

Full Duplex Spectrum Sensing and Energy Harvesting in Cognitive Radio Networks Based on Tow Antennas

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Abstract

Full-duplex Energy Harvesting Cognitive Radio Networks (FD EHCRNs), which is a combination of full-duplex (FD) technique, cognitive radio (CR), and radio frequency (RF) energy harvesting technique, is a new wireless communication model to improve spectrum efficiency (SE) and energy efficiency (EE). Using FD, the Energy Harvesting Cognitive Radio Networks (EH CRN) equipment of the cognitive users can perform spectrum sensing, data transmission, and energy harvesting simultaneously. Consequently, full duplex in EH CRNs can solve the spectrum waste and transmission discontinuation problems caused by traditional CRNs. In this paper, a new proposal model for FD EHCRN is presented focusing on detection threshold design and energy harvesting model to try improving the system performance. Therefore, the purpose of this paper is to redesign the existing EHCRN and proposes a new model for spectrum sensing technique using full-duplex with only two antennas. Both mathematical analysis and numerical results are presented in this paper.

Keywords: Cognitive Radio Networks (CRN), Energy Harvesting (EH), Full-duplex (FD), Spectrum sensing, Primary User (PU), Secondary User (SU), Residual Self- Interference (RSI), self- interference (SI).

تحسس الطيف وتحصيل الطاقة باستخدام النطاق الترددي المزدوج في شبكات الراديو الإدراكي على أساس هوائيين

المُلخَص:

النطاق المزدوج (FD) للطيف الترددي في شبكات الاتصالات اللاسلكية للراديو الإدراكي مع حصاد الطاقة (Full-duplex Energy Harvesting Cognitive Radio Networks "FD EHCNRs")، والتي هي عبارة عن مزيج من تقنية الإرسال المزدوج الكامل (FD) والراديو الإدراكي (CRN) وتقنية حصاد الطاقة (EH)، هي تقنية اتصالات لاسلكية جديدة الغرض منها تحسين كفاءة الطيف وتحسين كفاءة الطاقة.

باستخدام النطاق المزدوج (FD) للطيف يمكن لأجهزة الراديو الإدراكي عمل تحسس واستشعار متزامن لطيف الشبكات الأخرى التي يرغب في استخدام النطاق الترددي الغير مستخدم فيها وعمل نقل البيانات عبر هذا النطاق وكذلك عمل حصاد للطاقة بشكل متزامن في نفس الوقت، لذلك يمكن لنظام النطاق المزدوج في EHCNRs حل مشاكل الطيف المتقطع المتواجدة في شبكات CRN التقليدية.

في هذه البحث تم تقديم اقتراح نموذج جديد من FD EHCNR من خلال التركيز على تصميم حدود الكشف (detection thresholds) ونموذج تجميع الطاقة (energy harvesting) وذلك لغرض تحسين أداء النظام الراديو الإدراكي مع تحصيل الطاقة باستخدام النطاق المزدوج. مع العلم أن هذا البحث لا يسعى إلى تصميم تقنية جديدة لاستشعار الطيف من أجل EH-CRN بل إعادة تصميم واقتراح نموذج جديد لتقنية استشعار الطيف من خلال استخدام النطاق المزدوج باستخدام هوائيين. حيث تم عرض كل من التحليل الرياضي والنتائج العددية في هذا البحث.

1. Introduction:

Cognitive radio (CR) facilitates efficient spectrum use of current licensed spectrum that is highly underutilized and is considered as a potential solution to then problem of spectrum scarcity. In CR networks, secondary users (SU) opportunistically access spectrum allocated to licensed or primary users (PU) in such a way that quality of service (QoS) requirements of PUs are satisfied. For Full-duplex Energy harvesting cognitive radio networks (FD EHCRNs), a combination of cognitive radio (CR), RF energy harvesting (EH) technique, and full-duplex (FD) technique, is a new wireless communication model which aims to improve the spectrum efficiency utilization (SE) and energy efficiency (EE) as much as possible [10]. In FD EHCRN, the secondary users (SUs) can perform spectrum sensing, energy harvesting, and data transmission simultaneously. The harvested energy is consumed for energy requirements of the data transmission and spectrum sensing. So FD EHCRN is used to solve the spectrum waste and discontinuous transmission problems existing in traditional half duplex (HD) CRNs. The FD-EHCRN system is totally different from the traditional HD based on many aspects, including:

- ▶ Spectrum sensing: in FD EHCRNs, the sensing is continuous, but the received sensing signal causes an interference called "residual self-interference (RSI)" which causes degradation of the sensing signal-to-interference-plus-noise ratio (SINR). In HD EHCRNs, there is no RSI in the received sensing signal, and the sensing process is discontinuous and only takes a small portion of each slot.
- ▶ Data transmission: in HD EHCRNs, the SU sensing process uses a portion of each time slot and the remaining part is used for data transmission, while in FD EHCRNs, SU can sense the spectrum and transmit the data continuously when the primary users (PUs) are absent. However, in FD EHCRNs, the transmission power of the data affects the sensing process which is the constraint of transmit power to achieve acceptable performance on the sensing process.
- ▶ Energy Harvesting: in traditional HD EHCRNs, the harvesting time is a portion of the channel time slot that leads to inefficiency in Energy Harvesting and sensing performance due to time slot dividing to sensing, Energy Harvesting, and transmission sub slots. In FD-EHCRNs the harvesting process can be done from PU signal in sensing time slot, transmission time slot, or in both at the same time by using the two antennas.

