

# A Double Stage Random Access Scheme for Decentralized Single Radio Cognitive Networks

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**Abstract**—This work proposes a new scheme to coordinate the medium access of single-radio unlicensed users in a decentralized cognitive radio network. The proposed solution is based on two different stages. Unlicensed users randomly define the medium access sequence during the first stage and part of the second one. Then the nodes simply transmit their packets according to the reserved sequence. The performance of the proposed scheme is theoretically characterized in terms of the throughput achieved by unlicensed users and validated through simulation. Since a random access mechanism is used in the both stages, we also compare the performance of our proposal with a pure Slotted Aloha access scheme and an improved version of it. By comparing their performance, we conclude that the proposed scheme exhibits significant gains in terms of the throughput achieved by unlicensed users, and it can be recommended as a viable solution for future decentralized single radio cognitive networks.<sup>1</sup>

**Keywords:** Cognitive Radio, Distributed Medium Access Control, Performance Analysis.

## I. INTRODUCTION

In cognitive radio networks, wireless nodes can sense the activity from a given band of the radio spectrum and, depending on the detected activity, they can utilize it in an opportunistic basis. This ranks cognitive radio networks as an effective solution to alleviate the increasing demand for radio spectrum [1]. In these networks, non-licensed users, usually denominated secondary users (SUs), must be aware of the activity of the licensed users, denominated primary users (PUs), in order to dynamically access the spectrum without causing them harmful interference. In this work, we consider a single-radio cognitive network, indicating that SUs are only equipped with a single transceiver and can not sense the spectrum and simultaneously transmit the waiting packets. We also consider a decentralized network, where a distributed coordination policy is adopted.

The design of medium access control (MAC) schemes for decentralized cognitive radio networks (dCRNs) is still a challenging task because of the lack of a central coordinator or a dedicated common control channel [1]. Moreover, the performance of the schemes proposed for dCRNs depend on the considered MAC principle of operation. This is similar to

the classical decentralized wireless networks, where it is well known that by adopting a given principle of operation, e.g. Slotted Aloha [2], the maximum throughput of the system is limited to a specific value, which is only achieved when the optimal parametrization is adopted.

The design of efficient MAC protocols for dCRNs has been already considered in several works (see [3] and [4] for related surveys). The authors from [1] proposed a new MAC protocol which considers a time frame organization where each node starts to sense the radio spectrum before trying to transmit data. If a node does not detect PUs' activity during the sensing period, it applies a random backoff during the transmission period and the channel is granted to the first competing node accessing the channel. A collision can occur if the first access during the transmission period is attempted by multiple nodes. [5] proposes a carrier sensing multiple access/collision avoidance (CSMA/CA) protocol that exploits statistics of channel usage by PUs for decision making on SUs' channel access. Basically the protocol uses a common control channel to negotiate the transmission parameters with the receiver. A successful transmission rate is then defined from the exchanged information, which is after used to adapt the level of contention used by the SUs to access the medium. The work in [6] proposes a MAC for CSMA-based PU systems. A CSMA scheme is also used to regulate the access of SUs and the main feature of this protocol is the dynamic adaptation of SUs' physical layer parameters (e.g. transmission power) to allow simultaneous SUs and PUs transmission when interference to and from the PUs are acceptable. More recently, [7] proposed a two-level opportunistic spectrum access strategy to optimize the system performance of the secondary network. At the first level, SUs maintain a sufficient detection probability to avoid interference with PUs. At the second level, two contention-based MAC protocols called slotted cognitive radio ALOHA and cognitive-radio-based carrier-sensing multiple access were proposed to deal with the packet scheduling of the secondary network.

In this work, we consider a cognitive radio system where the SUs synchronously and periodically sense the channel in order to determine the level of PU's activity. SUs sense the channel activity using an energy-based sensing scheme, but our MAC scheme can accommodate other spectrum sensing techniques, such as the majority of the ones described in [8]. The timing organization of SUs consists of two periods that form a time

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frame. Spectrum sensing is performed in the first one in order to evaluate if a node is allowed to access the channel in the second one. The main concept behind our proposal is the adoption of two different stages for schedule the medium access during the transmission period. All stages occur when the SUs sense the channel idle during the sensing period. In the first stage and part of the second one the SUs express their willingness to send data. The second stage also includes the period when SUs access the channel. We describe our proposal and simultaneously present the analytical steps to characterize the aggregate throughput achieved by the SUs. The analytical results are then validated through simulations. Finally, we characterize the bounds for the aggregate throughput, which are compared with a protocol using a Slotted Aloha access policy and an improved version of it. The obtained results clearly identify the advantages of our proposal, making it a viable solution for future decentralized single radio cognitive networks.

