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Research Article

Self-Organized Efficient Spectrum Management through Parallel Sensing in Cognitive Radio Network

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In this paper, we propose an innovative self-organizing medium access control mechanism for a distributed cognitive radio network (CRN) in which utilization is maximized by minimizing the collisions and missed opportunities. This is achieved by organizing the users of the CRN in a queue through a timer and user ID and providing channel access in an orderly fashion. To efficiently organize the users in a distributed, ad hoc network with less overhead, we reduce the sensing period through parallel sensing wherein the users are divided into different groups and each group is assigned a different portion of the primary spectrum band. This consequently augments the number of discovered spectrum holes which then are maximally utilized through the self-organizing access scheme. The combination of two schemes augments the effective utilization of primary holes to above 95%, even in impasse situations due to heavy primary network loading, thereby achieving higher network throughput than that achieved when each of the two approaches are used in isolation. By efficiently combining parallel sensing with the self-organizing MAC (PSO-MAC), a synergy has been achieved that affords the gains which are more than the sum of the gains achieved through each one of these techniques individually. In an experimental scenario with 50% primary load, the network throughput achieved with combined parallel sensing and self-organizing MAC is 50% higher compared to that of parallel sensing and 37% better than that of self-organizing MAC. These results clearly demonstrate the efficacy of the combined approach in achieving optimum performance in a CRN.

1. Introduction

The demand for spectrum has grown exponentially over the last two decades due to unprecedented growth and proliferation of wireless devices, systems, and services. With the advent of massive Internet of Things- (IoT-) based applications, this problem has further been aggravated. The availability of spectrum is very limited, primarily due to static spectrum allocation policies, where the spectrum is exclusively allocated to licensed users, which prohibits the unlicensed users to access that portion of the spectrum. According to the Federal Communication Commission (FCC), there is a huge variation in the spatial and temporal spectrum utilization ranging from 15% to 85% in the band below 3 GHz [1], leading to virtual spectrum scarcity [2, 3]. To overcome the imbalance between the high spectrum demand and limited spectrum availability, FCC has suggested dynamic spectrum access. Cognitive radio (CR) has emerged as a key technology that realizes the principle of dynamic spectrum access (DSA), by enabling simultaneous access to the underutilized portion of the licensed spectrum for users other than those of the licensed network [4, 5]. The users in the cognitive radio networks (CRNs) are required not only to locate the opportunities in the primary network but also have to ensure that users of the licensed network are not affected by them. This requires additional functionality of spectrum handover or spectrum mobility as the primary user appears on the channel being opportunistically used by the CRN user. A wide range of techniques have been deployed for spectrum handover such as bioinspired techniques [6], Markov modeling [7], and supervised machine learning techniques [8].

Efficient spectrum utilization is the prime objective in CRN [9]. It requires an efficient discovery mechanism as well as maximal utilization of the discovered opportunities. To improve the channel utilization, the coordination among the CRN users, also called secondary users (SUs), is provided by introducing a common control channel (CCC) [10, 11]. However, it increases the overheads, which reduces the actual available transmission time to the SUs. To minimize these overheads for increased channel utilization, there have been various noteworthy research contributions in the recent past. To make the discovery efficient, the sensing time needs to be reduced and it has to be exhaustive and accurate too; this raised contradicting challenges [12–15]. Likewise, the access mechanism needs to be efficient so that opportunities are neither missed, wasted, nor inefficiently tapped [16, 17].

In an ad hoc CRN, this becomes even more challenging as there is no central entity to govern its users. In random access, unused channels of primary users (PUs) may remain underutilized either due to collision or remain unattempted. To minimize the wastage of discovered opportunities, a self-organizing collision-free CRN MAC has been proposed [18]. To create the pool of available resources, SUs perform cooperative sensing [19]. In another research, a parallel sensing scheme has been devised to maximize the channel time for data transmission [20]. Both schemes improve the performance in their respective domains. However, since both of these schemes require a coordinated effort among the CRN users and that too in an ad hoc network scenario, there is an associated overhead with each one of these two schemes.

To improve the efficiency, the existing MAC approaches for CRN either target to improve the utilization of the discovered holes or target the efficient discovery mechanism. Combining the two goals penalize one another due to excessive overhead, particularly in the ad hoc CRNs employing common control channel for coordination among the SUs. The goal is to provide a unified common control channel frame structure that facilitates to improve the utilization, maximize the hole discoveries, and extend the transmission time in a transmission cycle and adjusts dynamically to the varying network conditions.

In this work, parallel sensing along with self-organizing medium access control (PSO-MAC) has been proposed, which is an extension of work in [18, 20]. PSO-MAC provides parallel channel sensing and self-organizing channel access mechanism through a single unified frame structure, which improves channel utilization as well as idle channel discovery process and hence increases the overall network throughput. Parallel channel sensing can also be used with contention-based MAC protocols. The primary motivation for this work lies in the development of a unified frame structure that allows to harness the benefits of both approaches and yet keeps the overheads to a minimum. This requires removing redundancies, careful sequencing of different phases, and provisioning of dynamic adjustment according to the situation. The goal is to maximize the discovered resources and utilization of these resources while leaving maximum time for the secondary users for data transmission. The secondary users can transmit their data in the transmission cycle only after the allocation of a channel to the user and the rest of the period is overhead. Further, the existing parallel sensing scheme reduces the duration of the sensing phase through parallelism.

