Novel Sensing Mechanism for Full-Duplex Secondary Users in Cognitive Radio

M. R. Mortada*†, A. Nasser*†, A. Mansour*, K. C. Yao‡

* LABSTICC UMR CNRS 6285, ENSTA Bretagne, 2 Rue François Verny, 29806 Brest, France
† Faculty of Science, American University of Culture and Education (AUCE), Beirut, Lebanon
‡ LABSTICC UMR CNRS 6285, UBO, 6 Avenue le Gorgeu, 29238 Brest, France

***Abstract*—In this paper, we present a new Transmitting-Receiving-Sensing (TRS) mechanism for full-duplex cognitive radio. Our proposed mechanism permits Secondary Users (SUs) to establish a bidirectional communication over the same frequency band while keeping aware of the Primary User (PU) activity status. The activity period of SU in our proposed mechanism is composed of two stages: In the first stage SU communicates in bidirectional way with his peer SU. At the second stage, one of the SUs becomes silent in order to do not disturb his peer, which performs a spectrum sensing and remains active at the same time using self-interference cancellation technique. The probability of collision related to our mechanism is derived as well as the probability of waste and the average throughput. Our simulation results show that the proposed mechanism can significantly decrease the probability of collision at low SNRp (Signal to Noise Ratio of PU at SU).**

***Index Terms*—Cognitive Radio, Full-Duplex, Spectrum Sensing, Self-Interference Cancellation, Transmitting-Receiving-Sensing.**

I. Introduction

With the increasing demand on the wireless communication technologies, the available frequency resources become scarce. However, a large portion of the licensed spectrum is severely under utilization. In fact, the Federal Communication Commission (FCC) states that the utilization of the assigned spectrum only ranges from 15 to 85% [2].
The Cognitive Radio (CR) has been introduced by Mitola [13] to alleviate the spectrum scarcity problem as well as to increase the efficiency of spectrum utilization. In Opportunistic Spectrum Access (OSA)-based CR networks, Secondary Users (SU) are allowed to dynamically access the licensed spectrum on a non-interference basis, and to immediately evacuate the spectrum when the Primary User (PU) reappears in the same channel. Thus, the spectrum sensing of the PU activity becomes a challenging task to OSA.

Traditional spectrum sensing systems working under OSA use a Listen-Before-Talk (LBT) scheme to protect PU from the interference of SU. According to this scheme, SU must periodically interrupt its transmission and sense the channel for any PU activity. If the sensing decision outputs that PU is active, the SU should stop its transmission over that channel and must switch to another available channel. Otherwise, the SU proceeds with its transmission until the next sensing attempt [5]. Because of several factors (such as shadowing, fading, interference, $etc.$), the outcome of the sensing cannot be perfect and may result in a false alarm P_f or a miss-detection with probabilities $P_{md} = 1 - P_d$ respectively, where P_d is the probability of detection of PU activity.
In LBT scheme, there exists two major problems: (1) a reduced transmission time due to sensing periods, in which SU becomes silent, and (2) the high probability of collision between SU and PU since PU may return active back during the transmission time of SU.

Listen-And-Talk (LAT) protocol (namely know as simultaneous Transmit-Sense (TS) mode) for OSA systems has been proposed with the help of a Self-Interference Cancellation (SIC) technique allowing SUs to simultaneously sense and access the vacant spectrum. The idea of LAT protocol is that when PU is detected as absent, SU starts transmitting and sensing at the same time in order to get aware all the transmission frame.
Indeed, thanks to SIC techniques, In-Band Full Duplex (IBFD) communication, i.e. simultaneous transmission and reception over the same channel, becomes possible in wireless communications leading to approximately double the spectrum efficiency. Notice that in classic systems, Full-Duplex is achieved by separating the forward and reverse links in time (using Time Division Duplex (TDD)) or frequency (using Frequency Division Duplex (FDD)).
In CR context, even though SIC helps OSA to adopt TS, which decreases the collision probability with PU and enhance the SU throughput, such technique cannot lead SUs to establish IBFD communication (namely known as simultaneous Transmit-Receive (TR) mode in OSA systems). The problem refers to the fact that the spectrum sensing performed by a SU might be deteriorated by the signalling of his peer. Thus, SUs should adopt TDD to transmit on the same channel [11], [12].

