A New Throughput Analysis in Cognitive Radio Networks Using Slotted CSMA

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Abstract— **Cognitive Radio Networks (CRN) are a new area of interests for researchers and a new technology for the next generation wireless networks. Multiple access protocol is an important issue to define the networks performance. In this paper, the throughput of a primary and secondary network is analyzed considering the Capture Effect in both systems and the Packet Error Rate (PER) due to the interference between primary and secondary stations, considering that the slotted Aloha protocol is proposed for the licensed network and Slotted Carrier Sense Multiple Access (CSMA) protocol is used in the secondary network.**

Keywords- Cognitive Radio; Multiple Access; Throughput; Performance analysis

I. INTRODUCTION

The radio frequency spectrum is a natural resource [2] and it is partitioned into several bands that are generally attributed to licensed holders through long-term agreements [3][4]. Inside frequency spectrum there are some unlicensed portions reserved for industrial, scientific or medical (ISM) purposes and they are commonly used for data communication in smaller networks [3].

The studies and measurements performed by the Spectrum Policy Task Force (SPTF), linked to the Federal Communications Commission (FCC), concluded that certain spectrum bands are heavily used by licensed or unlicensed users (ISM users), while other spectrum fractions are used occasionally or rarely, depending on geographic location and time [2][5]. Also according to [6], in the future there could be scarcity of this precious resource due to increasing demand powered by a variety of factors, like the rapid economic growth of the telecommunications sector and the convenience offered by them, the emerging services and applications, the increasing of the human mobility and the appearance of new technologies [6].

Changes in the policy for the frequency spectrum that become more flexible the access to this resource, by using dynamic spectrum access (DSA), and the improvement in the spectrum management procedures would improve the efficiency in the using of this natural resource and would avoid its possible scarcity [2] [3] [4] [6]. According to [5], the DSA becomes viable by the emerging technology of the cognitive radio (CR). It is a new concept in the development of wireless communication systems enabling more efficient use of radio spectrum and, therefore, it is a strong candidate as a technological solution for the future wireless networks, so-called NeXt Generation (xG) networks or cognitive radio networks.

In [5], CR is defined as a radio that can change its transmission parameters based on the interaction with the operating environment and its main goals are to provide reliable and seamless communication and to enable the efficient spectrum utilization. The cognitive radios must also be able to reconfigure their communication parameters rapidly and in the real time [2].

The cognitive radio networks can be defined as "networks that can dynamically alter their functionality and/or topology in accordance with the changing needs of its users, taking into account current environmental conditions. This dynamic modification is done in accordance with applicable business rules and regulatory policies" [7].

The CRN architecture is formed by two groups: the primary network and the secondary network. These groups can coexist in the same geographic region and they can operate in the same spectrum band. According to [4], the primary network is an existing network where primary users (PU) have license to operate in a specific frequency band. Licensed users have higher priority in channel access. The secondary networks, or cognitive networks are those that do not have license to operate in the desired band [4] and the so-called secondary users (SU) operate in such network. According to [8], the secondary users have lower transmission priority and they exploit the frequency spectrum in an opportunistic fashion, through the spectrum holes and without causing harmful interference to licensed users transmissions.

According to [1], in the primary network, the protocols for medium access control (MAC) are important to organize access of the different primary users to the channels. In the secondary network, the MAC protocols are responsible for organizing access of the secondary users to the free primary network channels, avoiding or making the interference acceptable in the primary network.

The network throughput is affected by the capture effect. In [1], the performance of cognitive radio networks (CRN) is analyzed for several MAC protocols, including an analysis that considers using Slotted Aloha in the primary network and the slotted carrier sense multiple access protocol (CSMA) in the secondary network. In these analyzes the Capture Effect is also taken into account in primary and secondary networks: if the difference between the power level of a concerned packet signal in relation to others interfering packets is higher than a threshold called capture ratio (R), then the concerned packet can be detected by the receiver, whereas all others fail in medium access [9].

However, the analysis introduced in [1] does not consider the possible errors due to interference during the packet detection. In this paper, we extend the analysis of [1], taking into account the packet error rate due to multiple access scheme and their effects on the networks throughput.

The remainder of this paper is organized as follows. In Section II, we present the original model used in [1] for performance analysis; a new system model is introduced in Section III and the networks throughput is evaluated considering the PER; Section IV introduces and compares the analytical results for both models; and our conclusions are shown in Section V.