Increasing the number of groups increases parallelism that further decreases the duration of the sensing phase. However, for a given number of secondary users in a CRN, it is at the cost of a higher probability of a primary band being skipped in sensing and thus reducing the number of discoveries. Through dynamic adjustment of the number of groups according to the prevailing situation in terms of load on the primary network and number of secondary users, the optimal trade-off can be achieved between the parallelism and the overhead. The enhanced unified frame structure along with optimization of the number of parallel sensing groups in the proposed PSO-MAC provides the synergy for optimum performance gains.

1.1. Contributions. The key contributions of this paper are highlighted below.

(1) A unified frame structure for CRN MAC has been proposed that combines parallel sensing with the organized medium access to improve the utilization and maximize the hole discoveries

(2) The proposed PSO-MAC has been carefully designed to keep the overhead of the frame structure of the common control channel to a minimum so that the transmission time in a transmission cycle is extended and a synergic effect is achieved. The order of different phases has been critical to keep the flexibility of the frame structure for varying network conditions

(3) We have developed a model to evaluate overall performance gain in terms of throughput with due consideration of the overhead of the frame structure. Comparison with existing schemes is based on this model

(4) Parallel sensing has been optimized by dynamically adjusting the number of groups in parallel sensing according to the changing network conditions

The rest of the paper is organized as follows. The literature review is discussed followed by the proposed PSO-MAC. Then, the performance metrics are explained and simulation environment and results are evaluated. Finally, conclusion is presented.

2. Literature Review

Many efforts have been dedicated to optimize the spectrum sensing in CRN [20–33]. Spectrum sensing schemes are mainly classified into two main categories: (a) narrow band and (b) wide band.

In the narrow-band spectrum sensing, the SUs sense any particular channel to see if it is available or busy. The availability or unavailability of a channel is determined through (i) energy detection, which measures the energy of the signal and matches it to a given threshold; if the signal energy is higher than the predefined threshold, then it is assumed that the PU is present; otherwise, the channel is considered as idle [21, 22]; (ii) matched filter detection, which compares the received signal with the pilot signal obtained from a similar transmitter [23]; and (iii) machine learning-based sensing methods, which are considered as a classification problem that may be supervised or unsupervised [24, 25].

Developing a reliable and highly efficient spectrum sensing technique is a challenging task. The sensing performance of an individual SU may be affected by noise, shadowing, and fading causing uncertainty. Cooperative sensing schemes enhance the performance of the CRN by improving the accuracy of spectrum sensing [26]. When multiple CRs sense the PU detection then their individual results are shared among the CRN to evaluate the best PU channel by employing different techniques such as unanimous cooperative decision and consensus-based cooperative sensing but at the cost of additional overhead.

Cooperative spectrum sensing (CSS) schemes with adaptive sensing window with due consideration of bit error rate (BER) to improve spectrum utilization with an increase in SNR have been proposed in [27]. In [28], the authors proposed an optimal channel sensing with heavy-tailed idle times for CRN, which were modeled as hyperexponential distribution (HED). The authors in [29] proposed an autonomous compressive sensing algorithm that enabled the local SUs to choose the number of compressive samples automatically to reduce the sensing duration along with reduced complexity of data processing. Double threshold (DT) cooperative spectrum sensing mechanism with hard-soft combining has been proposed in [30] to enhance the reliability of spectrum sensing and reduce the communication overhead. Similarly, the authors in [31] have proposed a hybrid double threshold cooperative spectrum sensing mechanism in CRN. Sensing performance is improved by exploiting both the local and global detection in terms of energy and binary values at each SU, given the interference caused to the PU at an acceptable level. An additional threshold is used when the local sensing decision at each SU is not available.

The development in wireless communication systems requires high data rates which can be achieved with high bandwidth. From this aspect, SUs need to sense a wide range of the primary spectrum to find the pool of available channels. In the case of wide band, the whole spectrum is divided into multiple channels and then they are sensed using the narrow-band spectrum sensing schemes, either randomly, sequentially, or in parallel [32]. In [20], the authors have proposed cooperative parallel sensing in CRN to discover the vacant primary channels. The idea is to make SU groups according to their IDs. Spectrum is equally divided into the same number of portions, and each group of SUs is assigned a portion to scan for the vacant channels. Sensing information is shared in a separate sharing phase. Due to parallel sensing of the assigned portion of the spectrum, the total sensing time is reduced and the maximum number of vacant PU channels is discovered. Parallel sensing improves the spectrum utilization and throughput by minimizing the sensing time and maximizing the discovered resources. However, determining the number of groups to be formed to optimize the parallelism and coverage of the PU spectrum is not discussed.

The valuable resources discovered through cooperative parallel sensing then require an efficient MAC mechanism that can reduce the number of collisions and ensure no resource left untapped. In contention-based MAC protocols, the SU contends for medium access in a random fashion, leading to a waste of resources either due to collisions or inability to tap these resources. This adversely affects the spectrum utilization. Existing work has shown collisions can be greatly reduced by providing some form of contention-free channel access [18, 34–37].

In [35], a contention-free reporting scheme-based MAC protocol has been proposed to improve the sensing time and network throughput. Any SU willing to join the CRN and CSS process can randomly select a slot in a slotted ALOHA manner and send random access ready to send (RARTS). If a slot is selected by only one SU, the RARTS is successfully received at the fusion center (FC) and the FC responds with the random access clear to send (RACTS). The key concept of this paper is that the SU joining the network participates in the sensing phase and reports the sensing result to the FC, which leads to saving the sensing time and collision-free reporting. In this scheme, the reporting is contention free, yet the random sensing results in duplicate sensing of some of the spectrum portion and some spectrum portion being missed. These adversaries waste energy and cause lost opportunities.