Several adaptive mechanisms have been proposed in the literature to switch between TS and TR modes subject to increase the SU throughput while respecting a maximum level of collision with PU. Notice that no spectrum sensing is performed during TR.
In [8], the authors exploit recent advances in SIC to improve

978-9-0827-9703-9/19/$31.00 ©2019 IEEE

the performance of an OSA system. The system can operate in TS mode to decrease the collision probability to PUs, or in TR mode to enhance the SUs throughput.

In [10], the authors optimize the spectrum-awareness/efficiency trade-off by allowing the SU link to adaptively switch between various modes (such as TS mode, TR mode, sensing only (SO) mode and channel switch (CS) mode), depending on the predicted PU activity states. The proposed three-stage (belief stage, traffic stage and periodic sensing stage) adaptive mode-selection strategy maximizes a SU utility function subject to a constraint on the PU collision probability in an optimization problem. They also propose a protocol switching mechanism among aforementioned modes in a distributed fashion (SUs can communicate over a non-dedicated common control channel).

The authors of [1] propose an Asynchronous Full-Duplex Cognitive Radio (AFDCR) scheme in order to fully operate in a TR mode. Their scheme consists of two operation modes: CS mode and Full Duplex TR mode. At the CS stage SU_1 and SU_2 cooperate to reduce the miss-detection probability and to avoid a collision with PU. Upon a successful detection of a spectrum hole, both SUs start a bidirectional communication in a TR mode. SUs can operate in a FD mode, based on a perfect or a partial SIS capability. The detection of PU activity is implemented through feedback information using two events: (1) negative acknowledge (NACK) (i.e. when the primary signal reappears, it will collide with both SUs transmissions and this will end in SU packet and frame error) declared by SUs' receivers and (2) Undecode event (i.e. If one SU cannot decode the received packets without error). If Undecode or NACK events occur, SU must immediately stop their transmission and switch to CS mode again.

As mainly based on the interference sensing, i.e. the capability of SUs to decode their messages, the proposed TR mode in the aforementioned works suffer from the poor sensing performance when PU arrives at low SNRp. In fact, at low SNRp, SUs remain capable to decode their messages, therefore a collision may happen with the primary transmission.
In this paper, the problem of low SNRp is overcome by adopting spectrum sensing instead of the interference sensing used in the existing TR modes. One of the two communicating SUs should remain silent during the spectrum sensing period in order to do not disturb its peer. Hence, the sensing operation is performed in an alternative manner between the two communicating SUs. When SU_1 performs the spectrum sensing, he continues transmitting and cancelling his self-interference, meanwhile SU_2 remains silent. This mechanism is repeated when SU_2 is in charge of spectrum sensing, so SU_1 should be silent. However, this silent period of SU does not decrease much the throughput of the secondary transmission as the sensing time is relatively small comparing to the transmission time. On the other hand, this mechanism ensures a certain level of protection to PU against the SU interference since the spectrum sensing is more efficient in discovering the PU activity than the interference sensing as shown in the next sections.

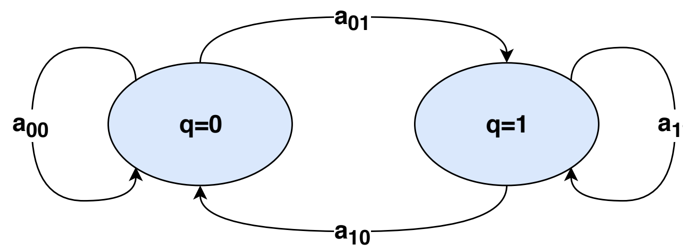

Fig. 1. PU activity is modelled by a Markov model with two states $q_t = 0$ (PU is absent) and $q_t = 1$ (PU is active) and four transition probabilities.