II. THE ORIGINAL SYSTEM MODEL AND ITS PERFORMANCE ANALYSIS

The Fig. 1 shows the network architecture analyzed in [1]. The primary network uses Slotted Aloha as multiple access protocol to access the medium and in the unlicensed network is considered Slotted-CSMA protocol. The primary access point (PAP) and the secondary access point (SAP) provide services for primary and secondary networks respectively. All primary users can be viewed by SAP and vice versa. In the primary network there are N_p primary users (PU) and among these, I_p stations are attempting to transmit their data packets during a time slot. On other hand, the secondary network has N_s secondary users (SU). During a time slot, there are J_s unlicensed users attempting to send their packets [1].

The primary users have priority to transmit their data packets and, therefore, the SUs sense the channel to avoid interference with PUs and to identify clearly the spectrum holes that occur when a time slot of slotted aloha is idle.

The Fig. 2 shows the structure of time slot for slotted aloha and slotted CSMA. In the primary network, each time slot can be busy or idle, depending on transmission states of PUs during a time slot. If there is no primary user attempting to transmit packets at the beginning of a time slot, then it is considered idle. This spectrum opportunity can be exploited by the secondary users [1].

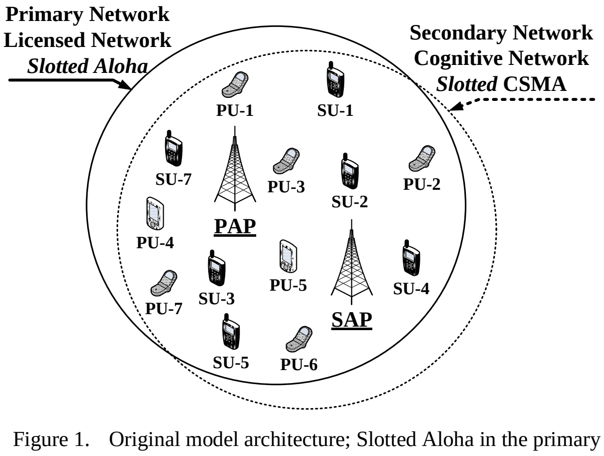

Figure 1. Original model architecture; Slotted Aloha in the primary network and Slotted CSMA in the cognitive network

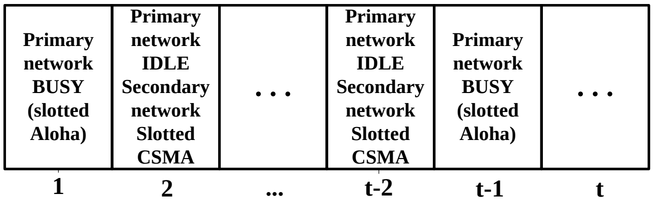

Figure 2. Slots structure of Slotted Aloha for primary users and Slotted CSMA for secondary users

A. *Primary Network Analysis*

According to the traffic model introduced in [1], 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 [1].

1) Fading Model in the Primary Networks: let x_p be the instantaneous power of a concerned packet signal in the primary network and be y_i the instantaneous power of the interfering packets signals generated by the others PUs during a time slot. The fading model considered in [1] is a Rayleigh fading channel with the following exponential distributions,

$$p_x(x_p) = \frac{1}{X_p} e^{-x_p / X_p} \qquad (1)$$

$$p_y(y_i) = \frac{1}{Y_i} e^{-y_i / Y_i} \qquad (2)$$

where X_p and Y_i are the average power of concerned and interfering packet signals, respectively. In [1], $X_p = Y_i$.

2) Capture Effect in the Primary Network: according to [1] and [9], the signals arriving at the receiver have different power levels due to transmission power practiced by the user, fading or shadowing. In this case, whether the power of the concerned data packet from a PU is greater than the sum of the powers levels of all interfering packets in this network and satisfies a given threshold, so-called capture ratio (R), the concerned packet can be detected by PAP and all others interfering users fail in access medium. Thus, the probability of capture ($P_{cap->PAP}$) can be calculated as [1],

$$P_{pcap->PAP}(I_p) = \Pr\left(\frac{x_p}{\sum_{i=1}^{I_p-1} y_i} > R \right) = \left(\frac{1}{R+1} \right)^{I_p-1}. \qquad (3)$$

Where I_p represents the total numbers of simultaneous transmitting primary users at a given time slot [1].