In [36], the authors have proposed a backoff (BO) algorithm-based cognitive radio MAC (BO-CRMAC). In this scheme, the collided SUs are allowed to recontend in the same cycle for an idle channel. The BO-CRMAC reduced the access delay and improves the overall utilization of the idle channel. However, if fair play is not ensured, all SUs are tempted to target the initial channels to have multiple reattempt options open and this could eventually choke the system. This scheme works well and shows improvement in the utilization when the pool of available resources is huge. Utilization of the discovered pool of resources improves and eventually gets better in BO-CRMAC than random access. The scheme provides more utilization gain when the number of channels is greater than the number of SUs; however, when the number of channels is less than the number of SUs, its performance is even poor than random access. This is a matter of concern as the actual challenge lies where the resources are limited and contenders are large in number.

The authors in [37] have proposed CR intelligent MAC (CR-i-MAC) with the aim to make the medium access contention-free, minimizing the loss of discovered idle channel and overhead in the context of CRN MAC. The process of CR-i-MAC is done in three phases, i.e., (i) the sensing and sharing, (ii) the contention, and (iii) the transmission phase. The contention phase is hybrid in the proposed scheme: a cooperative approach to overcome the hidden node problem

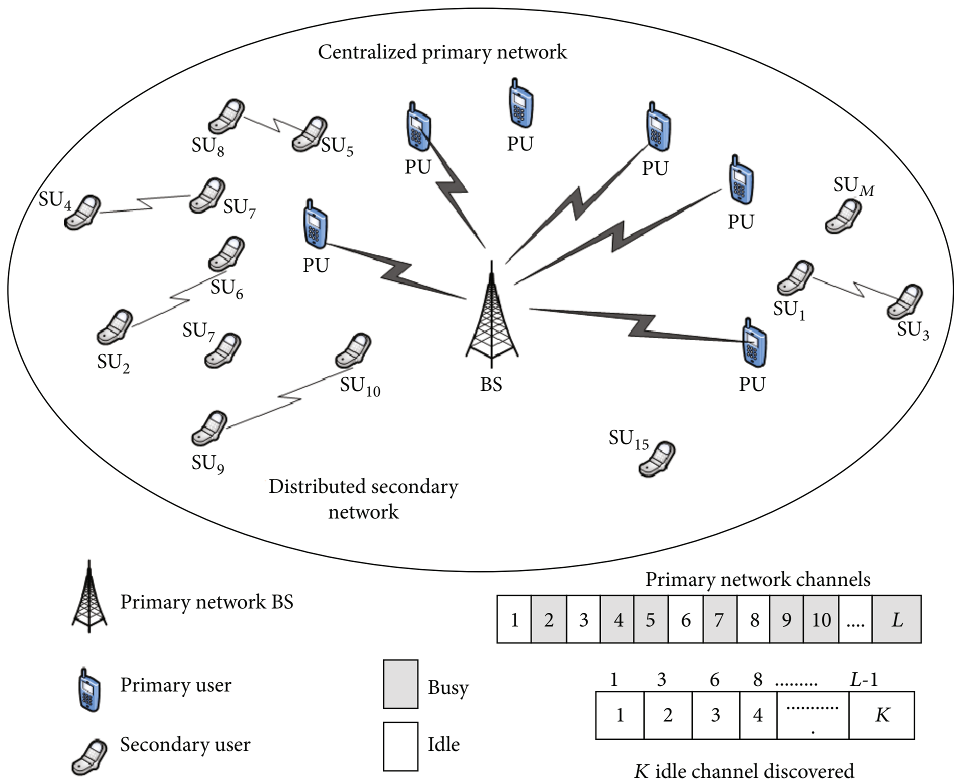

Figure 1: Network model.

and contention-free approach when multiple secondary users select the same channel. When only a single SU accesses the channel, the contention-free access is granted to it. The rest of the users determine their channel through an algorithm that eliminates the already allotted channels and SUs already granted access. The computational cost and scalability issues are raised as the network size increases.

To address this problem, the authors in [18] have proposed a self-organizing distributed (SOD) CR-MAC protocol. Loss of opportunities due to collisions and nonattempt is avoided by organizing and queuing the SUs through a timer value and directing them in an orderly fashion to use the discovered holes. In SOD, contention-free spectrum access is provided, consequently improving spectral efficiency.

The possibility to unify the parallel sensing approach with the self-organizing MAC scheme has been quite enticing and served to be the main motivation for this work. Therefore, the proposed PSO-MAC develops a unified frame structure that captures the benefits of the two approaches as presented in [18, 20]. Further, PSO-MAC incorporates the optimization of number parallel sensing groups to maximize the discovered resources as well as the utilization of discovered resources while keeping the overhead minimum.

3. PSO-MAC Protocol for CRN

In this section, the network model along with the frame structure of PSO-MAC and its algorithms is discussed.

3.1. Network Model. We have considered a centralized primary network having L licensed channels available to N PUs. There exists a distributed secondary network, also called CRN, with M SUs as shown in Figure 1. SUs access the channel only when PUs are not using the channel. Therefore, the number of channels available to SUs at any given time is K, where $[0 \leq K \leq L]$ and is a function of load on the primary network (ρ), which is the ratio of average number of channels being used by the primary network to the total number of primary channels. The ON-OFF process is considered to model the primary channel, where "ON" represents channel is busy and "OFF" represents channel is idle. Spectrum sensing is assumed as perfect by ignoring miss detection and false alarms. The detailed list of notations used in this paper is presented in Table 1.