The rest of this paper is organized as follows. In the next section we introduce the adopted system. Section III describes the MAC schemes and presents a simple model to characterize its throughput. Our proposal is presented in Subsection III-C. Performance results are discussed in Section IV. Finally, some concluding remarks are given in Section V.

## II. SYSTEM DESCRIPTION

In this work we consider that  $n$  SUs may access the channel opportunistically, when one or more PUs do not use the channel, as considered in [9]. SUs are equipped with a single radio transceiver. However, because SUs are unable to distinguish SUs and PUs transmissions, each SU will have to divide its operation cycle (time frame structure) into spectrum sensing and spectrum access periods, with durations  $T_S^{SU}$  and  $T_D^{SU}$  respectively, as illustrated in Figure 1. The time frame is divided into  $N_T$  slots where each slot duration is given by the channel sampling period. The first  $N_S$  slots are allocated to the spectrum sensing (channel sampling) and the remaining ones ( $N_S + 1$  to  $N_T$ ) are used to access the channel. In this paper we assume that SUs always have a packet to transmit. We assume that SUs are synchronized in the first slot of the sensing period.

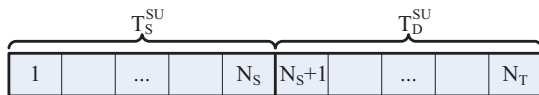


Fig. 1. SU's time frame structure.

### A. Spectrum Sensing

SUs sense the channel during the period  $T_S^{SU}$  using an energy-based sensing (EBS) technique [10]. To distinguish between occupied and vacant spectrum bands, SUs sample the channel during the sensing period, and for each sample  $k$  two hypotheses can be distinguished

$$\begin{aligned} \mathcal{H}_0 : x(k) &= w(k) & k &= 1, 2, \dots, N_S \\ \mathcal{H}_1 : x(k) &= w(k) + s(k) & k &= 1, 2, \dots, N_S, \end{aligned} \quad (1)$$

where  $s(k)$  denotes the transmitted signals by PUs, modeled as a Gaussian variable with mean  $\mu_s$  and variance  $\sigma_s^2$ , *i.e.*,

$s(k) = \mathcal{N}(\mu_s, \sigma_s^2)$ .  $w(k)$  is assumed to be zero-mean additive white Gaussian noise (AWGN) with unit variance, *i.e.*,  $w(k) = \mathcal{N}(0, 1)$ . The condition  $\mathcal{H}_0$  represents the case when PUs are absent.  $\mathcal{H}_1$  indicates that there exists a signal transmitted by a PU.

EBS relies on the classical energy detector [10]. In the detection stage, each SU calculates the amount of energy received in  $N_S$  samples, given by

$$Y = \sum_{i=1}^{N_S} |x(i)|^2, \quad (2)$$

and compares it with the energy threshold  $\gamma$  to decide whether a PU is present or absent. Under hypothesis  $\mathcal{H}_0$ , the decision variable  $Y$  follows a central chi-square distribution with  $2N_S$  degrees of freedom. Under hypothesis  $\mathcal{H}_1$ ,  $Y$  follows a non-central chi-square distribution also with  $2N_S$  degrees of freedom, and a non centrality parameter  $\lambda$ , denoting the signal-to-noise ratio (SNR) [11]. However, if the number of samples  $N_S$  is large enough<sup>2</sup>, it is possible to use the Central Limit Theorem (CLT) to approximate the chi-square distribution to a Gaussian distribution [12]:

$$Y \sim \begin{cases} \mathcal{N}(N_S, 2N_S), & \mathcal{H}_0 \\ \mathcal{N}(N_S + \lambda, 2(N_S + 2\lambda)), & \mathcal{H}_1. \end{cases} \quad (3)$$

Therefore, for a single SU the probability of detection ( $P_D$ ) and probability of false alarm ( $P_{FA}$ ) are represented by

$$P_D = Pr(y > \gamma | \mathcal{H}_1) = \mathcal{Q} \left( \frac{\gamma - (N_S + \lambda)}{\sqrt{2(N_S + 2\lambda)}} \right) \quad (4)$$

$$P_{FA} = Pr(y > \gamma | \mathcal{H}_0) = \mathcal{Q} \left( \frac{\gamma - N_S}{\sqrt{2N_S}} \right) \quad (5)$$

where  $\mathcal{Q}(\cdot)$  is the complementary distribution function of the standard normal distribution.

