Throughput Analysis in Cognitive Radio Networks with Imperfect Sensing Using Slotted Aloha and CSMA Protocols

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Abstract— **Cognitive radio is a promising technology for the next generation of wireless networks. Performance analysis of multiple access protocols in cognitive radio networks has been presented in the literature, but only considering the unreal situation of perfect channel sensing. In this paper, we extend an analytical model previously proposed to evaluate the performance of a cognitive radio network using Slotted Aloha and CSMA (Carrier Sense Multiple Access) multiple access protocols. In our new model, we consider imperfect channel sensing, resulting in more realistic performance analysis. After that, we investigate the influence of the parameters related to the performance of the channel sensing process in the performance of the network.**

Keywords— ***Cognitive Radio; Multiple Access; Imperfect sensing; Throughput; Performance analysis***.

I. INTRODUCTION

Cognitive Radio (CR) is a new paradigm for the design of wireless communications systems, which aims to enhance the utilization of the Radio Frequency (RF) spectrum [1][2]. The motivation behind CR is the scarcity of radio frequency spectrum due to the increase in traffic in wireless networks. A study made by the Spectrum Policy Task Force (SPTF) of the Federal Communications Commission (FCC) has shown that some frequency bands are heavily used by licensed systems, in some particular locations and periods of time, but there are also many frequency bands that are only partly occupied or largely unoccupied [2]. A way to overcome these limitations is to promote changes in the current licensing model, by allowing secondary users (SUs) to access spectrum opportunities, also called spectrum holes, without causing harmful interference to the licensed users or primary users (PUs).

Cognitive Radio is defined as a radio that can change its transmission parameters based on the environment in which it is operating. The main functions of CR include spectral detection, spectrum management, spectral mobility and spectrum sharing [2]. Its paramount objective is to provide adaptability to wireless transmission systems through Dynamic Spectrum Access (DSA) in order to optimize the performance of the system and improve the use of spectrum.

The components of the cognitive radio network architecture can be classified into two groups: primary network and secondary network. The primary network is the licensed network infrastructure, which is authorized to exploit a certain band of the frequency spectrum. The secondary network is not licensed to operate in the designated band and its stations can access the spectrum in an opportunistic way, exploring the bands unused by PUs.

Medium Access Control (MAC) is a key issue in Cognitive Radio Networks (CRN). In the primary network, the MAC protocols are important in order to organize the access to the channel of different PUs. In the secondary network, the MAC protocols have the responsibility to organize the access of SUs to the idle channels of the primary network and prevent the licensed network from harmful interference [3].

In [3], the performance of CRN is analyzed for several MAC protocols, including the analysis that considers Slotted Aloha in the primary network and Slotted Carrier Sense Multiple Access (CSMA) in the secondary network. In these analyses, the capture effect is taken into account in the primary and secondary networks. However, the analyses presented in [3] do not consider the Packet Error Rate (PER) due to simultaneously transmission of two or more stations. This lack in the performance analysis has been solved by the extension presented in [4]. However, the analyses presented in [3] and [4] do not consider one important aspect, the imperfect sensing in the secondary network, and therefore can lead to unrealistic results. Thus, the main goal of this paper is to extend the analyses presented in [3] and [4], by considering the effect of imperfect sensing in the mathematical formulation.

The remainder of this paper is organized as follows: in Section II, we present the proposal of a new analytical model to compute the performance of the primary and secondary networks considering the effect of imperfect sensing; Section III presents numerical results and a comparison between the results obtained with our model with the results previously presented in [4]; the conclusions are given in Section IV.

II. THE PROPOSED NEW SYSTEM MODEL

In the network architecture considered in this paper, the primary network uses Slotted Aloha as multiple access protocol and the secondary network uses Slotted-CSMA. The primary access point (PAP) and the secondary access point (SAP) provide services for primary and secondary networks, respectively. In the primary network, there are N_p PUs and, among these, I_p stations are attempting to transmit their data packets during a time slot. On the other hand, the secondary network has N_s SUs and during a given time slot there are J_s SUs attempting to transmit their packets [3][4].