3.2. PSO-MAC Frame Structure. The frame structure of the proposed PSO-MAC has been built upon the frame structures proposed in [18, 20] (see Figures 9 and 3 of [18, 20], respectively) and is shown in Figure 2. It consists of five phases, i.e., synchronization phase (T_{i}), organization phase (T_{o}), parallel sensing phase (T_{ps}), sharing phase (T_{s}), and transmission phase (T_{tx}). PSO-MAC frame structure is different from the standard MAC frame in a way that it has an additional organization phase and the sensing phase is replaced by an efficient parallel sensing phase.

The sequence of these phases has carefully been adjusted that eliminates redundancies and allows dynamic adjustments to work optimally according to the prevailing network conditions. This arrangement enables to maximize the gains

Table 1: List of notations.

Description	Parameter
Number of PU	N
Number of SU	M
Number of primary channel	L
Number of available channel	K
System capacity	C
Primary traffic load	ρ
Cycle time	T_c
Synchronization phase	T_i
Organization phase	T_o
Sensing phase	T_s
Parallel sensing phase	T_{ps}
Sharing phase	T_{sh}
Transmission phase	T_{tx}
Short interframe time	*a*SIFSTime
Slot time	*a*SlotTime
RTS time	*a*RTSTime
CTS time	*a*CTSTime
Number of bits in user ID	b_{ID}
Timer value	b_{TValue}
Number of slots required	$b_{SlotsReq}$
Bit duration	T_{bit}
Group ID	G_{id}
Number of groups	N_g

from the combination of the two approaches as mentioned above while keeping the incurred overhead to a minimum as well. For example, placing the organization phase before the parallel sensing phase allows the dynamic adjustment of the number of parallel groups that optimizes the sensed spectrum with the overhead so that discoveries and utilization are optimized. This is as the number of active SUs is known by the end of the organization phase.

3.2.1. Idle Phase. Each cycle starts with an idle phase T_i. In this phase, the SUs synchronize with each other and can share and collect the information from the common control channel. The length of this phase is

$$T_i = a\text{SIFSTime} + 2 \times a\text{SlotTime}, \quad (1)$$

where *a*SIFSTime and *a*SlotTime are the short interframe space time and the slot time, respectively, as in [36].

3.2.2. Organization Phase. PSO-MAC introduces a self-organization (T_o) phase, where SUs organize themselves in a queue in an ad hoc network. This organization of SUs facilitates the collision-free access to the channel and enables maximum utilization of the available channels. The organization is achieved through a user ID and a timer for each SU. Step 1 of Algorithm 1 shows the pseudocode of the organization method. An organization phase comprises multiple subslots and each subslot contains the information of each SU, i.e., user ID, its timer value, and the number of slots required by the user along with its RTS and CTS information. The length of this phase is

$$T_o = C \times \left(\left(b_{ID} + b_{TValue} + b_{SlotsReq}\right) \times T_{bit} + a\text{RTSTime} + a\text{SIFSTime} + a\text{CTSTime}\right), \quad (2)$$

where b_{ID}, b_{TValue}, and $b_{SlotsReq}$ are the number of bits in user ID, timer value, and number of slots required, respectively. T_{bit} is the duration of a bit and depends on the data rate (R) of the network [18].

The user ID is acquired by the SU at the time of entry into the CRN. For this purpose, the new entrant observes the announcement made by active SUs in the subslots of the organization phase (T_o). Any subslot without any information announcement is assumed to be vacant, and the user ID is considered available for contention. The SUs contend for the user ID, and with multiple SUs seeking entry in the network, the collision in ID acquisition is possible. However, since the entry into the network is a one-time process, the collision only delays the entry of the SU into the network and does not result in a waste of resources, i.e., the vacant primary channel. In case of collision, the new entrant has to contend for a vacant ID in the next T_c. Once it gets the successful access to a subslot of the T_o phase, then that subslot would be its user ID in the CRN.

The timer is started by an SU as soon as it is ready to transmit the data. The SU with higher timer value at the beginning of the T_c gets the priority in the queue. The timer value is announced by the SUs which might give rise to some fairness issues.

3.2.3. Parallel Sensing Phase. Once the SUs are organized in the T_o phase, distributed SUs sense for idle channels in the sensing phase T_{ps}. It allows multiple SUs to sense for the vacant channel in a parallel manner. The parallel sensing phase of the PSO-MAC is shown in Figure 2, having two groups of SUs. These groups are based on their IDs, e.g., SUs with even-numbered IDs in one group and SUs with odd-numbered IDs in another group. The grouping criteria and number of groups in an actual scenario are optimally adjusted according to the network conditions, and the group ID (G_{id}) is determined as follows:

$$G_{id} = \left(\text{SU}_{id} \bmod N_g\right) + 1, \quad (3)$$

where SU_{id} is SU's ID and N_g is the number of groups. For example, if an SU has $\text{SU}_{id} = 231$ and the number of groups $N_g = 6$, then its $G_{id} = (231/6) + 1 = 4$ and this SU will scan the 4th portion of the primary spectrum. Note that the primary spectrum is divided into N_g portions, i.e., 6 in this case. In this manner, each group senses L/N_g number of primary channels in parallel. The SUs sense the primary channel

