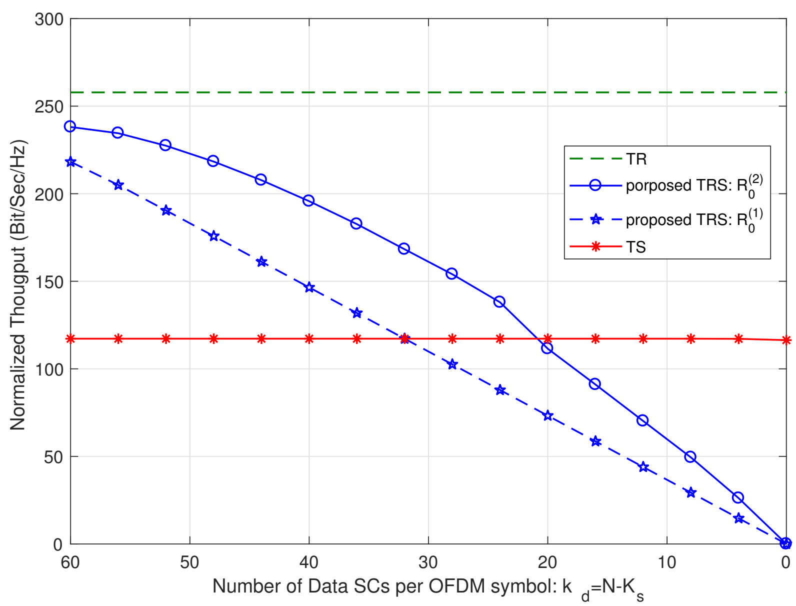


(b) Throughput Vs. Data SCs

Fig. 4. (a):The evolution of P_c and P_{md} for several values of SSCs per OFDM symbols under the proposed TRS and TS modes: The same total number N of SSCs is taken by TS and TRS. For TRS the N SSCs are to be within T. (b): Comparison of normalized throughputs of the proposed TRS mode Vs. TS and TR modes. The SNR of PU signal is set at -5 dB at two SU receivers and the SUs SNR is set to 0 dB.



(a) P_c and P_{md} Vs. Number of SSCs



(b) Throughput Vs. Data SCs

Fig. 5. (a): P_c and P_{md} as a function of SSCs per OFDM symbols under the proposed TRS and TS modes: The same activity duration $T = 15 \times 10^{-6}$ is set for the two operating modes: TS and the proposed TRS. TS can use all the SCs for sensing of PU signal whereas TRS uses K_s SSCs out of K. (b): Comparison of normalized throughputs of the proposed TRS mode Vs. TS and TR modes under the proposed scenario. The SNR of PU signal is set at -5 dB at two SU receivers and the SUs SNR is set to 0 dB.

(S1).

VIII. CONCLUSION

In this paper, we presented a new Transmitting-Receiving-Sensing (TRS) of an OFDM-based cognitive radio system. The new mode helps SUs to efficiently monitor the PU activity while establishing an in-band full-duplex communication. This possibility is achieved by performing the sensing on some null SCs, where no secondary transmission is made by the communicating SUs. The optimal number of sensing SCs per time slot is derived as well as the the number of sensing SCs per OFDM symbol. Numerical results show the robustness of our proposed mode in terms of detecting PU and its efficiency in terms of the secondary throughput rate.
Future directions may address the case when the PU is active on only some SCs. Here, SUs may face the challenge of how to select the SSCs in order to efficiently monitor the status of PU. In addition, our work can be extended to be applied with Narrow-Band Internet of Things (NB-IoT) and with new multi-carrier modulation techniques for 5G such as Filter Bank Multi-Carrier (FBMC).

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