A. *Structure of Time Slot and Mini-Slot*

The channel is time slot based on the primary network and mini-slot based on the secondary network. So, each time slot of Slotted Aloha is subdivided into mini-slots. The duration of each mini-slot is equal to the maximum propagation delay (τ) found in the primary and secondary networks and corresponds to the distance from point *a* to *b* in Figure 1 [3][4].

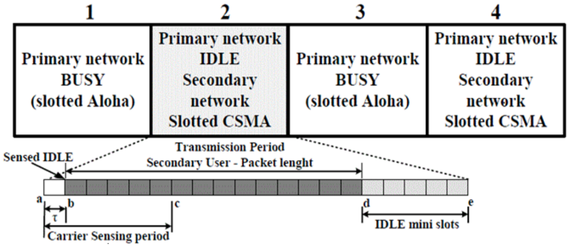

Figure 1. Slots structure of Slotted Aloha for primary users and Slotted CSMA for secondary users.

There are two types of mini-slots: a few intended for carrier sensing, defining the carrier sensing period (S_{mi}), and the most of them intended for packet transmissions, defining the transmission period (T_{mi}) to the SUs, as illustrated in Figure 1 [3][4]. According to Figure 1, the maximum sensing period allowed is from point *a*, i.e., in the beginning of a time slot, to point *c;* the sensing point is set to happen at the beginning of each mini-slot. The distance between point *c* and point *e* is specified as the maximum length of the data packets (T_{mi}) from the secondary network in terms of the number of mini-slots. Therefore, the packet length of the secondary network is shorter than the packet length of the primary network due to the carrier sensing period [3][4].

B. *Fading Model for Primary and Secondary Network*

In this paper, following [3] and [4], a quasi-static fading model is used, according to the Rayleigh statistical model, wherein the instantaneous power of the received signal have an exponential distribution, as represented by (1):

$$p(\delta) = \frac{1}{\Delta} e^{-\delta/\Delta}. \tag{1}$$

where Δ is the mean power of the received signal and δ is the instantaneous power of the received signal.

C. *Channel Sensing*

The spectral sensing is one of the most critical parts of the CRN. Before transmit, the secondary network performs channel sensing, which can be modeled as a hypothesis testing problem. We assumed that H_0 denotes the hypothesis that the channel is inactive, and H_1 denotes the hypothesis that the channel is active. Thus, $\hat{H}_0$ denotes the decision that there are not primary users in the channel and $\hat{H}_1$ denotes the decision that there are primary users in the channel. With the result of the decision and the true nature of the activity of the primary network, we can define the probability of a correct decision about the channel when a PU is active, given by (2), and the probability of false alarm when the primary network is inactive, given by (3) [5][6]:

$$P_d = \Pr\left[\hat{H}_1 \middle| H_1\right] \tag{2}$$

$$P_f = \Pr\left[\hat{H}_1 \middle| H_0\right] \tag{3}$$

D. *The Interfering Model*

In the model used in [4], denominated original model, the sensing process is considered perfect. As a consequence, if the primary network uses a time slot, the SUs do not transmit in that slot. Thus, only other PUs can interfere with the transmission of a given PU. Similarly, the SUs will transmit only in idle slots (slots without transmission of PUs) and, as a consequence, only other SUs can interfere with the transmission of a given SU. In the model proposed in this paper, we consider imperfect sensing, resulting in that SUs and PUs can transmit simultaneously and therefore can interfere with each other.

E. *Traffic Model for the Primary and Secondary Network*

During a time slot, any PU that is not in a retransmission state can generate a new packet with probability σ_p. Therefore, the probability that a PU does not generate any packet is ($1-\sigma_p$). If a new packet is generated in the network, it is transmitted immediately in the next time slot. If the packet is not successfully transmitted during a time slot, it is retransmitted with probability σ_p in the following time slots until that packet is successfully transmitted. Users in the retransmission state cannot generate new data packets.