To measure the performance of Energy Harvesting FD CRNs, many metrics such as the received power, transmitted power, sensing performance, energy harvesting performance will be studied in this paper.

The paper is organized as follows: section two for the related works, section three for the proposed model of Full Duplex Spectrum Sensing in Cognitive Radio Networks, section four for the proposed Full Duplex Energy Harvesting in Cognitive Radio Networks, section five for the design of sensing thresholds and secondary throughput, finally section six for the simulation and numerical results which are done by matlab program.

2. Related Work:

In half duplex (HD) transmission mode, the objective in the design of the sensing period and the transmission period is to improve SU throughput. However, half duplex transmission mode has two major problems [14, 18, 20]:

1. The SUs have to loss a portion of each transmission time slots for spectrum sensing, and the data transmission needs to be split into small discontinuous slots even if the spectrum hole is long and continuous.
2. During SUs transmission, the changes of PU states cannot be detected by SU which cause the interference with the PU that leads to a collision with PU and a waste in spectrum when PUs arrive and leave respectively.

Recently, the ability of FD communications has been studied in several works (see [16, 3]). These studies presented the various types of self- interference suppression (SIS) techniques such as digital baseband interference cancellation, RF analog cancellation, and phase shifters to overcome the self interference (SI) problem which allowed FD communications to be achieved [4, 5, 7, 8, 9, 11, 12, 13, 16, 17, 20].

The authors in [15] evaluated and compared the performance of the FD CRNs with HD CRNs in underlay white space usage. The SI and PU interference are considered under various constraints of spectrum sharing. The authors concluded that the FD CRN is better than HD CRN in the spectrum utilization.

The authors in [1] proposed overlay mode with opportunistic spectrum access (OSA), and they used two antennas and centralized architecture. The SUs use FD mode in which the sensing process and transmit process are done simultaneously. The authors used the underlay approach as a complex problem to determine the level of the target power that should be allocated for FD CRNs.

The authors in [2] proposed the first practical study of FD CRN using the interweave architecture of CRN and FD radios. They studied the transmission range and the achievable rate gain for the in-band full-duplex transmissions using directional multi-reconfigurable antennas. The results have shown that the multi-reconfigurable antennas directionality can increase both the rate and the range of the full-duplex transmissions over omni-directional antenna.

In [6] the authors proposed an transceivers design of FD-cognitive cellular and FD-cognitive ad hoc networks. They used the optimization approach as a subject to the power constraints to minimize the sum of all mean-squared errors (MSEs).

The authors in [19] explored how to improve SU throughput with the help of digital SIS for SUs with RF energy harvesting and FD capability.

The authors in [10] studied the optimizing detection threshold problems with three antennas to maximize both energy efficiency (EE) and harvesting efficiency (HE) in FD CRNs powered with RF under the constraint that guarantee protection of PU.

Unlike all above papers, this paper proposes a new model for FD EHCRN using only two antennas to fully optimize the spectrum sensing.

This paper focuses on the following important issues:

- How to design the sensing strategy so that the benefits of the FD can be fully employ with EH.
- How to select the secondary transmit power in FD CRN which can achieve high SU throughput as well as satisfactory sensing performance.
- How well can the proposed FD EHCRN perform in terms of spectrum utilization efficiency, energy harvesting efficiency, and secondary throughput.

These questions will be answered in this paper by both theoretical analysis and simulation.

3. Full Duplex Spectrum Sensing model in Cognitive Radio Networks:

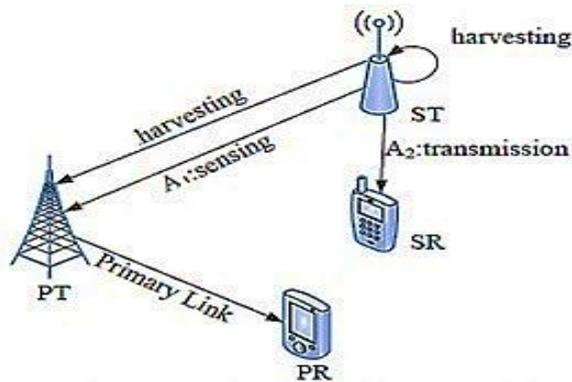


Figure 1 : The proposed system model

The proposal model of Full duplex Energy Harvesting cognitive radio consists of one SU pair (transmitter and receiver) and one PU pair (transmitter and receiver) with full duplex capability, where primary transmitter (PT) transmits data to primary receiver (PR) and secondary transmitter (ST) transmits data to secondary receiver (SR) as shown in Figure (1), and the ST is equipped with an RF energy harvesting circuits.