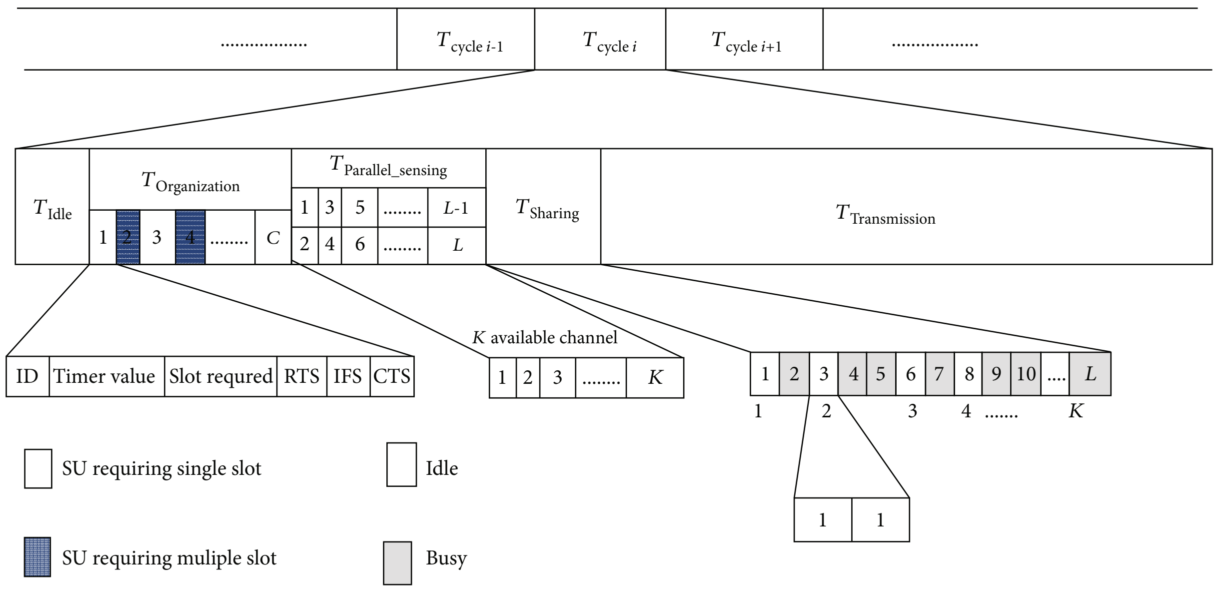

Figure 2: PSO-MAC frame structure.