In the secondary network, using Slotted CSMA multiple access protocol, each SU can generate a new packet with probability (σ_{mi}) during a mini-slot. Consequently, the probability of an SU does not generate a new packet is ($1-\sigma_{mi}$). Whether an SU is in the retransmission state, it cannot generate a new packet. In the beginning of a time slot, the SAP senses the channel and decides if it is idle or busy by the PU. If the decision is given as busy, a SU with a packet to transmit does not use the channel, stores the packet in a buffer and try again to transmit the packet in the next time slot. If the SAP decision regarding of the channel is idle, an SU with a packet to transmit has permission to sense the channel in the next detection point inside the carrier detection period. If the decision of the SU is idle, the packet is transmitted immediately. If the decision of the SU is busy, the packet is stored in a buffer and the SU attempts to transmit it again in the next time slot. If an SU generates a packet outside of the carrier detection period, this packet is stored and the transmission is attempted in the next time slot. If an SU transmits a packet and a collision occur, the SU goes to the retransmission state and tries to retransmit the packet in the next time slot.

When the channel state is busy, the SAP and SU have P_{dSAP} and P_{dSU} as the detection probability of the channel state, respectively. However, if the channel state is idle, the

SAP and SU have P_{fSAP} and P_{fSU} as the probability of false alarm, respectively.

F. Probability of Secondary User Transmissions in a Given Time Slot

To compute the performance of primary and secondary networks, we need to calculate the probability mass function (PMF) of the number of SUs attempting to transmit in a given time slot.

The computation of the probability of J_s SUs attempting to transmit in a time slot ($P_{tx}(J_s)$) depends on the state of the channel. If the channel is busy, the transmission will only occur if the SAP miss detects the status of the channel, which occurs with probability $1- P_{dSAP}$, and the SU also miss detect the status of the channel, which occurs with probability $1- P_{dSU}$. If the channel is idle, the SU only transmits if the SAP correctly detects the status of the channel, with occurs with probability $1-P_{fSAP}$, and the SU also correctly detects the status of the channel, with occurs with probability $1-P_{fSU}$. In both hypotheses, channel busy or idle, this probability can be computed by (4), where $P_{SAP} = P_{dSAP}$ if the channel is busy and $P_{SAP} = P_{fSAP}$ if the channel is idle and $P_{SU} = P_{dSU}$ if the channel is busy and $P_{SU} = P_{fSU}$ if the channel is idle.

In (4), S_{mi} denotes the number of mini-slots that compose the carrier detection period, numbered from 0 to S_{mi-1}. The number of stations that will detect the carrier at the beginning of mini-slot i is equal to the number of stations that generated packets during the mini-slot $i-1$. The stations that generated packets in the S_{mi-1} mini-slot will detect the carrier in the beginning of the S_{mi} mini-slot, which already belongs to the transmission period. Still in (4), Bi $(i = 0,1,2 ..., S_{mi})$ denotes the maximum number of stations that can generate packets to be transmitted starting from the mini-slot i; X_i $(i = 0,1,2 ..., S_{mi})$ denotes the number of stations that effectively generated packets to be transmitted starting from the mini-slot i; j_i $(i = 0,1,2 ..., S_{mi})$ denotes the number of stations that missed detected the status of the channel and effectively transmitted starting from the mini-slot i. The other parameters define the limits in the sums and are defined in Table (1).