### B. PU activity model

Each PU has an ON-OFF behavior, meaning that it is active during a  $T_{ON}^{PU}$  period, and inactive during a  $T_{OFF}^{PU}$  interval. The PU's activity is modeled by two random processes. The first one models the active period duration and the second models the inactive period duration. Both durations are sampled from exponential distributions with mean  $\lambda_{ON}$  and  $\lambda_{OFF}$ , respectively. The probabilities of a PU staying OFF and ON are respectively given by  $P_{OFF}^{PU} = \lambda_{OFF} / (\lambda_{OFF} + \lambda_{ON})$  and  $P_{ON}^{PU} = \lambda_{ON} / (\lambda_{OFF} + \lambda_{ON})$ .

## III. MAC PROTOCOL

The MAC protocol presented in this section is proposed for a single-hop operation scenario, where  $n$  SUs want to access to a SU access point when the channel is vacant. The protocol operates in a distributed-way and does not need a central node, such as a coordinator, to grant the channel access. In Subsections III-A and III-B we start to present two

<sup>2</sup>The sampling rate must satisfy the Nyquist sampling theorem.

classical MAC protocols adapted to the cognitive scenario, which will be considered for performance comparison. Our MAC proposal is presented in Subsection III-C.

#### A. Single Stage of Contention

This subsection presents a scheme for accommodate a Slotted Aloha-like [2] medium access protocol in the cognitive system considered in Section II. In the cognitive network, the SUs declare an idle or busy transmitting period with duration  $N_T - N_S$ , if the EBS applied during the  $N_S$  slots indicates absence or presence of the PU. We adopt the terminology idle frames to denote the frames detected idle by the EBS system and busy frames to denote the opposite.

The SUs start to decide their medium access from the moment when the present frame is declared idle or busy, which occurs after the  $N_S$ -th channel sampling slot. If a frame is declared busy by the EBS, the nodes do not perform any operation until the sensing decision of the next frame. If a frame is declared idle, then a SU may access the medium during the time interval equivalent to  $N_T - N_S$ , depending on a randomly decision. This means that SUs are only granted to randomly access the medium after sensing an idle frame, which occurs with probability

$$P_{idle} = P_{OFF}^{PU}(1 - P_{FA}) + P_{ON}^{PU}(1 - P_D). \quad (6)$$

$P_{idle}$  accounts with the sensing accuracy by including the EBS' probabilities of misdetection ( $1 - P_D$ ) and correct rejection ( $1 - P_{FA}$ ).

The SUs may access the medium in the beginning of the slot  $N_S + 1$  of each idle frame and, to avoid collisions between SUs, their medium access decision is randomized. When a SU has a new packet to transmit, it randomly chooses an idle frame to transmit. This frame is chosen from the interval  $\{1, 2, \dots, cw\}$  of the next  $cw$  idle frames, and consequently a frame is chosen with probability  $\tau = 1/cw$ . Note that the channel can be declared idle due to a misdetection of the PUs, which occurs with probability  $P_{ON}^{PU}(1 - P_D)$ . Consequently, a SU only has a chance to successfully transmit in the chosen frame if the frame is declared idle due to a correct rejection, which occurs with probability  $P_{OFF}^{PU}(1 - P_{FA})$ , and when the SU is the unique node granted to access the medium on that frame, which occurs with probability  $\tau(1 - \tau)^{(n-1)}$ . Consequently, the aggregate throughput achieved by the  $n$  SUs is given by

$$S_A = n\tau(1 - \tau)^{(n-1)}P_{OFF}^{PU}(1 - P_{FA})\alpha_s, \quad (7)$$

where  $\alpha_s = T_D^{SU}/(T_S^{SU} + T_D^{SU})$  represents the loss of throughput due to the period where SUs sense the channel. The throughput can be maximized by choosing a  $cw$  that maximizes  $S$ , which can be achieved by solving the equation

$$\frac{dS_A}{dcw} = nP_{OFF}^{PU}(1 - P_{FA}) \left(1 - \frac{1}{cw}\right)^{(n-1)} \times \left( \left(1 - \frac{1}{cw}\right)^{-1} (n-1) - cw \right) \alpha_s = 0 \quad (8)$$

for  $cw$ . We conclude that  $cw = n$  maximizes the throughput, which is the optimal solution for the classical Slotted Aloha.