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Input: number of primary users N, number of secondary users M, number of primary channels L, number of discovered idle channel K, number of parallel groups N_g, primary traffic load ρ
Output: channel utilization
Step 1: organization phase;
Assign IDs as in [18];
Start timer value when data is ready;
Share IDs and timer values among all SUs;
for all M SUs do
    if all M have different timer value then
        SUs position in queue based on descending order of timer values;
    else
        SU with lower ID get higher preference;
    end
end
SUs organized in a queue;
Step 2: parallel sensing phase;
Number of channels scan by each group is L/N_g;
for all N_g do
    Scan the specific portion of L
end
Step 3: sharing phase;
for all L slots do
    Share the sensing result;
    if channel sensed idle then
        Set the second bit of subslot to 0;
    else
        Set the second bit of subslot to 1;
    end
end
Step 4: transmission phase;
if SU in queue and channel sensed idle then
Transmit the data of SU standing at the first position in queue;
    end
if SU needs multiple slots then
    Use round-robin scheduling
end
```

Algorithm 1: PSO-MAC algorithm.

based on their group ID (G_{id}) and repeat the sensing after the number of group N_g till L.

3.2.4. Sharing Phase. Sharing phase, T_s, is where the spectrum sensing results of different groups are shared among the SUs both within and outside the group. The sensing of the channel is done in a parallel manner; however, the status of the channel cannot be shared in parallel. So the total number of subslot required in the sharing phase is the same as the number of primary channels, i.e., L. The length of this phase is

$$T_s = L \times 2T_{bit}. \quad (4)$$

Each subslot in the sharing phase carries two-bit information. The first bit represents whether the channel is sensed "1" or skipped "0," and the second bit represents the status of the sensed channel according to the reporting user, i.e., "0" for idle and "1" for busy, as shown in Table 2. All the users in a group sensing a particular channel report their findings through these two bits. The decision about the presence or absence of a primary user on a channel is made locally by each user through these bits. If there are conflicting reports for a channel, i.e., some reporting the channel idle and other as busy, then the channel is considered as busy by the user. This provides complete protection to the primary user against the interference from the CRN. The channel is considered as not sensed if the first bit is "0" regardless of the value of the second bit which is marked as "x."

3.2.5. Transmission Phase. All the SUs are organized in a queue after the organization phase (T_o) and after the channel state information is shared among the distributed SUs in the sharing phase, where K vacant channels from the primary band have been identified, the channel access is smooth and efficient, i.e., without contention and channel skipping. The first SU in the queue gets access to the first vacant channel in the list the second SU gets the second vacant channel and so on. If all the SUs have got access to a channel and the list of vacant channels is not exhausted, then the SUs demanding multiple channels can get access to additional channels in the same T_c using a scheduling mechanism such as round-robin scheduling, because preferably used to access the remaining idle channels as all the SUs have already been organized. On the other hand, if an SU does not get access to a channel in the current T_c, it gets automatic priority in the next T_c by the virtue of its higher timer value. Since the access is collision-free, the SUs getting access to the channel can start their data transmission after the T_s phase, i.e., the T_{tx} phase.

3.3. PSO-MAC Algorithm. The challenge in a CRN is to maximize channel utilization through sensing of the maximum vacant primary channels for data transmission. In contention-based random channel access, there exists a possibility of collision, where multiple SUs access the same channel, as well as the possibility of an idle channel being skipped, i.e., no SU attempting to access a particular channel. In either case, the result is a waste of valuable resources and eventually degrades the performance of CRN.

Table 2: Sharing phase subslot and channel status.

Subslot bit no.	Value	Channel state
First bit	1	Channel sensed idle
Second bit	0	
First bit	1	Channel sensed busy
Second bit	1	
First bit	0	Channel not sensed
Second bit	x	

PSO-MAC protocol reduces both the duplicated and the missed idle channel sensing through parallel sensing and maximizes the successful utilization by organizing the SUs in a queue and enabling the channel access without contention. In the organization phase, all SUs share their timer values and the number of slots required. The timer value indicates the age of data, so the SU with the highest timer value gets top priority in the queue. When two SUs have the same timer value, then priority in the queue is decided through user ID, which is acquired at the time of entry into the CRN. All the SUs are aware of their exact location in the queue at the end of the organization phase.

Once the SUs are organized in a queue, the parallel sensing phase is initiated. PSO-MAC prefers parallel sensing instead of random sensing to maximize the sensing of vacant channels and minimize the sensing time. In parallel sensing, the primary band is divided into the same number of portions as the number of groups N_g and every member of the same group senses the specific portion of the primary band. PSO-MAC offers a dynamic grouping of the SUs for parallel sensing with due consideration of the load on the primary network and the number of active SUs in the CRN. This feature is missing in the existing work, but it is important as increasing the number of groups does not keep on increasing the gain. The sensing time is reduced through parallel sensing, but at the same time, the increased parallelism reduces the probability of idle channel discovery as chances of a portion of a band with no SU falling in that group are increased. Consequently, the gain achieved through parallelism in sensing is overwhelmed by the loss due to skipping of portions of bands during sensing. By determining the optimal number of groups (N_g) according to the number of channels (L), load (ρ) on the primary network, and the active number of SUs (M), we can maximize the product of available time and available channels at the disposal of CRN; i.e., the spectrum utilizable time (U) by the CRN.