$$P_{tx}(J_s)=(1-P_{PAS})\sum_{x_0=0}^{B_0=N_s}\sum_{j_0=C_0}^{D_0}\sum_{x_1=A_1}^{B_1}\sum_{j_1=C_1}^{D_1}\cdots\sum_{x_{s_{mi}-1}=A_{s_{mi}-1}}^{B_{s_{mi}-1}}\sum_{j_{s_{mi}-1}=C_{s_{mi}-1}}^{D_{s_{mi}-1}}\sum_{x_{s_{mi}}=A_{s_{mi}}}^{B_{s_{mi}}}$$
$$\left(\left(\binom{B_0}{x_0}\sigma_{mi}^{x_0}(1-\sigma_{mi})^{B_0-x_0}\right)\left(\binom{x_0}{j_0}(1-P_{SU})^{j_0}(P_{SU})^{x_0-j_0}\right)\right)$$
$$\left(\left(\binom{B_1}{x_1}\sigma_{mi}^{x_1}(1-\sigma_{mi})^{B_1-x_1}\right)\left(\binom{x_1}{j_1}(1-P_{SU})^{j_1}(P_{SU})^{x_1-j_1}\right)\right)\cdots$$
$$\left(\left(\binom{B_{s_{mi}-1}}{x_{s_{mi}-1}}\sigma_{mi}^{x_{s_{mi}-1}}(1-\sigma_{mi})^{B_{s_{mi}-1}-x_{s_{mi}-1}}\right)\left(\binom{x_{s_{mi}-1}}{j_{s_{mi-1}}}(1-P_{SU})^{j_{s_{mi-1}}}(P_{SU})^{x_{s_{mi}-1}-j_{s_{mi-1}}}\right)\right)$$
$$\left(\left(\binom{B_{s_{mi}}}{x_{s_{mi}}}\sigma_{mi}^{x_{s_{mi}}}(1-\sigma_{mi})^{B_{s_{mi}}-x_{s_{mi}}}\right)\left(\binom{x_{s_{mi}}}{j_{s_{mi}}}\left((1-P_{SU})^{j_{s_{mi}}}\right)(P_{SU})^{x_{s_{mi}}-j_{s_{mi}}}\right)\right). \tag{4}$$

TABLE 1. VALUES THAT THE LOWER AND UPPER BOUNDS CAN ASSUME IN EACH MINI-SLOT OF THE CARRIER SENSING PERIOD

Mini-Slots	Lower and Upper Bounds in the Packet generation	Lower and Upper Bounds in the Packet transmission
$N=1$	$A_0=0.$ . . . . . $B_0=N_s$ $0 \le x_0 \le B_0$	*if* $(N_s - x_0) \ge J_s$ $C_0=0$ *else* $C_0= J_s - (N_s - x_0)$. *if* $x_0 \le J_s$ $D_0= x_0$ *else* $D_0=J_s$ $P_{SU}= P_f$ $C_0 \le j_0 \le D_0$
$N=2$	*If* $(Ns - x_0) \ge (Js-j_1)$ $A_1=0$ *Else* $A_1=(Js-j_1)-(Ns- x_0)$. $B_1=(Ns- x_0)$. $A_1 \le x_1 \le B_1$	*If* $(Ns- x_0- x_1) \ge (Js- J_0)$ $C_1=0$ *Else* $C_1= (J_s- j_0)- (Ns- x_0- x_1)$. *If* $x_1 \le (J_s-j_0)$ $D_1= x_1$ *Else* $D_1=(J_s-j_0)$. *If* $j_0>0$ $P_{SU} =P_d$ *Else* $P_{SU} =P_f$ $\{C_1 \le j_1 \le D_1\}$.
...	...	....
$N=S_{mi}-1$	*if* $(Ns-x_0-x_1-\ldots x_{Smi-2}) \ge (Js-j_1-j_2-\ldots j_{Smi-2})$ $A_{Smi-1}=0$ *Else* $A_{Smi-1}=(Js-j_1-j_2-\ldots j_{Smi-2})-(Ns-x_0- x_1-\ldots x_{Smi-2})$. $B_{Smi-1}=(Ns- x_0- x_1-\ldots x_{Smi-2})$. $A_{Smi-1} \le x_{Smi-1} \le B_{Smi-1}$	*If* $(N_s- x_0- x_1-\ldots x_{Smi-2}+ x_{Smi-1}) \ge (Js-j_0-\ldots j_{Smi-2})$ $C_{Smi-1}=0$ *Else* $C_{Smi-1}= (J_s- j_0-\ldots j_{Smi-2})-(N_s- x_0- x_1-\ldots x_{Smi-2}+ x_{Smi-1})$. *If* $x_{Smi-1} \le (J_s-j_0 -\ldots j_{Smi-2})$ $D_{Smi-1}= x_{Smi-1}$ *Else* $D_{Smi-1}=(Js-j_0- \ldots j_n+ j_{Smi-2})$ For any of the j $(j_0, j_1,j_2 \ldots j_{Smi-2})>0$ $P_{SU}=(P_d)$ *Else* $P_{SU} =(P_f)$ $C_{Smi-1} \le j_{Smi-1} \le D_{Smi-1}$
$N= S_{mi}$	$\{ A_{Smi}=Js-J_0-J_1-\ldots- j_{Smi-1}\}$ $B_{mi}=(Ns- x_1- x_2-\ldots x_{Smi-1})\}$. $\{ A_{Smi} \le x_{Smi-1} \le Bs_{mi}$	$\{C_{Smi}=Js-J_0-J_1-\ldots J_{Smi}\}$ For any of the j $(j_0, j_1,j_2 \ldots j_{Smi-1})>0$ $P_{SU} =(P_d)$ *Else* $P_{SU} =(P_f)$ $\{J_{Smi} =J_s-j_0-j_1-\ldots j_{Smi-1} \}$