II. System Model

In our project, we are interested in the interweave cognitive radio network, which is the most popular one in the literature. The SU can transmit its message only after sensing an idle [15]. In our model, we consider a PU and two SUs which are seeking to establish a communication between each other and opportunistically access the licensed PUs' channel. For a seek of simplicity, we focus on a single channel, switching policy to another channel are not considered in this manuscript. As depicted in figure 1, the traffic of the primary network can be modeled as a two state discrete Markov process [7] with an initial probability distribution $\pi = \{\pi_0, \pi_1\}$ and a state space $X = \{0, 1\}$, where 0 means an idle PU and 1 represents the busy state. The hypotheses of absence and presence of the PU are denoted by $H_0 \triangleq \{q_t = 0\}$ and $H_1 \triangleq \{q_t = 1\}$ where q_t is the state of the PU channel at time slot t, $A = (a_{ij})$ is given by the transition probability matrix:

$$a_{ij} = P(q_{t+1} = j | q_t = i) > 0 \quad (1)$$

In this work, both PU and SU are assumed to follow a synchronous time-slotted communication protocol with a slot length T. We assume that the PU activity (idle or active) slot is much greater than the activity (transmit and sensing) slot of SU. Therefore, we consider the PU activity stays unchanged during one single SU activity slot. Each slot is considered as one frame for SU, in which SU transmits and receives for a while then senses the channel for a T_s period while transmitting his data, meanwhile the other SU should remain silence during a T_s period.

III. Proposed Transmitting Receiving Sensing Mechanism

As shown in figure 2, our mechanism consists of four functioning modes: transmit receive (TR), transmit sensing (TS), cooperative sensing (CS) and Receive Only (RO). The two SUs exchange data over detected white space in PU channel (idle zone); SUs should begin transmit and receive in a full-duplex manner over a period T_r of TR mode (gray

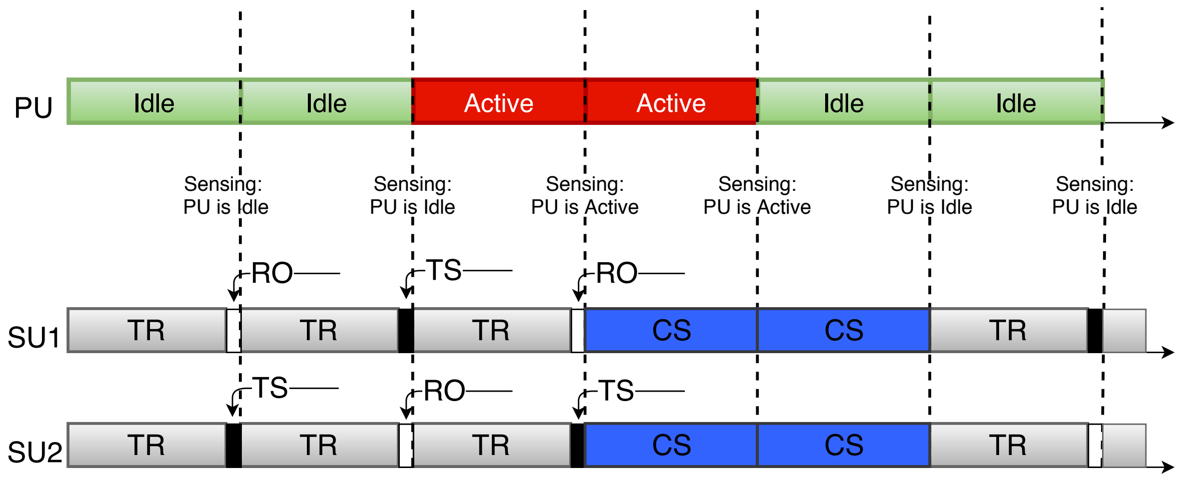

Fig. 2. Proposed Mechanism

rectangle). At the end of T_r, one of two SUs should sense the channel and transmit simultaneously (TS mode the black rectangle), while the other SU stops its transmission and switches to RO until the end of the TS phase. When the PU reappears (red rectangles), SUs stop their transmission and switch to CS mode (blue rectangle), where SUs sense the channel in alternated and cooperative way, i.e., if any SU detects the PU, he informs the other SU.
In order to detecting the PU activity state, SUs use channel sensing based on the energy detection method, the probabilities of false alarm and detection are as follow, respectively [16]:

$$P_f(\epsilon, T_s) = \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - 1\right)\sqrt{N}\right) \tag{2}$$

$$P_d(\epsilon, T_s) = \mathcal{Q}\left(\left(\frac{\epsilon}{\sigma_u^2} - \gamma - 1\right)\sqrt{\frac{N}{2\gamma + 1}}\right) \tag{3}$$

where ϵ is the detection threshold, σ_u^2 is the noise variance, γ is primary's SNRp at the secondary receiver, $N = T_s \times f_s$ is the number of samples where f_s is the sampling frequency, and $\mathcal{Q}(.)$ is the complementary distribution function of the standard Gaussian.