3) Primary Network Throughput: according to [1], the primary network throughput, S_{po}, can be calculated as below,

$$S_{po} = \sum_{i_p=0}^{N_p} i_p \binom{N_p}{i_p} \sigma_p^{i_p} \left(1-\sigma_p\right)^{N_p-i_p} \left(\frac{1}{R+1}\right)^{i_p-1} . \qquad (4)$$

B. Cognitive Network Analysis for the original model

In this network, Slotted CSMA protocol is used for medium access and its proposed slot structure is presented in the Fig. 3 [1].

In the Fig. 3, the first and third time slots of the primary network are busy, i.e., they are used by PUs. The second and fourth ones represent spectral opportunities and they can be exploited by SUs. Each of idle time slots of Slotted Aloha is subdivided into mini-slots. So, the channel is time slot based for primary network and mini-slot based for secondary users. The duration of each mini slot is equal to the maximum propagation delay (*p*) found in the primary and secondary networks and corresponds to the distance from point *a* to *b* in the Fig. 3 [1].

There are two kinds of mini-slots: (1) few are designed for carrier sensing period (S_{mi}), and (2) the most are aimed for packet transmissions (T_{mi}) of the SUs [1]. According to the Fig. 3, the maximum sensing period allowed is from point *a*, i.e., the beginning of an idle time slot, to point *c* and 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 [1].

1) Traffic model for the secondary network: in the secondary network, using Slotted CSMA as protocol to access the channel, each SU can generate a new packet with probability (σ_{mi}) during a mini-slot. Consequently, the probability of a SU does not generate a new packet is (1-σ_{mi}). Whether an unlicensed user is in the retransmission state, it cannot generate a new packet [1].

During an idle or busy time slot in the primary network, if a new packet is generated by a SU within carrier sensing period of a mini-slot, it senses the channel in the following sensing point of the carrier sensing period. If the channel is idle, its packet is transmitted immediately. If the channel is busy, the SU gives up and starts sensing the channel with probability σ_{mi} during each sensing point of the remaining carrier sensing period in the current time slot, i.e., the point *c* in Fig. 3. And whether the channel remains busy during this carrier sensing period, the process continues with probability σ_{mi} during each sensing point in the following time slots until the channel is idle and the packet is successfully transmitted. If a new packet is generated outside the designated carrier sensing period, the new packet is stored and the station begins to sense the channel with probability σ_{mi} during each sensing point in the following carrier sensing periods until the channel becomes idle and the new packet is successfully transmitted. According to [1], a packet transmission of a SU can start from any sensing point of the carrier sensing period that channel is sensed idle [1].

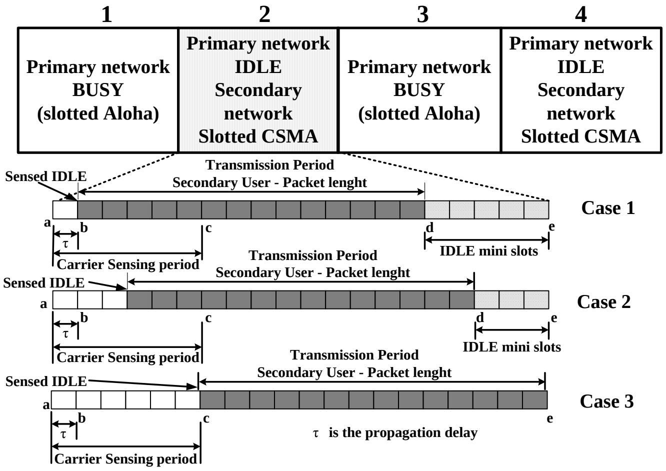

Figure 3. Time slot structure of Slotted CSMA for secondary users

Observing the cases (1) and (2) in the Fig. 3, one can observe that if the channel is sensed idle before the end of the carrier sensing period in the current time slot (point *c* in the Fig. 3), then after the end of packet transmission remains some unused mini-slots [1]. Finally, in the model proposed in [1], SU should be able to sense the channel and determine if it is busy or not. The idle time slots represent spectral opportunities that are disputed by the secondary users within an environment for cooperation between themselves.

2) Fading Analysis and Capture Effect for the Secondary Network: let x_s and z_j be instantaneous power level of the concerned packet signal and the interfering packet signals originated in this network, respectively. In [1] is considered a Rayleigh fading channel with the following exponential distributions [1],

$$P_x(x_s) = \frac{1}{X_s} e^{-x_s / X_s} \qquad (5)$$

$$P_z(z_j) = \frac{1}{Z_j} e^{-z_j / Z_j} \qquad (6)$$

where X_s an Z_j are the mean power level of that signals. In Slotted CSMA, the capture probability can also be calculated as below [1],

$$P_{scap->SAP}(J_s) = \Pr\left(\frac{z_j}{\sum_{j=1}^{J_s-1} z_j} > R \right) = \left(\frac{1}{R+1}\right)^{J_s-1} . \qquad (7)$$

Where J_s denotes the number of SUs are attempting packet transmission during an idle time slot and *R* is the Capture Ratio [1].