To validate the PMF expressed by (4), we compare the results obtained with the equation with the results obtained using Monte Carlo simulation.

G. Power Level Applied in the Network

Let X_p and X_s be the mean values of instantaneous power of the concerned packet from primary and secondary networks, respectively. Let Y and Z be the mean values of the interfering powers of one packet from the primary and secondary networks, respectively. Following [3], we define $X_p=Y$ and $X_s=Z$. Having in mind that the SUs work with lower levels of transmission powers, in order to minimize interference in the PU's, denoting the relation between the powers in the primary and secondary networks by γ, we have [3]:

$$\gamma = \frac{X_p}{Z} = \frac{Y}{X_s}. \tag{5}$$

H. Analysis of the Capture Effect

According to [7], the signals arriving at the receiver have different power levels due to different transmission powers practiced by the users and also due to the fading in the wireless channel.

If the ratio between the received power of the concerned packet and the sum of the received powers of all interfering packets is greater than a given threshold, called capture ratio (R), then the concerned packet is captured by the access point.

The capture probabilities for the primary and secondary networks have been analyzed in [4] considering perfect sensing. In this paper, we modify the analyses presented in [4] in order to consider the effect of imperfect sensing.

In the primary network, if a given time slot is occupied by a PU, there are two scenarios in terms of interfering power: the SAP correctly detect the channel as occupied and the interfering power comes only from other PUs; the SAP miss detect the channel as idle and the interfering power comes from other PUs and also from SUs that miss detect the channel as idle too. In this latter case, the PMF of the number of SUs attempting to transmit in a given time slot is given by (4) considering that the channel is busy. Considering these scenarios, the capture probability can be computed by (6).

$$\mathrm{P}_{\mathrm{pcap}\rightarrow\mathrm{PAP}}(I_p,J_s) = \left(\frac{x_p}{\sum_{i=1}^{I_p-1} y_i + \sum_{j=1}^{J_s} z_j} > R \right) = \\ = \left[\left(\left(\frac{\gamma}{R+\gamma} \right)^{J_s} P_{tx}(J_s) \left(\frac{1}{R+1} \right)^{I_p\text{-}1} \right) + \left(\frac{1}{R+1} \right)^{I_p\text{-}1} P_{dSAP} \right] \tag{6}$$

In the secondary network, if a given time slot is occupied by a PU, there is a transmission from SUs only if the SAP and some SUs miss detect the channel as idle. In this case, the interfering power comes from PUs and other SUs; the PMF of the number of SUs attempting to transmit in a given time slot is given by (4) considering that the channel is busy. On the other hand, if a given time slot is idle, there are transmissions from SUs only if the SAP correctly detect the channel as idle and the transmissions come from SUs that correctly detect the channel as idle; the PMF of the number of SUs attempting to transmit in a given time slot is given by (4) considering that the channel is idle. Considering these scenarios, the capture probability can be computed by (7).