$$U = E[K] \times T_{tr}, \quad (5)$$

where $E[K]$ is the mean of discovered idle channels, which is determined through (10) of [20], i.e.,

$$E[K] = (1-\rho)\, L \left[1 - \left(1 - \frac{1}{N_g}\right)^{M}\right], \quad (6)$$

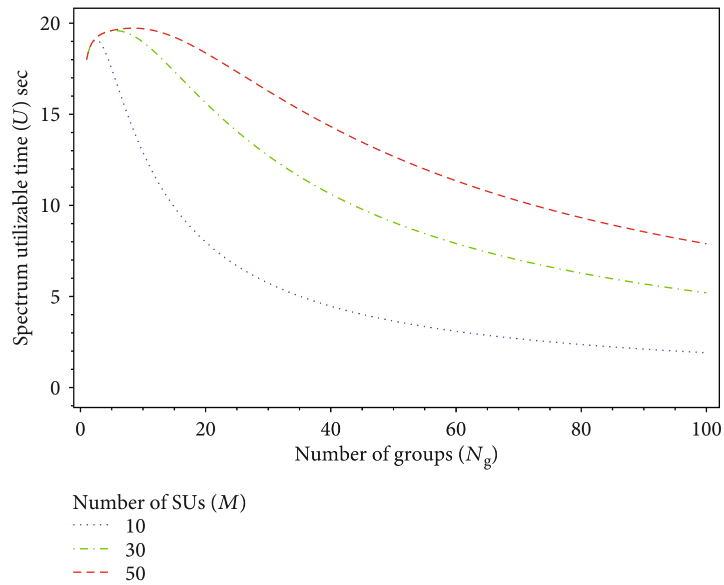


Figure 3: Spectrum utilizable time for SUs in the CRN.

and T_{tr} is the transmission time available to the SUs after the overhead in a transmission cycle (T_c), i.e.,

$$T_{tr} = T_c - \left(T_i + T_o + T_{ps} + T_{sh}\right). \quad (7)$$

While T_c, the idle time duration (T_i), the duration of the organization phase (T_o), and sharing phase (T_s) are fixed, the duration of parallel sensing phase (T_{ps}) is a function of N_g, i.e.,

$$T_{ps} = \frac{L \times \tau_s}{N_g}, \quad (8)$$

where τ_s is the duration of the sensing slot, i.e., the time taken by an SU to sense a channel.

Figure 3 shows the net utilizable time, i.e., the product of number of discovered idle channels and the time available for useful transmission on each discovered idle channel, for the CRN. Three plots are shown for identical network conditions ($L = 100$, $\rho = 0.8$, $T_c = 1$ sec, $T_i = 54$ nsec, $T_o = 37\,\mu$ sec, $\tau_{sh} = 37$ nsec, $T_{sh} = L \times \tau_{sh}$, and $\tau_s = 1$ msec), but with different numbers of SUs in the CRN (i.e., $M = 10$, 30, and 50). Initially, the net spectrum utilizable time (U) increases by increasing the number of groups (N_g). However, this trend does not continue with further increase in number of groups; rather, it starts to fall down sharply and the peak in each case is reached at a different value of N_g.

In order to ascertain the optimum number of groups, as per the network conditions and number of SUs, we determine the maxima of $U(N_g)$. The minima and maxima points are obtained through first derivative (U'), i.e., by solving

$$\frac{d}{dN_g} U = 0, \quad (9)$$

and to single out the maxima, the second derivative test is applied; i.e., if $U''|_{g_i} < 0$, then g_i is the point of maxima and the optimal number of groups (N_g^*) is

$$N_g^* = \text{round}(g_i). \quad (10)$$

For the three cases being considered, i.e., $M = 10$, 30, and 50, the optimal number of groups are 3, 6, and 8, respectively. In the scenario, where $L = 100$, $\rho = 0.8$, and $T_c = 1$ sec, the maximum spectrum utilizable time is 20 sec. Without using the parallel sensing mechanism, i.e., $N_g = 1$, the spectrum utilizable time that can be made available to the CRN for data transmission is 17.999 sec; however, with the optimal number of groups, the spectrum utilizable time for the CRN can be extended by 5.5% to 18.9973 sec, by 8.8% to 19.583 sec, and by 9.6% to 19.7243 sec for $M = 10$, 30, and 50, respectively. This gain becomes even more prominent at low primary traffic.

After parallel sensing, the sensing results are shared among the SUs in the sharing phase. This phase concludes with the list of idle channels in the current cycle. The SUs arranged in the queue access the vacant channel without contention for data transmission. The first available channel is allocated to the first SU in the queue and so on until all the idle channels are occupied by the SUs or all SUs get the required slots. When an SU requires multiple slots, it can get access to additional slots, provided all other SUs have got at least one, in the same transmission cycle in a round-robin fashion. This feature further improves channel utilization. The complete procedure of the proposed scheme is shown in Algorithm 1.

Parallel sensing along with the self-organized access allows the CRN to continue to offer a certain level of service to the secondary users even when the primary network has heavy traffic load and the opportunities for the secondary network are scarce.

4. Performance Metrics

The performance of the proposed PSO-MAC is analyzed in terms of the number of idle channels discovered, successful channel allocations to the SU, and the network throughput compared with the parallel sensing scheme of [20] and self-organizing distributed cognitive radio MAC protocol (SOD CR-MAC) [18]. In this section, we define these performance metrics in the context of PSO-MAC.

4.1. Discovered Idle Channels. For a sensing scheme in the CRN, the ultimate goal is to maximize the pool of available resources. Sensing techniques are employed to discover the idle channels; "discovered idle channels" is defined as the number of vacant channels of the PU band that are being successfully declared unused or idle by the sensing mechanism. These discovered idle channels can be used by the SUs for the data transmission. The probability distribution of idle channel discovery is [38]

$$p_K(k) = \binom{L}{k}(1-\rho)^k(\rho)^{(L-k)}, \quad (11)$$

where k is the number of discovered idle channels, L is the total number of channels in the primary band, and ρ is the primary traffic load. So the average number of idle channels discovered in a random sensing scheme is

$$E[K] = \sum_{k=0}^{L} k p_K(k). \quad (12)$$

For a random sensing scheme, such as RSO-MAC, the average number of channels discovered idle is

$$E^{\mathrm{RSO}}[K] = L(1-\rho)\left(1-\frac{L-j}{L}\right)^M, \quad (13)$$

where j is the number of channels that every SU is required to sense during the sensing phase.

The average number of channels sensed during the parallel sensing is obtained as [20]

$$E[S] = L\left[1-\left(1-\frac{1}{N_g}\right)^M\right], \quad (14)$$

and the average number of discovered idle channels for a parallel sensing scheme such as PRA-MAC is

$$E^{\mathrm{PRA}}[K] = L\left[1-\left(1-\frac{1}{N_g}\right)^M\right](1-\rho), \quad (15)$$