As depicted in figure 2, SUs make a decision at the end of each frame. A collision may occur in two situations: 1) After a correct detection of PU presence, a collision can occur if the PU reapers at the beginning of next frame. 2) Another scenario, SUs miss-detect the PU presence, a collision happens if the PU keeps active at the next frame. Therefore, the probability of collision, P_{col}, can be evaluated as follows:

$$P_{col} = P(H_0)(1 - P_f)a_{01} + P(H_1)(1 - P_d)a_{11} \tag{4}$$

where H_0 is the event that the PU is not active at the start of the frame, and its complement is H_1. $P(H_0)$ and $P(H_1)$ are calculated as a stationary distribution of the transition state matrix of PU in a Markov model.

A wasted slot can be observed if the SU stops his transmission while the PU is idle. Two events lead to wasted slot, the first one: a false alarm happens, and PU keeps silent in the next frame, the other one: a SU detects the presence of PU correctly but PU goes inactive in the next frame. Therefore, the probability of wasted slot is

$$P_{wast} = P(H_0)P_f a_{00} + P(H_1)P_d a_{10} \tag{5}$$

In N slots, SU transmits within N_t useful slots i.e. without any collision with PU where

$$N_t = N\Big(P(H_0) - P_{wast}\Big) \tag{6}$$

the first term in equation (6) is the number of idle slots where PU is absent, the second term is the number of wasted slots.

Assuming R is the number of overall slots in which the two communicating SUs transmits over $N_t \times T$ seconds. For each transmitted slot, one SU transmits for the whole duration of slot, while the second SU stops its transmission for T_s seconds (which is the sensing duration within a single slot), in order to not disturb the sensing of his counterpart SU. The throughput of our system is directly related to the number of slots R which can be presented as follows:

$$\begin{aligned} R &= N_t \times \frac{T - T_s}{T} + N_t \\ &= N_t\left(2 - \frac{T_s}{T}\right) \\ &= N\Big(P(H_0) - P_{wast}\Big)\left(2 - \frac{T_s}{T}\right) \end{aligned} \tag{7}$$

As it can be shown from equation (7), R approaches $2N_t$ as T_s approaches 0. This means that the spectrum efficiency becomes the double. However, this efficiency cannot be achieved due to the need of the secondary system to make the spectrum

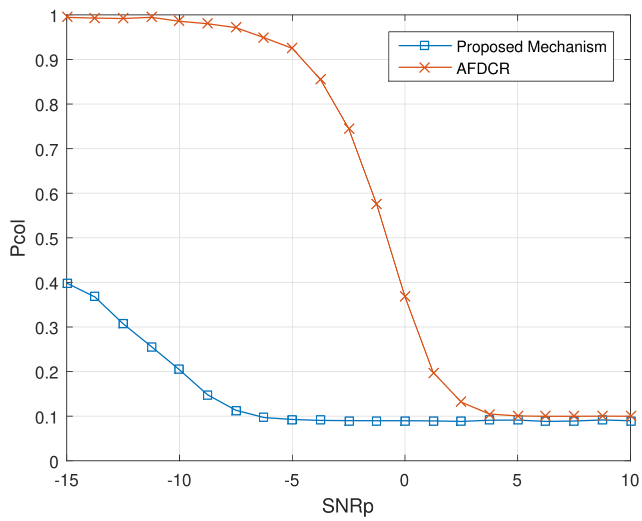

Fig. 3. Evalution of collision probability vs SNRp for AFDCR and our proposed mechanism.