$$\mathrm{P}_{\mathrm{pcap}\rightarrow\mathrm{PAS}}(I_p,J_s) = \left(\frac{x_s}{\sum_{i=1}^{I_p} y_i + \sum_{j=1}^{J_s-1} z_j} > R \right) = \\ = \left(\left[\left(\frac{1}{R\gamma+1} \right)^{I_p} + \left(\frac{1}{R+1} \right)^{J_s-1} P_{tx(J_s)} \right] + \left(\frac{1}{R+1} \right)^{J_s-1} P_{tx(J_s)} \right) \tag{7}$$

I. Packet Error Rate Analysis

In this paper, following [4], the PER is calculated for a fading channel as a function of SIR, through the use of a fairly accurate upper bound presented in [8]. The SIR in the primary and secondary networks depends on the number of PUs and SUs attempting to transmit and are given, respectively, by (8) and (9), which I_p is the number of PUs attempting to transmit and J_s is the number of SUs attempting to transmit, whose PMF is given by (4).

$$\Delta_p = \frac{1}{\left(I_p - 1\right) + {}^{J_s}\!/_{\gamma}}, \tag{8}$$

$$\Delta_s = \frac{1}{\gamma I_p + J_s - 1}. \tag{9}$$

Let *f(δ)* be a function that relates the PER with the instantaneous SIR at the receiver in an Additive White Gaussian Noise Channel (AWGN), and *p(δ)* the probability density function of the SIR in the receiver, considering a Rayleigh channel, which has an exponential distribution, as represented in (1).

According to [8], the PER, represented by $P_{ave}(\Delta)$, can be calculated by (10):

$$P_{ave}(\Delta) = \int_0^{\infty} f(\delta)\, p(\delta)\, \mathrm{d}\,\delta, \tag{10}$$

Considering the modulation techniques, packet lengths and coding schemes, it is difficult to compute (10) for a general case. An approximation is then proposed for the upper bound of the PER, according to the following inequality [8]:

$$P_{ave}(\Delta) \cong 1 - \mathrm{e}^{-w_0/\Delta}. \tag{11}$$

The Packet Success Rate (PSR) is then given by:

$$PSR(\Delta) \cong \mathrm{e}^{-w_0/\Delta}, \tag{12}$$

where w_0 is a constant value for Rayleigh channel and its value can be computed by [8]:

$$w_0 = \int_0^{\infty} f(\delta)\,\mathrm{d}\,\delta. \tag{13}$$

Not considering channel coding and considering *n*-bit packets, *f(δ)* can then be obtained as follows [8]:

$$f(\delta) = \left\{1 - \left[1 - b(\delta)\right]^n\right\}, \tag{14}$$

where *b(δ)* is the BER in AWGN channels. Considering a BPSK modulation with coherent detection, *b(δ)* can be calculated by [8]:

$$b(\delta) = \frac{1}{2} erfc(\sqrt{\delta}). \tag{15}$$

Applying (15) in (14) and then (14) in (13), we can compute (using Mathcad software) w_0. Considering *n=127 bits* per packet, the same value used in [8], we obtain $w_0 = 3.4467$.

J. *The Primary Network Throughput for the New model*

The primary network throughput (V_{np}) is defined as the mean number of packets transmitted by the PUs and correctly received by the PAP during a time slot and can be computed by:

$$V_{np} \cong \left[\begin{array}{l} \left(\sum_{i=0}^{N_p} \binom{N_p}{i} \sigma^i{}_p \left(1-\sigma_p\right)^{N_p-i} .i\left[\left(\frac{1}{R+1}\right)^{i-1} .e^{-w_0(\mathrm{i}-1)}(P_{dSAP})\right]\right) + \\ \left(\sum_{i=0}^{N_p}\sum_{Js=0}^{N_s} \binom{N_p}{i} \sigma^i{}_p \left(1-\sigma_p\right)^{N_p-i} . \right. \\ \left. .i\left[\left(\frac{1}{R+1}\right)^{i-1} \left(\frac{\gamma}{R+\gamma}\right)^{J_s} P_{tx(J_s)} .\, e^{-w_0\left(\left(\frac{J_s}{\gamma}\right)+(\mathrm{i}-1)\right)}\right]\right) \end{array}\right] \tag{16}$$