#### B. Double Stage of Contention

It is well known that for a fixed access probability the Slotted Aloha does not scale for a high number of nodes, meaning that the throughput quickly decreases as the number of nodes competing for the channel increases [2]. Motivated by this fact, we consider a different scheme from the previous one, where the nodes adopt two stages of contention. Once again, the SUs employ the described scheme in idle frames.

The first stage of the scheme is applied during the first frame detected idle (idle frame). Once again this event occurs with probability  $P_{idle}$  described in Eq. (6). The transmission period  $T_D^{SU}$  of this frame is divided in  $cw_1$  mini-slots<sup>3</sup>. The nodes can randomly transmit at most one mini-packet in one of the mini-slots with probability  $\tau_1 = 1/cw_1$  to announce its intention to access the medium. The first stage of this scheme finishes in the end of the first timing frame detected idle. When this occurs, we defined a method to identify the SUs that will compete in the second stage. We have adopted a simple criterion: if a node does not listens a busy mini-slot before transmitting its mini-packet, it knows that it should compete in the second stage of our scheme. Assuming that there are  $n$  SUs competing for the medium in the first stage, then the expected number of nodes selected to compete in the second contention stage is given by

$$n_2 = \max \left( 1, \sum_{k=1}^n k \binom{n}{k} \tau_1^k (1 - \tau_1)^{n-k} \right). \quad (9)$$

The rationale behind the operation of second contention stage is similar to the single stage described in Subsection III-A. Assuming that there are  $n_2$  nodes competing for the medium in the second stage, they can access the medium by selecting a single frame in the interval  $\{1, 2, \dots, cw_2\}$  of future idle frames, meaning that a frame is chosen with probability  $\tau_2 = 1/cw_2$ . The first stage only lasts a single frame, while the second one lasts for  $cw_2$  frames. Since the frame where the first stage is implemented is never used for transmitting purposes, it represents a performance attenuation factor represented by  $\alpha_B = cw_2/(cw_2 + 1)$ , which is finally used to the define the aggregate throughput  $S_B$  achieved by the SUs

$$S_B = n_2\tau_2(1 - \tau_2)^{n_2-1}P_{OFF}^{PU}(1 - P_{FA})\alpha_s\alpha_B. \quad (10)$$

#### C. Double Stage with Reservation

In the previous scheme, the second stage of contention always lasts a period of time that includes  $cw_2$  idle frames. Because the medium access policy applied in the second contention stage is similar to Slotted Aloha, some of the  $cw_2$  idle frames may not be selected for transmission. Consequently, they represent a situation of underutilization of idle frames from SUs. The scheme proposed in this subsection overcomes this problem.

This scheme also includes two stages. The operation of the first stage is as described for the previous scheme, meaning

<sup>3</sup>Note that we use the term mini-slots for MAC purposes and the term slot, adopted in Section II, is only used for channel sensing purposes.

that the expected number of nodes selected for competing in the second stage ( $n_2$ ) is given by Eq. (9). Contrarily to the previous scheme, the nodes selected in the first stage do not start accessing the medium in the first idle frame of the second stage. Instead, the transmission period  $T_D^{SU}$  of the first idle frame of the second stage is divided in  $cw_2$  mini-slots, which are used to reserve future idle frames for channel access.

To exemplify the reservation mechanism we consider that during the first stage 3 SUs, A, B and C, are selected for the second stage, because both SUs transmitted a mini-packet in the first busy slot observed in the  $cw_1$  mini-slots. During the second stage the SU A transmits a mini-packet in the second mini-slot and two other SUs, B and C, transmit their mini-packets in the fifth mini-slot. After elapsing  $cw_2$  mini-slots, the SUs know what are the mini-slots where one or more mini-packets were transmitted, because they sense the channel activity in each mini-slot. The information about the mini-slots found busy is then used to reserve the future idle frames to the nodes that have manifested their intention on accessing the channel during the  $cw_2$  mini-slots. In the previous example, all SUs have sensed transmissions in the second and in the fifth slots. From this information the SUs reserve an equal number of idle frames (two), and thus the second stage lasts for a number of idle frames equal to the number of busy mini-slots observed in the first stage plus the initial idle frame where the  $cw_2$  mini-slots were defined. The SU A will access the medium in the first reserved idle frame, because it knows that it was the first node accessing the medium during the  $cw_2$  mini-slots. The SUs B and C will access the medium in the second idle frame, which will result in a collision.