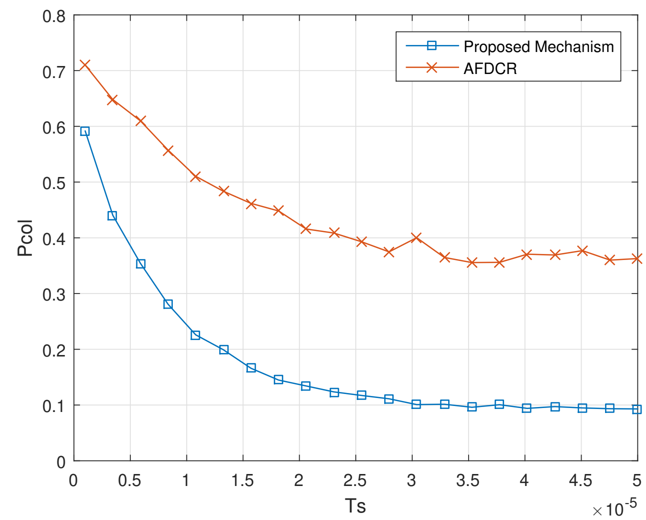

Fig. 4. collision probability vs Ts

sensing in order to be aware of the primary activity.

IV. Numerical Results

In this section, simulation results are provided to evaluate the performance of the proposed mechanism. We assume that the activity of PU is 90% idle and 10% active, i.e. $P(H_0) = 0.9$ and $P(H_1) = 0.1$. SUs signal to noise ratio = 10 dB, $T_s = 1ms$ and the sampling frequency is $f_s = 1MHz$ until a further notice.

Figure 3 depicts the probability of collision against SNRp. We notice that in low SNRp the collision probability of AFDCR (red curve) is very high, while this probability under our mechanism keeps a collision rate of 0.1 starting SNRp $= -6$ dB. This means that AFDCR is not applicable at low SNRp as this mechanism do not ensure the protection of PU against the secondary interference. However, due to the unavoidable collision when PU returns back, SU always collides with PU at the first active slot of PU. This explains why P_{col} becomes stable at high SNRp and do not become null for both evaluated mechanisms. We can also note that at the high SNRp value, these two curves converge toward approximately the same minimum of P_{col}, so the two mechanism have the same collision probability at high SNRp.

In figure 4, we show the collision probability while changing the value of sensing duration T_s. SNRp is fixed to 0 dB. As this figures shows, the probability of collision related to our mechanism decreases with T_s from 0.6 at $T_s = 0.1 \times 10^{-5}$ sec to 0.1 for $T_s \geq 3 \times 10^{-5}$ sec. In turn, the probability of collision of AFDCR decreases from 0.72 to 0.37 for the aforementioned values of T_s. This means that our mechanism is much more efficient than the one of AFDCR for the different values of T_s and a moderate PU SNR (SNRp=0 dB) from the sensing point of view.

figure 5 and figure 6 show the throughput against SNRp. For the two figures we consider a total number of slots $N = 10^5$ slots. Figure 5 presents the slot numbers in which SUs transmit their data with and without collision. As shown, in AFDCR SUs keep transmitting continuously as they cannot detect the PU at low SNR. However, the throughput of our proposed mechanism is lower to that of AFDCR as SUs in our mechanism are able to detect PU when he is active so they should stop transmission. This fact is explained 6. Knowing that PU is active during 10% of the overall slots sine $P(H_1) = 0.1$, the number of colliding slots related to AFDCR is approximately 10^4 at SNRp $leq - 11$ dB. That means AFDCR collides with the 10% of the overall number of slots $N = 10^5$ AFDCR at low SNRp. In turn our mechanism reduces this number of colliding slots to 4000 at SNRp of -15 dB and becomes 1000 for SNRp ≥ -6 dB.

Figure 7 depicts the throughput (i.e. the number of slots where SU transmits its data) vs sensing duration Ts, under $N = 100000$ slots. For this comparison, SNRp is fixed to 3 dB. As we can see AFDCR throughput is slightly better than our mechanism. At very low sensing time ($T_s = 0.1 \times 10^{-5}$ AFDCR presents approximately 9.4×1^4 transmit slots where our proposed mechanism is about 8.7×10^4. This number of transmit slots becomes constant for the two mechanisms starting $T_s = 1.5 \times 10^{-5}$ sec and achieve 9×10^4 and 8.1×10^4 for AFDCR and our mechanism respectively. However, the superiority of AFCDR in throughput comes at the cost of collision with the primary transmission.