K. *The Secondary Network Throughput for the New Model*

The definition of the secondary network throughput (V_{ns}) is similar to the definition for the primary network: the mean number of packets transmitted by the SUs and correctly received by the SAP during a time slot. However, to consider the overhead due to the detection period used by the CSMA protocol, it is necessary to consider an additional factor, which is the length of the packet in terms of mini-slots (T_{mi}) divided by the total number of mini-slots used in the transmission process, including both transmission period and carrier sensing period (T_{mi} + S_{mi}). The secondary network throughput can be computed by:

$$V_{ns} \cong \left[\begin{array}{l} \left[\frac{T_{mi}.\left(1-\sigma_p\right)^{N_p}}{T_{mi}+S_{mi}} . \sum_{J_s=0}^{N_s} J_s \left[\left(\frac{1}{R+1}\right)^{J_s-1} e^{-w_0\left(J_s-1\right)} P_{tx(J_s)}\right]\right] + \\ \left[\frac{T_{mi}}{T_{mi}+S_{mi}} . \sum_{i=1}^{N_p}\sum_{J_s=0}^{N_s} \binom{N_p}{i} \sigma^i{}_p \left(1-\sigma_p\right)^{N_p-i} . \right. \\ \left. .J_s \left[\left(\left(\frac{1}{R\gamma+1}\right)^{i} \left(\frac{1}{R+1}\right)^{J_s-1} P_{tx(J_s)} .\, e^{-w_0\left((i\gamma)+\left(J_s-1\right)\right)}\right)\right]\right] \end{array}\right] \tag{17}$$

III. NUMERICAL RESULTS

The curves presented in Figures 2, 3, 4 and 5 show the throughput for the primary network and secondary network. They are plotted as a function of the primary traffic load, defined as $G_p = N_p\sigma_p$, considering the original model presented in [4] and the new model proposed here, which take into account the imperfect sensing of the channel. To compare the numerical results between the models, we considered the same parameters used in [4], i.e., N_p=N_s=10, w_0=3.4467, γ=10 and R=3 *dB*, S_{mi}=5 and T_{mi}=10. For the new model, we set additionally the values of P_{dSAP}, P_{dSU}, P_{fSAP} and P_{fSU} as specified in the figures.

In Figures 2 and 3, we plotted the throughput in the primary network varying P_{dSAP} and P_{dSU}, respectively. Analyzing the figures, we can conclude that the performance of primary network tends to decrease as the values of P_{dSAP} or P_{dSU} decreases. The results obtained with the original model are optimistic due to consider a perfect sensing process. Also, we can observe that the effect of imperfect sensing can not be neglected in the performance analysis of the system.

In Figure 4, we plotted the throughput in the secondary network varying P_{fSAP}. The performance of the network tends to decrease according to the value of P_{fSAP} increase. Comparing the models, it is verified that the original model presents an optimistic result in relation to the results obtained with the new model. Again, the effect of the imperfect sensing process can not be neglected in the performance analysis of the system.