Each SU device is equipped with two antennas denoted as A1 and A2. A1 is used for spectrum sensing and energy harvesting either in power splitter mode (PS) or time switching mode (TS), while A2 is used for SU data transmission or energy harvesting according to PU activity cases. ST uses both A1 and A2 for spectrum sensing, energy harvesting, and data transmission at the same time (i.e, simultaneously), while SR uses only A2 to receive signal from ST. The time-slotted mode CRN is used in this paper in which the transmission time slots are divided into T unit time slots.

In the FD EHCRN, the secondary transmitter performs energy harvesting, spectrum sensing, and data transmission simultaneously as follows:

A1 of ST harvests the energy and performs spectrum sensing simultaneously with sensing duration T_s and makes a decision about the PTs status at the end of each sensing duration T_s . The simultaneous harvest energy and spectrum sensing are done by using either power splitter mode or time switching mode, while the energy harvested by A1 is done either from PT RF power signal, if PT is busy, or from A2 itself, when ST transmits data to SR.

A2 of ST performs either transmitting data to SR at the same time as A1 performs spectrum sensing if the sensing result of PT state is idle, or harvesting energy

from PT RF power signal if the sensing result of PT state is busy and ST does not transmit data to SR. The harvested energy of ST is used for its sensing and data transmitting processes. It should be noted that the spectrum sensing process is performed at all times.

The proposal model uses the energy detection sensing type, where the SU uses the energy of the PU signal to detect the presence of PU. The energy detection uses the average received power in each time slot as the test statistics T_{ed} as follows:

$$T_{ed} = \frac{1}{N_s} \sum_{n=1}^{N_s} |y_i(n)|^2$$

Where $y_i(n)$ is the received signal and N_s is the number of samples to be detected. The distribution of T_{ed} tends toward a Normal Distribution according to Central Limit Theorem when N_s becomes large. Since the desired goal is to be the required SNR low, a very large number of samples must be used during the detection process which can be obtained by considering the distribution T_{ed} as a Gaussian with a mean μ_{ed} and a variance σ_{ed} .

Because the proposed model uses FD, then there are four states of spectrum access as follows:

1. State1 (H_{00}): both PU and ST are not active, so there is a waste in the spectrum caused by false alarm.
2. State2 (H_{01}): only PU occupies the spectrum, and SU is silent.
3. State3 (H_{10}): the spectrum is idle from PU, while ST uses the spectrum.
4. State4 (H_{11}): both PU and ST transmit over the same spectrum band, so a collision occurs as a result of missing detection P_m .

Since there are different states regarding whether ST transmits data or not, a better sensing performance can be achieved by changing the threshold based on ST activity states. Therefore, the situations when ST transmits or not are considered separately by using two detection thresholds λ_0 and λ_1 , where λ_0 represents ST when it is silent (not in transmission), and λ_1 represents ST when it is active (transmitting).

Also the previous four states can be divided into two cases according to SU states as follows:

1. When ST is silent:

The received signal through A1 is a component of PU received signal and noise. Therefore the busy and idle states of PU are represented by hypothesis tests H_{01} and H_{00} , respectively.

The received signal $y(n)$ at ST for these two states can be written as [14]:

$$y(n) = \begin{cases} w & H_{00} \\ h_p s_p + w & H_{01} \end{cases} \quad (2)$$

Where h_p represents the channel gain from PT to ST which is modeled as Rayleigh channel with variance σ_h^2 , s_p represents the PSK modulated signal of PT with variance σ_p^2 , and w represents a zero mean Gaussian noise with variance σ_w^2 .

At these states, the detection probability $P_d^0(\lambda_0)$ and false alarm probability $P_f^0(\lambda_0)$ at ST can be calculated as [10, 14]:

$$P_d^0(\lambda_0) = Q\left(\left(\frac{\lambda_0}{(1+\gamma_p)\sigma_w^2} - 1\right)\sqrt{N_s}\right) \quad (3)$$

$$P_f^0(\lambda_0) = Q\left(\left(\frac{\lambda_0}{\sigma_w^2} - 1\right)\sqrt{N_s}\right) \quad (4)$$

Where $\gamma_p = \frac{\sigma_h^2 \sigma_p^2}{\sigma_w^2}$ is the sensing SNR, N_s number of samples, $Q(\cdot)$ is the standard Gaussian complementary cumulative distribution function, i.e., $Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\frac{u^2}{2}\right) du$.

2. When ST transmits data to SR:

self-interference suppression (SIS) is introduced to the received signal at A1. In this case, the busy and idle states of PU are represented by hypothesis tests H_{10} and H_{11} , respectively.