To determine a bound for the maximum achievable throughput of this scheme, we start to define the expected number of idle mini-slots in the second stage. Since  $n_2$  nodes compete in the second stage (computed from (9)), the expected number of mini-slots found idle in the second stage is given by

$$\Gamma_{idle} = cw_2(1 - \tau_2)^{n_2}, \quad (11)$$

where  $(1 - \tau_2)^{n_2}$  is the probability of finding an idle mini-slot and  $\tau_2 = 1/cw_2$  is the probability of a SU transmitting the mini-packet in a given mini-slot. The expected number of idle frames reserved for SUs access during the  $cw_2$  mini-slots is given by

$$\chi_{res} = cw_2 - \Gamma_{idle}, \quad (12)$$

which shows that, at most,  $cw_2$  future idle frames are reserved when none of the  $cw_2$  mini-slots is sensed idle ( $\Gamma_{idle} = 0$ ). Note that the two stages last for  $2 + \chi_{res}$  idle frames, since 2 idle frames are used to implement the  $cw_1$  and  $cw_2$  mini-slots. Given that the maximum number of reserved frames is  $cw_2$ , we define the performance weight  $\alpha_C = cw_2/(2 + \chi_{res})$ , which expresses the relative gain ( $\alpha_C > 1$ ) due to the suppression of unused idle frames in the second stage whilst also accounting with the two idle frames used for implementing  $cw_1$  and  $cw_2$  mini-slots. Similarly to the scheme presented in Subsection

III-C, the throughput of this scheme can be approximated by

$$S_C = n_2\tau_2(1 - \tau_2)^{n_2-1}P_{OFF}^{PU}(1 - P_{FA})\alpha_s\alpha_C, \quad (13)$$

which is a bound for the maximum achievable throughput. Note that, due to lack of space, Eq. (13) does not accounts with the case when PUs are mis-detected during the frames where both mini-slots  $cw_1$  and  $cw_2$  are implemented.

#### IV. PERFORMANCE ANALYSIS

This section compares the performance for the schemes described in Subsections III-A, III-B and III-C. We have considered a scenario formed by one PU transmitter-receiver pair and multiple SUs transmitting to a single SU receiver. The operation mode of PUs and SUs is as described in Section II. The mean duration of PU's active period ( $\lambda_{ON}$ ) was set to 140ms, while the mean duration of the inactive period ( $\lambda_{OFF}$ ) was set to 327ms in order to obtain a probability of a PU staying ON of approximately 30% ( $P_{ON}^{PU}=0.3$ ).

The adopted parameters for the PU's transmitting signal and for the energy detector implemented in the SUs are described in Table I. The energy detector threshold ( $\gamma$ ) was defined to be 77.5 Joules, following the parametrization criterion  $C_4$  presented in [13]. The parameterization used in the energy detector represents a scenario of high spectrum sensing accuracy, with  $P_D > 0.99$  and  $P_{FA} < 0.01$ .

TABLE I  
PARAMETERS USED IN THE ENERGY DETECTION.

Sensed band	10 kHz	Channel Sampling Period	25 $\mu$ s
$T_S^{SU} + T_D^{SU}$	20.0 ms	$N_S$	40
$\mu_s$	3.16 (5dB)	$\sigma_s^2$	3
$\mu_w$	1 (0dB)	$\sigma_w^2$	1
$\lambda$ (SNR)	5 dB	$\gamma$	77.5 J

Hereafter, we will name the schemes described in Subsection III-A, III-B and III-C by scheme A, scheme B and scheme C, respectively. For comparison purposes the parametrization used in scheme B and C was the same:  $cw_1 = 6$  and  $cw_2 = 16$ . In turn, scheme A, we adopted  $cw = cw_2 = 16$ .

We have implemented the three schemes in a simulator. Figure 2 illustrates the throughput results obtained for a different number  $n$  of SUs competing for the medium.  $10^6$  SUs timing frames were simulated in the three schemes. The confidence interval for the simulations at 95% of confidence level was computed but, because it is too small, we decided to not plot it in the figure. The numerical results from theoretical approximations for  $S_A$ ,  $S_B$  and  $S_C$  are also plotted.

Observing the simulation results, we conclude that the throughput of scheme A sharply decreases as the number of SUs competing for medium access increase. Scheme B scales better for higher number of nodes, but it underperforms scheme A when the number of nodes is small (approximately  $n = 35$  in Fig. 2). The simulated results clearly show the advantage of adopting scheme C when a good level of spectrum sensing accuracy is achievable.