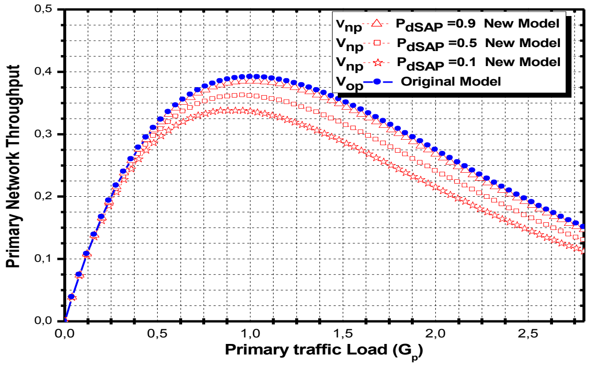

Figure 2. Influence of P_{dSAP} in the primary throughput with P_{dSU}*=0.9.*

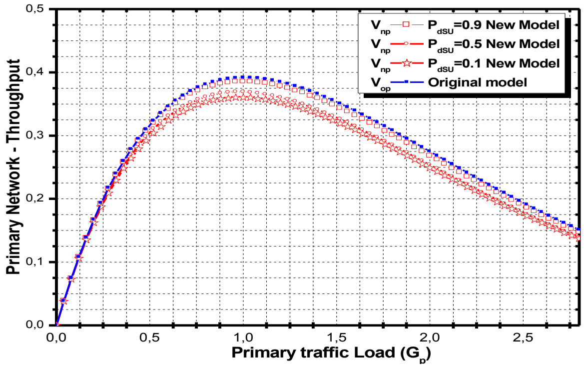

Figure 3. Influence of P_{dSU} in the primary throughput with $P_{dSAP}=0.9$.

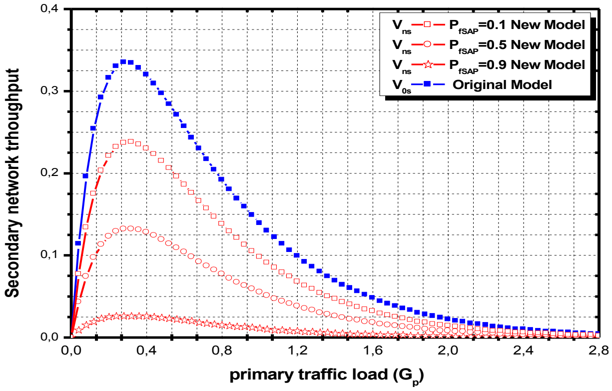

Figure 4. Influence of P_{fSAP} in the secondary network throughput with $P_{dSU}=P_{dSAP}=0.9$ and $P_{fSU}=0.1$.

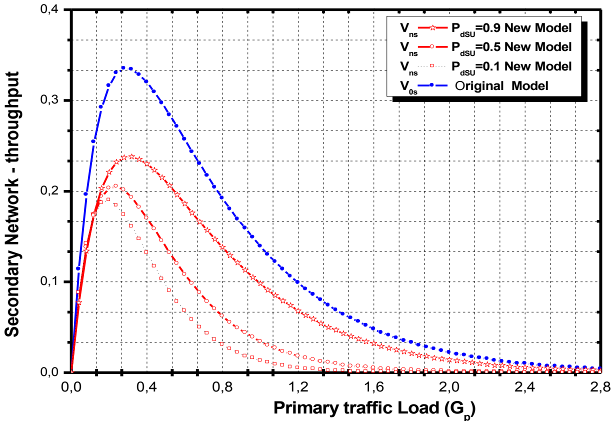

Figure 5. Influence of P_{dSU} in the secondary network throughput with $P_{dSAP}=0.9$ and $P_{fSU}=P_{fSAP}=0.1$.

In Figure 5, we plotted the throughput in the secondary network varying P_{dSU}. Analyzing the figure, we can conclude that the performance of the network tends to decrease as the value of P_{dSU} decreases. Once more, the original model presents an optimistic result in relation to the results obtained with the new model and the effects of the imperfect sensing process can not be neglected in the performance analysis of the network.

IV. CONCLUSIONS

In this paper, we extended the analysis presented in [4], considering the effect of imperfect sensing in the throughput of a cognitive radio network that uses Slotted Aloha and CSMA multiple access protocols in the primary and secondary network, respectively. We conclude that the throughput in the primary and secondary network reduces when we consider the effects of the imperfect sensing and, therefore, the effect of the imperfect sensing in the performance of the networks can not be neglected. Also, we analyze the influence of the parameters P_{dPAS}, P_{dSU} , P_{fPAS} and P_{fSU} in the performance of the system. As a future study, one can investigate the influence of channel coding and cooperative sensing techniques in the performance of the system. Also, one can analyze the performance of the system in terms of delay.

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