3) The Secondary Network Throughput: according to [1], the secondary network throughput is defined as the packet length in terms of number of mini-slots divided by the total number of mini-slots that are spent in the process of packet transmission, including in this case both busy and idle slots. Then, the secondary network throughput, S_{so}, is computed by [1],

$$S_{so} = \frac{\left(1-\sigma_p\right)^{N_p} T_{mi}}{(T_{mi}+S_{mi})} \sum_{s=1}^{S_{mi}} \left(\left(1-\sigma_{mi}\right)^{N_s}\right)^{s-1} \times$$
$$\times \sum_{j_s=0}^{N_s} j_s \binom{N_s}{j_s} \sigma_{mi}^{j_s} \left(1-\sigma_{mi}\right)^{N_s-j_s} \left(\frac{1}{R+1}\right)^{j_s-1}. \tag{8}$$

C. Overall Networks Throughput

The overall networks throughput, S_{oto}, is the sum of primary network throughput and secondary network throughput, as calculated below [1],

$$S_{oto} = S_{po} + S_{so}. \tag{9}$$

III. THE PROPOSED NEW SYSTEM MODEL

In this section, we propose an extension to the original model considering the influence of PER in the calculation of throughput. Transmission errors occur during the packet detection due to the network interfering signals. This approach becomes a more realistic model, since the packets received with errors are discarded and retransmitted in the most of data communication applications.

The system architecture shown in Fig. 1 is also used for the new model, as well as the structure of time slots and mini-slots introduced in the Fig. 2 and Fig. 3 in the original model.

In this new model, the USs also use Slotted CSMA protocol to access the medium and they can sense the channel. Thus, during a packet transmission in a given network, primary or secondary, in the SIR calculating are considered only the interfering signals generated by users of that network, i.e., SUs cannot transmit packets when there are PUs attempting to transmit their packets. The Users from cognitive network only can transmit packets when a time slot of the primary network is idle.

A. Packet Error Rate

The knowledge of the packet error rate in communication systems is important, since in most of these systems, data are transmitted in packets rather than bit streams. Moreover, their performance is determined by PER instead of bit error rate (BER) or symbol error rate (SER) [10]. The PER is dependent of the signal-to-interference plus noise ratio (SNIR) in the considered channel. However, as in [11], the additive noise is negligible in interference-limited channels. Therefore the model called signal-to-interference ratio (SIR) is used in this paper.

References [12], [13], [14], [15], [16] and [17] introduce empirical or approximate methods for PER calculating. Their conclusion is that such calculation is quite complex, imprecise and cannot be generalized to the real applications. All proposed methods above to calculate or estimate the PER model the communication channels according to a Markov chain, where the signal-to-noise ratio (SNR) is partitioned into a finite number of states that can range between two and several. The difficulties of working with Markovian models are in to set the transition probabilities of states to reflect the real channel behavior. In [18], [19] and [20] methods for PER calculating are analyzed and is proposed to study such behavior by collecting the real statistical information or even by using suitable simulation tools on computers.

Due to the exposed above, in this paper, we choose to work with the methodology introduced in [10], which allows the calculation of PER as a function of SIR, in a direct and simple fashion by using a highly accurate upper bound for the system analyzed.

Considering that the SUs can listen the channel and they cannot cause interference to PUs, we can obtain the expected value for SIR in the primary network, Δ_p, as below,

$$\Delta_p = \frac{X_p}{(I_p-1)Y_i} = \frac{1}{(I_p-1)}. \tag{10}$$

Taking into account that the SUs compete for idle time slots from the primary network, then the average SIR for the unlicensed network, Δ_s, is given by,

$$\Delta_s = \frac{X_s}{(J_s-1)Z_j} = \frac{1}{(J_s-1)}. \tag{11}$$

Now, let $f(\delta)$ be a function that links the PER with the instantaneous SIR at reception (δ) in a channel with additive white Gaussian noise (AWGN) and $p(\delta)$ is the probability density function of SIR in the receiver, with exponential distribution. According to [10], the average PER, represented by $P_{ave}(\Delta)$, can be calculated by the following integrals,

$$P_{ave}(\Delta) = \int_0^{\infty} f(\delta) p(\delta) d\delta \tag{12}$$

$$P_{ave}(\Delta) = \frac{1}{\Delta} \int_0^{\infty} f(\delta) e^{-\delta/\Delta} d\delta. \tag{13}$$