Regarding the theoretical approximations proposed for the throughput of schemes A, B and C, we observe that the

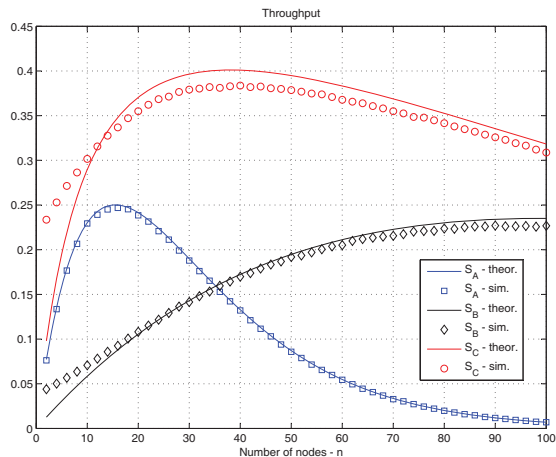


Fig. 2. Aggregated normalized throughput for  $PUN^{PU} = 0.3$  ( $cw_1 = 6$ ,  $cw_2 = 16$ ).

approximation for scheme A is successfully validated. The theoretical results for scheme B deviate from the simulation when the number of competing SUs is too small. This fact is due to an unrealistic numerical scenario, which occurs when  $n$  is low and the expected number of nodes selected to compete in the second stage ( $n_2$  given by Eq. (9)) is less than 1. This explanation can also be applied to justify the deviation observed in scheme C when  $n < 12$ . As mentioned in Section III-C,  $S_C$  is a bound for the best-case scenario in terms of throughput, because the impact of misdetection that can occur during the  $cw_1$  and  $cw_2$  mini-slots is not considered. However, the numerical curve slightly follows the trend observed in the simulations.

The results illustrated in Fig. 2 are for fixed values of  $cw$ ,  $cw_1$  and  $cw_2$ . To increase the fairness of the comparative analysis, we compared the maximum numerical values of throughputs  $S_A$ ,  $S_B$  and  $S_C$ . For maximizing  $S_A$  we simply used  $cw = n$  to solve (7), as described in Subsection III-A. For  $S_B$  and  $S_C$  we used a numerical optimization package to solve the following optimization problem

$$\max_{\substack{1 \leq cw_1 \leq 16 \\ 1 \leq cw_2 \leq 16}} S,$$

where  $S$  was replaced by  $S_A$  or  $S_B$  and  $cw_1$  and  $cw_2$  were limited to 16 mini-slots, due to the finite duration of the idle frame transmitting period ( $T_D^{SU}$ ). The numerical results are plotted in Fig. 3, and confirm that scheme C can achieve higher aggregated throughput than schemes A and B (note however that in scheme B it was not possible to compute the numerical results for  $n < 13$ ).

## V. CONCLUSIONS

This work proposes a new scheme (scheme C) to coordinate the medium access of single-radio unlicensed users in a cognitive radio network. The proposed scheme considers two stages to schedule SUs medium access in a decentralized way. We considered simulation and analytical results to characterize the performance of the proposed scheme. Its relative performance was evaluated with two schemes that follow the traditional

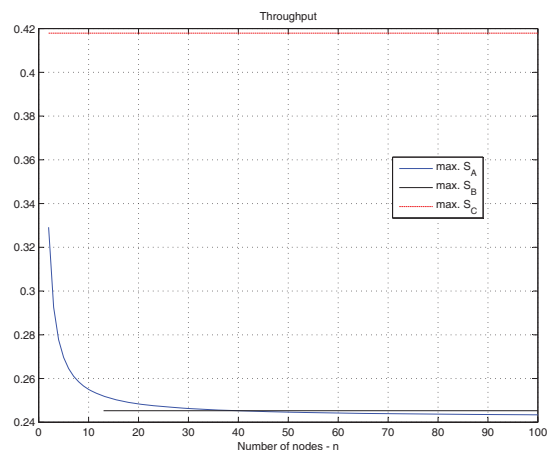


Fig. 3. Maximum aggregated normalized throughput.

Slotted Aloha approach. The reported results confirm the effectiveness of our proposal.

Further developments of this work will include a better characterization of the proposed scheme in lower spectrum sensing accuracy scenarios, as well as the assumption of hypothetical hidden PUs.

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