The received signal $y(n)$ at ST for these two states can be written as [14]:

$$y(n) = \begin{cases} h_s s_s + w & H_{10} \\ h_p s_p + h_s s_s + w & H_{11} \end{cases} \quad (5)$$

where h_s is the channel gain of the self-interference signal from A2 to A1. s_s denotes the ST signal with variance σ_s^2 which $h_s \sigma_s$ can be modeled as zero mean Rayleigh distribution channel with variance $\chi^2 \sigma_s^2$, where χ^2 represents the degree of self-interference suppression factor χ^2 ($0 < \chi^2 < 1$) and it is

known as the ratio of received self-interference signal power from ST to itself to the transmitting power by ST.

The detection probability $P_d^1(\lambda_1)$ and false alarm probability $P_f^1(\lambda_1)$ in these states can be written as [10, 14]:

$$P_d^1(\lambda_1) = Q\left(\left(\frac{\lambda_1}{(1 + \gamma_p + \gamma_s)\sigma_w^2} - 1\right)\sqrt{N_s}\right) \quad (6)$$

$$P_f^1(\lambda_1) = Q\left(\left(\frac{\lambda_1}{(1 + \gamma_s)\sigma_w^2} - 1\right)\sqrt{N_s}\right) \quad (7)$$

Where $\gamma_s = \frac{\chi^2 \sigma_s^2}{\sigma_w^2}$ denotes the SINR of the SU. Based on the above mathematical analysis, the whole system probabilities can be obtained as [14]:

$$P_d(\lambda_0, \lambda_1) = \frac{P_d^1}{1 - P_d^0 + P_d^1} \quad (8)$$

$$P_f(\lambda_0, \lambda_1) = \frac{P_f^1}{1 - P_f^0 + P_f^1} \quad (9)$$

4.Full Duplex Energy Harvesting model in Cognitive Radio Networks:

The power splitter is used in this paper for energy harvesting in FD EHCRN, also there are four states must be taken into account as follows [10]:

1. state H_{00} : both PU and ST are not active due to false alarm. In this state the ST performs spectrum sensing only, so it consumes the energy in the sensing process and cannot harvest any energy.

The harvested energy in this state:

$$E_H^{00} = 0; \quad (10)$$

2. state H_{01} : only PU occupies the spectrum, and SU is silent. In this state the ST harvests the energy from PT signal through the two antennas [A1, A2], consumes some energy for continuous spectrum sensing and the remaining is stored for data transmission requirements (see Appendix A).

The harvested energy in this state [author]:

$$E_H^{01} = \rho_p \eta E_{p1} p_1 P_d^0 (1 - a_n) + \eta E_{p2} p_1 P_d^0 (1 - a_n) \quad (11)$$

3. state H_{10} : the spectrum is idle from PU. In this state ST uses this idle spectrum channel for its data transmission and harvests the energy from A2 through A1. The harvested Energy is consumed in the spectrum sensing process and data transmission process (see Appendix A).

The harvested energy in this state [author]:

$$E_H^{10} = \rho_p \eta E_s p_0 (1 - p_f^1) a_n \quad (12)$$

4. state H_{11} : both PU and ST are transmitting over the same spectrum band which cause a collision. In this state the ST harvests the energy from A2 and PT through A1 and consumes the harvested energy in the spectrum sensing and data transmission processes (see Appendix A) (i.e, harvests energy through A1 from PT and ST).

The harvested energy in this state [author]:

$$E_H^{11} = \rho_p \eta E_{p1} p_1 (1 - P_d^1) a_n + \rho_p \eta E_s p_0 (1 - P_d^1) a_n \quad (13)$$

Then the total harvested energy [author]:

$$\begin{aligned} E_H^T &= E^{10} + E^{01} + E^{11} \quad (14) \\ E_H^T &= \rho_p \eta E_s a_n [p_0 (1 - p_f^1) + p_0 (1 - p_d^1)] \quad (15) \\ &+ \rho_p \eta E_{p1} p_1 [a_n (1 - P_d^1) + (1 - a_n) p_d^0] \\ &+ \eta E_{p2} p_1 p_d^0 (1 - a_n^1) \end{aligned}$$

And the total consumed energy E_c^T is:

$$E_c^T = P_{sen} T_s + P_t T_t a_n [(1 - p_f^1) p_0 + (1 - P_d^1) p_1] \quad (16)$$

Where all states have been implemented by Markov chain model as shown in Appendix A.

where E_s represents the ST energy arrived from A2 to A1, $E_{p1} = h_{p1}^2 P_p T$ represents the PU signal arrived to A1, $E_{p2} = h_{p2}^2 P_p T$ represents the PU signal arrived to A2. h_{p1}^2 and h_{p2}^2 represent the channel gain coefficient from PU to ST A1 and A2, respectively, T_s is sensing time, T_t is frame time, P_{sen} is the sensing power, P_t is the ST transmitted power, ρ_p is the power splitter coefficient, η is the efficiency of RF to DC converter of energy harvester circuit. a_n is the activity state of SU, p_0 is the probability of spectrum access of the idle band or probability of the PU absent, and p_1 is the probability of spectrum access of the occupied band or probability of the present of PU, which are defined as [14]:

$$p_0 = Pr\{PU = 0\} = P_{acc} (1 - P_f) \quad (17)$$

$$p_1 = Pr\{PU = 1\} = P_{acc} (1 - P_d) \quad (18)$$

where P_r is the probability, P_{acc} is the probability of the spectrum access of the idle and occupied channel, which is related to the collision probability, and

it is defined as [14]:

$$p_1 = Pr\{PU = 1\} = P_{acc}(1 - P_d) \quad (19)$$

Determination of P_0, P_1 is done by channel access modes and it is out of this paper.