Considering the modulation techniques employed, packet lengths and the coding schemes used, the resolution of (13) for the general cases is quite difficult. Then in [10] an approximation to calculate the PER by upper bound is proposed, according to the following inequality,

$$P_{ave}(\Delta) \leq 1 - e^{-w_0/\Delta}. \tag{14}$$

The successfully transmitted packets rate (PSR) is then given by the equation below,

$$PSR \geq e^{-w_0/\Delta}. \tag{15}$$

Where w_0 is a constant value for the Rayleigh fading channel and can be obtained through the integral below [10],

$$w_0 = \int_0^{\infty} f(\delta) d\delta. \tag{16}$$

And $f(\delta)$ can be obtained as follows [10],

$$f(\delta) = \{1 - [1 - b(\delta)]^n\}. \tag{17}$$

Where $b(\delta)$ is the BER in AWGN channels. For a modulation technique as the binary phase shift keying (BPSK) with coherent detection, without using the channel coding scheme and considering packets of n bits, $b(\delta)$ can be calculated according to the equation given below [10],

$$b(\delta) = \frac{1}{2} erfc(\sqrt{\delta}). \tag{18}$$

Reference [10] presents an analytical resolution of the upper bound and the corresponding simulations for the expected values for PER as a function of average SNR. From the results presented in [10], we can observe that the upper bound provides an accurate value for the PER under some assumptions, e.g., when coherent BPSK is employed as a technique for modulation, with or without a channel coding scheme and by using some packet lengths (greater than or equal to 127 bits when channel coding is not used). In our analysis we assume coherent BPSK modulation without a channel coding scheme and with packets length of 127 [bits]. According to the considerations above, in this paper, we consider that the PER and the PSR are obtained in an approximate fashion by the equations presented below,

$$P_{ave}(\Delta) \cong 1 - e^{-w_0/\Delta} \qquad (19)$$

$$PSR(\Delta) \cong e^{-w_0/\Delta}. \qquad (20)$$

Using MATLAB and comparing to the results presented in [10], the values obtained for w_0 are shown in the Table I.

B. The Primary Network Throughput for the New model

The primary network throughput is defined as the total number of packets transmitted by the licensed users and received correctly by PAP during a time slot [1].

In the new system model, a packet is considered successfully transmitted when it is captured by the receiver and it does not have any errors due to interference present in the networks. In this case, the primary network throughput, S_{pn}, is approximately given by:

$$S_{pn} = S_{po} \times PSR(\Delta_p) \cong S_{po} \times e^{-w_0(I_p-1)}. \qquad (21)$$

Where S_{po} is the primary network throughput for the original model and $PSR(\Delta_p)$ is the successfully transmitted packet rate.

C. The Secondary Network Throughput for the New Model

Referring to the secondary network, the throughput is defined as the length of packet in terms of mini-slots divided by the total number of mini-slots used in the transmission process, including both busy and idle slots [1]. When one considers only the packets received without errors due to interference of the networks, the secondary network throughput, S_{sn}, is given approximately by,

$$S_{sn} = S_{so} \times PSR(\Delta_s) \cong S_{so} \times e^{-w_0(J_s-1)}. \qquad (22)$$

Where S_{so} is the secondary network throughput for the original model and $PSR(\Delta_s)$ is the successfully transmitted packet rate.

D. The Overall Networks Throughput for the New Model

The overall throughput for the new system model, S_{otn}, is the sum of the primary and secondary networks throughput, as below:

$$S_{otn} = S_{pn} + S_{sn}. \qquad (23)$$

IV. NUMERICAL RESULTS

The Fig. 4, Fig. 5 and, Fig. 6 shown the analytical results obtained for throughput of primary and secondary network throughput and overall throughput system. To compare the results between the new model and the original model, in the following graphics are used the same parameters introduced in [1], i.e., N_p = 20 (users), N_s = 20 (users), R = 3 (dB), γ = 10, S_{mi} = 10 (mini slots), T_{mi} = 100 (mini slots) e $\sigma_p = \sigma_{mi}$.