V. Conclusion And Future Work

In this paper we present a new Transmit-Sense-Receive mechanism for a full duplex cognitive radio. In our proposed mechanism, two SUs could simultaneously transmit and receive at the same channel. At the end of each frame, one of SUs senses the channel while transmitting using Self-Interference Suppression technique, whereas the another SU

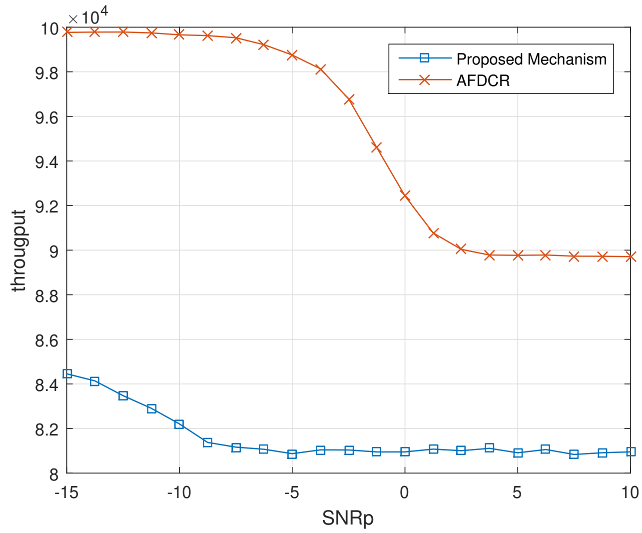

Fig. 5. throughput vs SNRp all slots: This figure shows the useful (without collision) and he un-useful (colliding) throughputs for both AFDCR and our proposed mechanism.

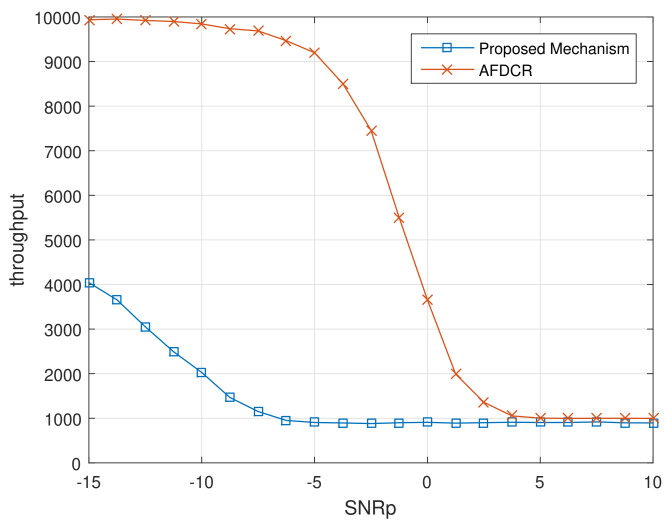

Fig. 6. throughput vs SNRp: only collided slots are shown for both AFDCR and our proposed mechanism.

stops his transmission in order to do not corrupt the decision of the sensing operation. Numerical results show that at low SNR of the PU at the secondary receivers our approach still has an efficient detection of PU activity, then low collision probability compared to existing approaches.

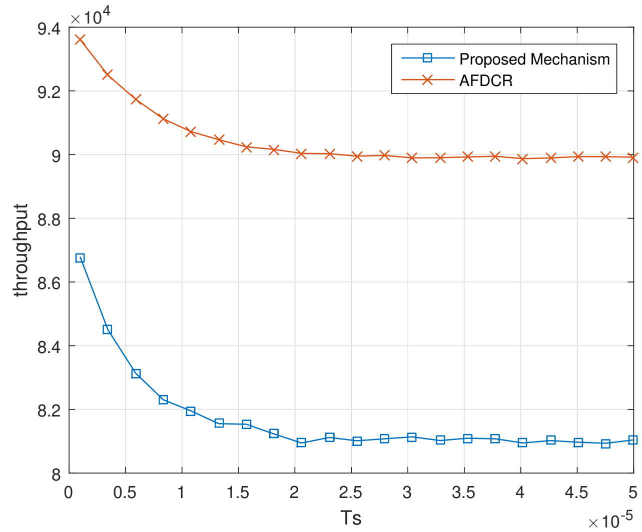

Fig. 7. Throughput vs Ts for the AFDCR and the proposed mechanisms

REFERENCES

[1] V. Towhidlou, M. Shikh Bahaei, "Asynchronous full-duplex cognitive radio, " 2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)