5.Design of Sensing Thresholds and Secondary Throughput

The Sensing thresholds are the major parameters in the design of FD EHCRN. Actually two independent variables of the secondary network design are required which denoted by λ_0 and λ_1 . These thresholds λ_0 and λ_1 can be obtained as [14]:

$$\lambda_0 = \left(\frac{Q^{-1}(P_d^0)}{\sqrt{N_s}} + 1\right)(1 + \gamma_p)\sigma_w^2 \quad (20)$$

$$\lambda_1 = \left(\frac{Q^{-1}(P_d^1)}{\sqrt{N_s}} + 1\right)(1 + \gamma_p + \gamma_s)\sigma_w^2 \quad (21)$$

So the $P_f^0(\lambda_0)$ and $P_f^1(\lambda_1)$ can be obtained as follows [14]:

$$P_f^0(P_d^0) = Q(Q^{-1}(P_d^0)(1 + \gamma_p) + \gamma_p\sqrt{N_s}) \quad (22)$$

$$P_f^1(P_d^1) = Q(Q^{-1}(P_d^1)(1 + \frac{\gamma_p}{1 + \gamma_s}) + \frac{\gamma_p}{1 + \gamma_s}\sqrt{N_s}) \quad (23)$$

The SU throughput can be determined by assuming the two states of PU when the SU in the active state as follows:

1. In state H_{10} the SU is active and the PU is idle with Probability $p_0(1 - P_f)$, so the throughput is [14]:

$$R_0 = p_0(1 - P_f^1)\log_2(1 + \gamma_t) \quad (24)$$

2. In state H_{11} the SU is active and the PU is busy with Probability $p_1(1 - P_d)$ then the SNR of SU is interfere with PU signals thus the throughput is [14]:

$$R_1 = p_1(1 - P_d^1)\log_2(1 + \frac{\gamma_t}{1 + \gamma_p}) \quad (25)$$

Then the total throughput of the SU is [14]:

$$R = R_0 + R_1 \quad (26)$$

$$R = p_0(1 - P_f^1)\log_2(1 + \gamma_t) + p_1(1 - P_d^1)\log_2(1 + \frac{\gamma_t}{1 + \gamma_p}) \quad (27)$$

The goal of FD EHCRN is to improve the spectral efficiency (η_{SE}), Energy efficiency (η_{EE}) (bits/Joule.Hz), and harvesting energy (η_{HE}) which are denoted as [10]:

$$\eta_{SE} = \frac{R}{Bw} \quad (28)$$

$$\eta_{EE} = \frac{R}{E_c/T} \quad (29)$$

$$\eta_{HE} = \frac{EH}{E_c} \quad (30)$$

where Bw represents the bandwidth, R represents the throughput, E_c represents the consumed energy, and EH represents the harvested energy.

6. Simulation and Numerical results:

The key parameters used in the simulation of the proposed FD-EHCRN are set as follows:

The sampling frequency $f_s = 1\text{MHz}$; the sensing duration is $T_s = 1\text{ms}$ with frame duration $T = 10\text{ms}$; the number of samples in each slot $N_s = 1000$; the sensing SNR from PU to SU $\gamma_p = -10\text{dB}$; the SNR from SU A2 to A1 $\gamma_s = 5\text{dB}$; Without loss of generality, the noise power is normalized $\sigma_n = 1$; ST transmit power $P_t = 10\text{dB}$ unless otherwise stated; target detection probability $P_d = 0.9$ and target false alarm probability $P_f = 0.1$; power splitting factor $\rho = 0.2$; and SIS factor $\chi = 1$ unless otherwise stated.

Firstly, Figure (2) illustrates the primary user (PU) SNR (γ_p) Vs P_d for FD and HD as simulation of equation (3). It shows that the sensing performance of HD is better which required PU SNR smaller than in FD, because the interference effect from SU transmitted signal (γ_s) on P_d . As well as seen from this figure, the decreasing in χ value which decreasing γ_s lead to a better value of P_d at target value of γ_p , so it can be obtained an acceptable target value of P_d in FD.