TABLE I. VALUES OF W0 CONSIDERING COHERENT BPSK MODULATION

Packet length in n (bits)	***w_0***
Uncoded 127 (bits)	3.4467
Uncoded 1023 (bits)	5.3361

The graphs of Fig. 4, Fig. 5 and, Fig. 6 show that the effect of the PER on the primary and secondary networks transmissions, due to interference caused by their stations, cannot be disregarded. When one considers the PER, there is a significant reduction in the primary and secondary network throughput and also in the overall network throughput.

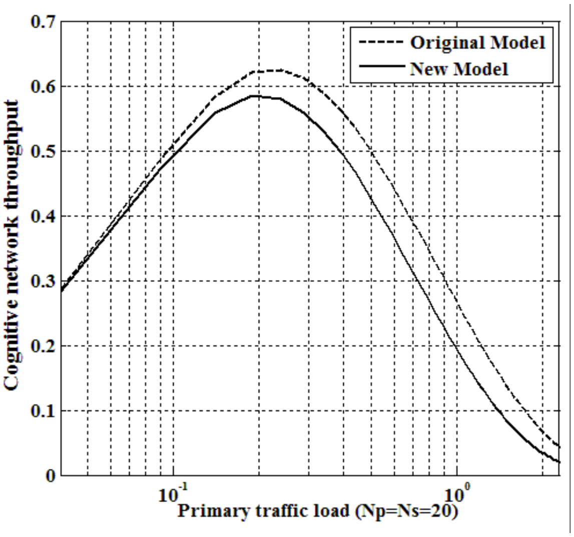

Figure 4. Cognitive network throughput (N_p=N_s=20, S_{mi}=10, R=3 dB)

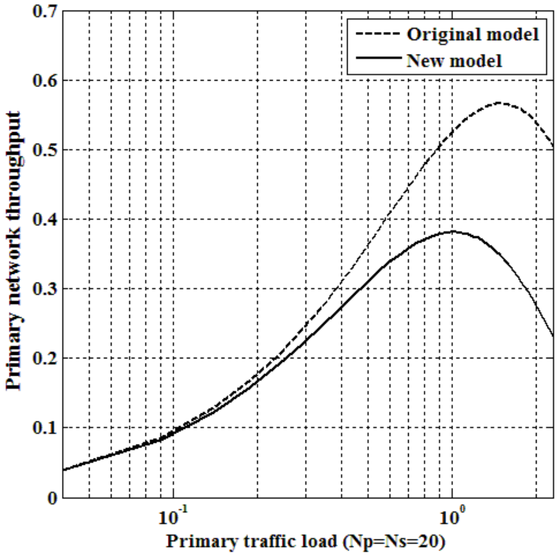

Figure 5. Primary network throughput (N_p=N_s=20, S_{mi}=10, R=3 dB)

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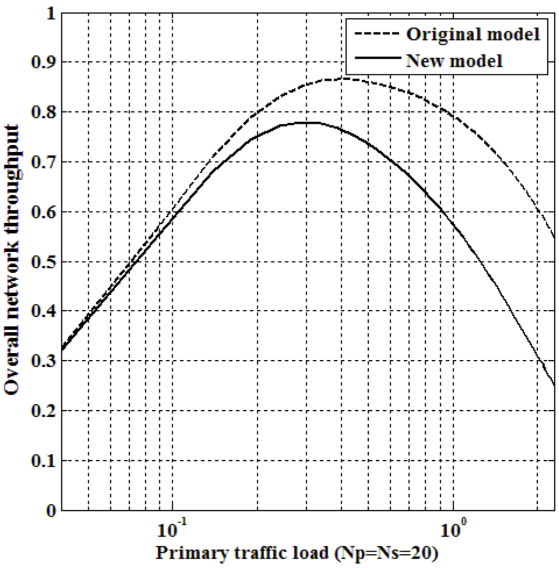

Figure 6. Overall network throughput (Np=Ns=20, Smi=10, R=3 dB)

V. CONCLUSION

In this paper, we propose a new model to compute the throughput in a cognitive radio network, considering Slotted Aloha in the licensed network and Slotted CSMA in the cognitive network. This proposed model is an extension of the model analyzed in [1].

The new model proposed considers the interference between the stations of the networks and their effects over the throughput of each network. It is verified that the interference increases the packet error rate and reduces the primary network throughput, the secondary network throughput and overall networks throughput. Therefore, it is concluded that the PER, due to interference between radio stations of both networks, cannot be neglected, as happens in [1].

As suggestion for future study, it is proposed to investigate mechanisms to reduce the packet error rate on the networks and thereby improve the throughput of each network and the overall throughput.

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