[2] FCC:"Spectrum policy task force report', ET 02-155, November 2002

[3] D. Willkomm, S. Machiraju, J. Bolot, "Primary user behavior in cellular networks and implications for dynamic spectrum access",IEEE Commun, Mag., 2009, 47, (3), pp. 88-95

[4] X. Xing, T. jing, H. Li, Y. Huo, X. Cheng, T. Znati, "Optimal spectrum sensing interval in cognitive radio networks",IEEE Transactions on paralelle and distributed systems, Volume: 25 , Issue: 9 , Sept. 2014

[5] W. Afifi, M. Krunz, "TSRA: an adaptive mechanisme for switching between communication modes in full-duplex opportunistic spectrum access systems", IEEE transactions on mobile computing, vol. 16, no. 6, june 2017

[6] Y. Liao, T. Wang, L. Song, Z. Han, "Listen-and-Talk: protocol design and analysis for full-duplex cognitive radio networks", IEEE Transaction and Vehicular Technology.Volume: 66 , Issue: 1 , Jan. 2017

[7] Z. Chen, Z. Hu, and R. C. Qiu, "Quickest spectrum detection using hidden markov model for cognitive radio," in MILCOM 2009 - 2009 IEEE Military Communications Conference, Oct 2009, pp. 1-7.

[8] W. Afifi and M. Krunz. Adaptive "Transmission-Reception-Sensing Strategy for Cognitive Radios with Full-duplex Capabilities". In International Symposium on Dynamic Spectrum Access Networks (DYSPAN), pages 149 160, McLean, VA, USA, 2014

[9] V. Towhidlou and M. Shikh-Bahaei." Adaptive full-duplex communications in cognitive radio networks". IEEE Transactions on Vehicular Technology, 67(9):83868395, Sep. 2018

[10] W. Afifi and M. Krunz. TSRA: "An Adaptive Mechanism for Switching between Communication Modes in Full-Duplex Opportunistic Spectrum Access Systems". IEEE Transactions on Mobile Computing, 16(6):1758 1772, Jun 2017.

[11] A Nasser, A Mansour, K. C. Yao, H Abdallah and H Charara, " In-band Full-Duplex communication for cognitive radio", 23rd Asia-Pacific Conference on Communications (APCC), pages 1-5, Perth, WA, Australia, Dec. 2017

[12] A. Nasser, A. Mansour, K. C. Yao and H. Abdallah, "Spectrum Sensing for Half and Full-Duplex Cognitive Radio", Chapter in an Elsevier book " Spectrum Access and Management for Cognitive Radio Networks, Signals and Communication Technology", Editor M. Matin, DOI 10.1007, 978-981-10-2254-8-2, 2017.

[13] J. Mitola and G. Q. Maguire, Jr., "Cognitive radio: making software radios more personal", IEEE Personal Communications Magazine, vol. 6, nr. 4, pp. 1318, Aug. 1999.

[14] C. Santivanez, R. Ramanathan, C. Partridge, R. Krishnan, M. Condell, S. Polit,"Opportunistic spectrum access: challenges, architecture, protocols",WICON '06 Proceedings of the 2nd annual international workshop on Wireless internet Article No. 13 Boston, Massachusetts, USA August 02 - 05, 2006 ACM New York, NY, USA 2006.

[15] B. Liu, Z. Li, J. Si, F. Zhou, "Optimal sensing interval in cognitive radio networks with imperfect spectrum sensing", IET Commun., 2016, vol. 10, Iss. 2. pp. 189-198

[16] Y.C. Liang, Y. Zeng, E.C.Y. Peh, and A. T. Hoang, "Sensing-throughput tradeoff for cognitive radio networks", IEEE Trans. on Wireless Comm., vol. 7, no. 4, Apr 2008.