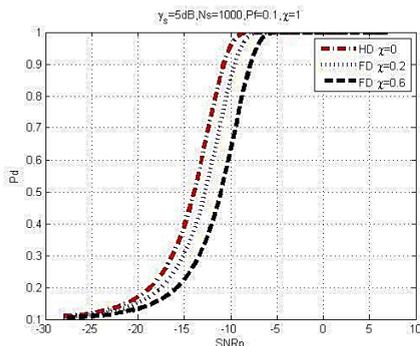


Figure 2 : γ_p Vs P_d

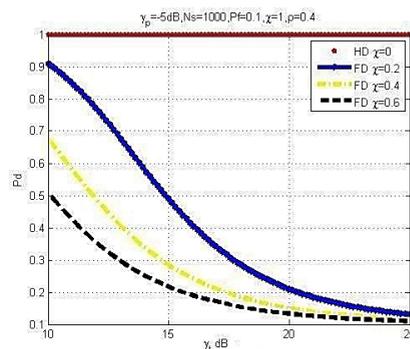


Figure 3 : γ_t Vs P_d

Figure (3) demonstrates the effects of the SU's transmit power γ_t on the sensing performance P_d at different values of χ as simulation of equation (6). As shown, the sensing performance is affected by the γ_t which causes an interference signal to SU A1. Therefore it causes a degradation in the sensing performance. consequently, the transmit power of SU must be decreases as much as possible to obtain an acceptable sensing performance. Also as noted, the performance of the sensing is improved when the SIS factor χ decreases which leads to a low interference power and high P_d .

Figure (4) illustrates the transmitting power SNR (γ_t) of SU Vs SU throughput R with variation in χ as simulation of equations (24,25,27), from the figure it can be observed the achievable throughput of SUs when the transmission Power is changed within a certain range. As shown, there exists an optimal transmit power in the low power range to achieve the maximum possible throughput, and the SU throughput R increases with increasing in γ_t and decreases of SIS factor χ . However the increasing in γ_t will cause degradation in the sensing performance. Also, the SU throughput R will decrease when γ_t become high because FD will suffer from a severe interference signal.

The results from Figure (4) clearly show the tradeoff between transmit power and the SU throughput in the presence of residual self-interference (RSI). It is shown that SU throughput decreases when the value of χ increases at target γ_t due to the effect of the SI, so an optimal tradeoff point appears at the lower values of γ_t . It can be observed that for $\chi = 0$, i.e., perfect SI cancellation, the SU throughput increases with the increases in γ_t .

Practically, the perfect SI cancellation is impossible in practice. In the real cases when $\chi \neq 0$, the SU throughput first increase until it reaches to the maximum point and then decreases, so increasing in γ_t causes decreasing in throughput which can reach to 0 at high γ_t due to the degradation in the sensing performance. This figure is used in the design of an FD CRN to select the best value of γ_t which does not affect the sensing performance and SU throughput.

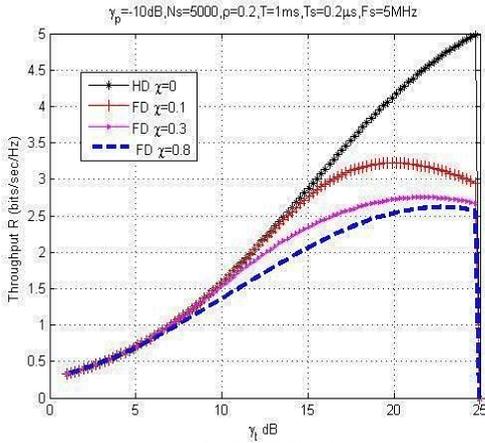
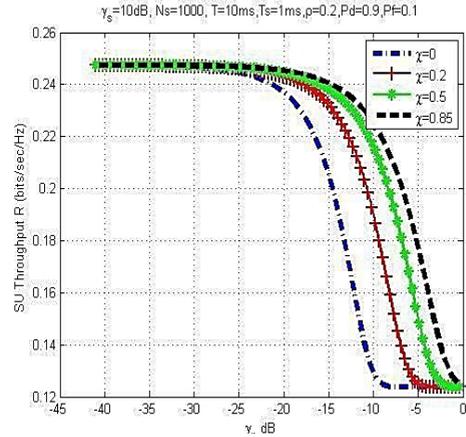
Figure 4 : γ_p Vs SU RFigure 5 : γ_p Vs SU R

Figure (5) as simulation of equations (25,27) clarify the SU throughput R versus the SNR of the received signal from PU γ_p for both FD "when $\chi \neq 0$ " and HD "when $\chi = 0$ ". This figure shows the maximum SU throughput in FD spectrum sensing and the SU throughput in HD spectrum sensing. It is obvious that FD spectrum sensing can greatly increase the SU throughput compared with HD spectrum sensing at higher γ_p . This is because in FD spectrum sensing, it is possible for SU to detect the idle spectrum during all SU frames, while in HD the SU dose not able to detect the idle spectrum when the PU is not active through the transmission duration. Also it can be observed that the SR throughput decreases at the higher received power due to the presence of PU that means the ST must stop its data transmission to protect the PU from the interference.

Figure (6) shows the SNR of the SU transmitted power γ_s from A2 to A1 after SIS versus Energy Harvesting at different values of χ as simulation of equation (15). It is noted that EH is increasing with increasing γ_s because the increasing in γ_s means more energy harvested from SU A2.

Figure (7) shows the SNR of the PU transmitted power γ_p to SU A1 versus Energy Harvesting at different values of χ as simulation of equation (15). It is noted that EH is increasing with γ_p increasing, because the increasing in γ_p means more energy harvested from PU and also means high power for the SU for sensing therefore the sensing performance will be improved. Also shows that the EH increases with increasing in χ due to the EH from SU transmitted power.

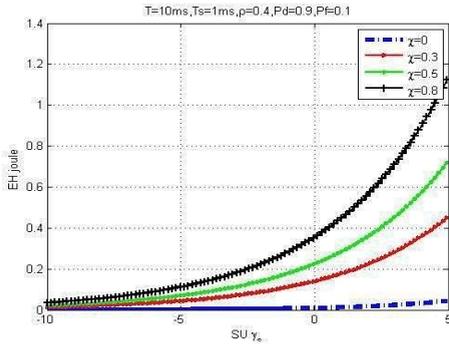


Figure 6 : EH Vs SU γ_s

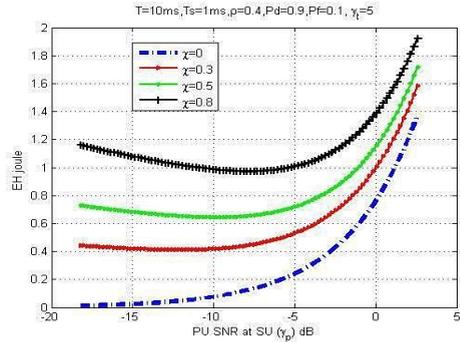


Figure 7 : EH Vs SU γ_p

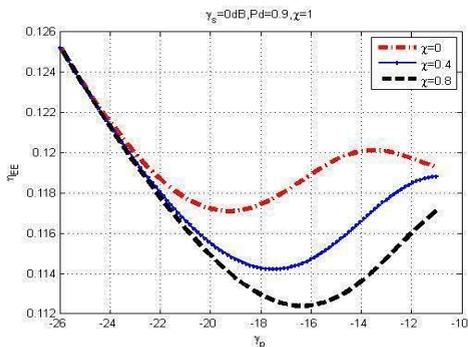


Figure 8 : η_{EE} Vs SU γ_p

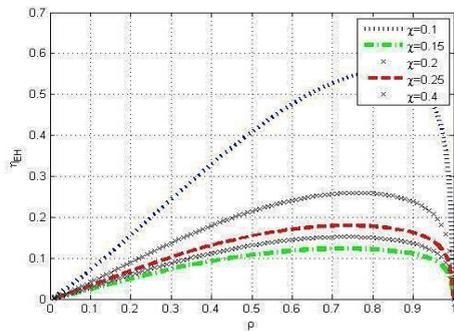


Figure 9 : η_{HE} Vs ρ

Figure (8) shows the simulation of equation (29) for the sensing SNR γ_p and Energy Efficiency η_{EE} with different values of χ . It is obviously noted that the η_{EE} decreases with increasing γ_p and decreasing χ . These results show that the increment in γ_p is done as a result of presence of PU and no data transmitted from SU, so the η_{EE} is decreasing. On the other hand, when γ_p is low that means absence of PU, so the SU uses the idle channel for its data transmission which leads to increasing in SU R and therefore increasing in η_{EE} .

The performance of the harvesting energy efficiency η_{HE} with the effects of power splitting factor ρ are shown in Figure (9) at different values of χ as simulation of equations (15,16,30). As shown, the η_{HE} is slowly increasing with increasing in ρ and decreasing in χ decreases. That means the increasing in ρ leads to decreasing in received power used for EH but the higher power used for the spectrum sensing leads to a better sensing performance. Also noted, when $\rho = 1$, all the received power are used for the sensing processes therefore no energy is remaining for EH.

7. Conclusion and Future works:

The most results in this paper for the Energy Harvesting Cognitive Radio Network using full-duplex technique can be summarized as the following:

- Result (1): There is optimum values of λ_1 and λ_0 to keep P_d and P_f at acceptable values according to the receiving signal from PU.
- Result (2): When the SU transmit power become high, the FD suffers from self-interference which causes decreasing in R.
- Result (3): There are optimal values of γ_t and γ_s in the low power range to achieve maximum throughput, and the optimal power is decreasing with the increment of SIS factor χ .
- Result (4): The secondary throughput R is increasing as the received power at the secondary receiver is increasing.
- Result (5): The self-interference signal (SI) caused the degradation in the sensing performance and the SU throughput, so the SI must be decreased as much as possible.

And the main conclusion from this paper is that the performance of FD is better than HD in the following aspects:

- SU throughput rate R.
- PU protection.
- Energy Harvesting performance.
- Harvested Energy rate.
- the spectrum utilizations.

Focusing on the major issues of this paper, the models and the results of this paper can be used for future works on the development of full duplex technique for Energy Harvesting Cognitive Radio that has other research problems. There are some optimization research issues which still have not been well investigated in this paper such as:

- Throughput Optimization problem in Full-duplex Energy Harvesting Cognitive Radio.
- Energy and Harvesting Efficient Optimization problem in Full-duplex Energy Harvesting Cognitive Radio.
- Full-duplex Energy Harvesting in cooperative Cognitive Radio.

- Integrating Full-duplex Energy Harvesting Cognitive Radio with other Networks such as internet of things and WiFi networks and mobile networks.
- Design and Implementation of Full-duplex Energy Harvesting on Hardware Devices.

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Appendix A: Markove chain models of Users States Transitions:

The proposed model in this paper assume the state of PU can change at any time (i.e. PU may again occupy the idle spectrum), so the activity of PU must be considered as a random distribution. The activity states of PU (busy, idle) is modeled by the discrete-time Markov chain (DTMC). In Full Duplex CRN the sensing is done continuously, so the change in the state of PU can be detected at any instance of the transmission frame, while the SU in HD cannot detect the states change of the PU transitions.

For collision ratio, the system design needs all the four states because of the relationship among the collision ratio, sensing error probabilities, and the state of PU. Since this paper is considered the time slots in which the PU may be changes its state is related together with the other time slots, so, the system state transitions can be modeled as a Discrete-Time Markov Chain (DTMC), therefore the system can be shown as total time-slotted with T slot duration length [14].

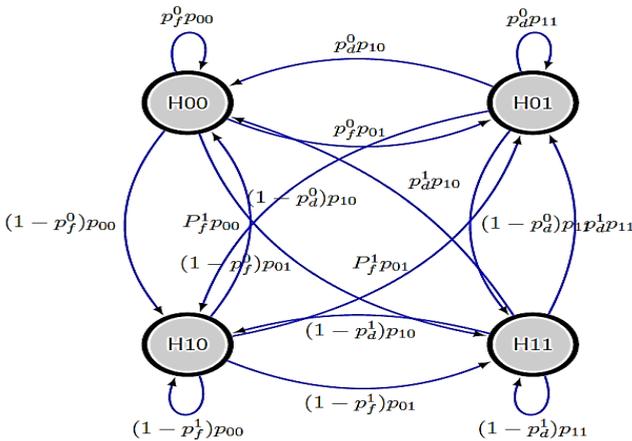


Figure A1 : State transition of the system

The state transition of PU from state i to state j represented by p_{ij} , also the four states of PU represented by [P0,P1,P2,P3]. Where P0=prob[H00], P1=prob[H01], P2=prob[H10], and P3=prob[H11].

The change among the four states modeled as four DTMC as illustrated in Figure (A1).

The probabilities derivation of the PU and SU can be done by obtain the SU states as independent from PU states, so SU state change or stay in the same state according to PU activity state, also PU states is independent from SU states.

As shown in Figure (A1) the four states of PU and SU are denoted by $H_{ij}=0,1$. The probabilities for the system staying in each state ($P_i, i=0,1,2,3$) can be determined by take the steady-state distribution of the Markov chain into account as follows:

$$\Psi P = P \quad (\text{A.1})$$

Where $P = [P_0, P_1, P_2, P_3]^T$ are the steady states probabilities vector, and Ψ is the matrix of the state transitions obtained from Figure (A1) as follows [author]:

$$\Psi = \begin{bmatrix} p_f^0 p_{00} & p_a^0 p_{10} & p_f^1 p_{00} & p_a^1 p_{10} \\ p_f^0 p_{01} & p_a^0 p_{11} & p_f^1 p_{01} & p_a^1 p_{11} \\ (1 - p_f^0) p_{00} & (1 - p_a^0) p_{10} & (1 - p_f^1) p_{00} & (1 - p_a^1) p_{10} \\ (1 - p_f^0) p_{01} & (1 - p_a^0) p_{11} & (1 - p_f^1) p_{01} & (1 - p_a^1) p_{11} \end{bmatrix} \quad (\text{A.2})$$

Then by solving the equation $\Psi P = P$ an $\sum_{i=0}^3 P_i = 1$ $P_i = 1$ it can be find all probabilities of the four states and derive the probability of collision and spectrum waste ratio. The solving of that matrix is out of scope this paper. however, from solving markove equations it can be find the probability that stay in the collision state H_{ij} is $P_c = P_3$ [14]. To ensure that the result is true, the probabilities of PU is busy $P_B(t)$ and idle $P_I(t)$ can be considered as [14]:

$$P_B(t) = P_1 + P_3 = \frac{p_{01}}{p_{01} + p_{10}} \approx \frac{\tau_1}{\tau_1 + \tau_0}$$

$$P_I(t) = P_0 + P_2 = \frac{p_{10}}{p_{01} + p_{10}} \approx \frac{\tau_0}{\tau_1 + \tau_0}$$

which are the same results as obtained by take only the PU traffic into account.