where N_g is the number of parallel groups. The number of groups in [20] is fixed and randomly chosen, whereas in the proposed PSO-MAC scheme, the number of groups is adaptive according to (5) and is determined by evaluating (9), applying second derivative test and (10). The goal is to reduce the sensing time through parallelism and yet maximize the number of channels to be sensed. Covering the entire band during sensing would increase the probability of finding all the vacant channels. So for PSO-MAC, the average number of discovered idle channels is

$$E^{\mathrm{PSO}}[K] = L\left[1-\left(1-\frac{1}{N_g^*}\right)^M\right](1-\rho), \quad (16)$$

where N_g^* is the optimum number of groups, determined through (10).

4.2. Channel Utilization. In a CRN, the availability of discovered resources is dynamic and generally ephemeral, so maximizing their utilization is even more important than in traditional communication systems. For example, random access wastes many opportunities due to collisions and non-attempt on the channels. Utilization of the discovered resources, which is the ratio of the successfully utilized channels to the total number of discovered idle channels, in random access and in organized access has been studied in [18]. Using the Monte Carlo simulations, the probability of successful channel utilization (P_{su}) is determined, which we use to analyze the network throughput.

4.3. Network Throughput. The network throughput of the CRN depends on idle channel discovery, successful channel utilization, and overhead of the frame structure. Higher number of discovered resources and their maximal utilization would definitely increase the network throughput. However, the PSO-MAC scheme is designed for an ad hoc network, which has no infrastructure cost but lays the onus of coordination on the distributed nodes. The coordination among the users is achieved through a common control channel (CCC) with a frame structure that enables several critical functions for CRN operation; this arrangement does incur an associated overhead that needs to be analyzed. Network throughput provides a suitable measure to encompass all aspects and compare various schemes.

The cycle time consists of number of phases that include idle time, organization period, sensing duration, sharing time, contention period in case of random access, and the transmission time.

$$T_c = T_i + T_o + T_s + T_{sh} + T_{tr} + T_{ct}, \quad (17)$$

where T_{tr} is the data transmission time and the rest of the contributing factors in T_c are overhead so

$$T_{tr} = T_c - (T_i + T_o + T_s + T_{sh} + T_{ct}). \quad (18)$$

The transmission time (T_{tr}) for random sensing-organized MAC (RSO-MAC) [18], parallel sensing-random access MAC (PRA-MAC) [20], and parallel sensing-organized MAC (PSO-MAC) schemes is, respectively, as follows:

$$T_{tr}^{\mathrm{RSO}} = T_c - (T_i + T_o + T_s + T_{sh}), \quad (19)$$

$$T_{\mathrm{tr}}^{\mathrm{PRA}} = T_{\mathrm{c}} - \left(T_{\mathrm{i}} + T_{\mathrm{ps}} + T_{\mathrm{sh}} + T_{\mathrm{ct}}\right), \quad (20)$$

$$T_{\mathrm{tr}}^{\mathrm{PSO}} = T_{\mathrm{c}} - \left(T_{\mathrm{i}} + T_{\mathrm{o}}, T_{\mathrm{ps}}^{*} + T_{\mathrm{sh}}\right), \quad (21)$$

where

$$\begin{aligned} T_{\mathrm{s}} &= \tau_{\mathrm{s}} \times L, \\ T_{\mathrm{sh}} &= \tau_{\mathrm{sh}} \times L, \\ T_{\mathrm{ps}} &= \tau_{\mathrm{s}} \times \frac{L}{N_{\mathrm{g}}}, \\ T_{\mathrm{ps}}^{*} &= \tau_{\mathrm{s}} \times \frac{L}{N_{\mathrm{g}}^{*}}. \end{aligned} \quad (22)$$

N_{g}^{*} is the optimal number of groups as obtained through (10), and T_{ct} is the duration of the contention phase as required in random access schemes.

In PSO-MAC, the parallel sensing scheme is used to reduce the sensing time and efficiently discover the maximum vacant channels by dividing the SUs into an optimal number of groups. Additionally, the discovered channels are accessed in an organized manner, which eliminates the need for contention and the probability of successful utilization of channels $P_{\mathrm{su}}^{\mathrm{PSO}} \approx 1$ [18], thus leading to improved network throughput. The network throughput for PSO-MAC is obtained as follows:

$$\mathrm{Throughput}^{\mathrm{PSO}} = P_{\mathrm{su}}^{\mathrm{PSO}} \frac{E^{\mathrm{PSO}}[K] \times T_{\mathrm{tr}}^{\mathrm{PSO}} \times R}{T_{\mathrm{c}}}, \quad (23)$$

where $E^{\mathrm{PSO}}[K]$ is the expected number of idle channels discovered in the PSO-MAC and is obtained using (16), whereas $T_{\mathrm{tr}}^{\mathrm{PSO}}$, which is the transmission time after the user gets access to the channel, is determined through (21). R is the channel data rate and T_{c} is the cycle time duration.

The corresponding expressions of throughput for RSO-MAC [18] and PRA-MAC [20] are as given below:

$$\mathrm{Throughput}^{\mathrm{RSO}} = P_{\mathrm{su}}^{\mathrm{RSO}} \frac{E^{\mathrm{RSO}}[K] \times T_{\mathrm{tr}}^{\mathrm{RSO}} \times R}{T_{\mathrm{c}}}, \quad (24)$$

$$\mathrm{Throughput}^{\mathrm{PRA}} = P_{\mathrm{su}}^{\mathrm{PRA}} \frac{E^{\mathrm{PRA}}[K] \times T_{\mathrm{tr}}^{\mathrm{PRA}} \times R}{T_{\mathrm{c}}}. \quad (25)$$

The values of $E^{\mathrm{RSO}}[K]$ and $T_{\mathrm{tr}}^{\mathrm{RSO}}$ are obtained using (13) and (19), respectively. The values of $P_{\mathrm{su}}^{\mathrm{RSO}}$ and $P_{\mathrm{su}}^{\mathrm{PRA}}$ are obtained in [18] through Monte Carlo simulations. $E^{\mathrm{PRA}}[K]$ and $T_{\mathrm{tr}}^{\mathrm{PRA}}$ are determined using (15) and (20), respectively, where the number of parallel groups N_{g} is randomly chosen and not by determining the optimal value.

Table 3: Simulation parameters.

Parameter	Value
Number of channels in the primary network (L)	20~100
Primary traffic load (ρ)	0~1
Number of secondary users (M)	2~100
Number of SU groups (N_{g})	2~50
Idle time duration for synchronization (T_{i})	54 μs
Slot duration in sensing (τ_{s})	1 ms
Cycle time (T_{c})	1 s
Slot duration in sharing (τ_{sh})	37 ns
T_{SIFT}	16 μs
T_{RTS}	24 μs
T_{CTS}	24 μs

5. Simulation Scenario, Analysis, and Comparison

In this section, we present the simulation-based performance analysis of the proposed PSO-MAC protocol and compare results with the following two schemes:

RSO-MAC. The authors in [18] used the self-organized contention-free access scheme, while the sensing of the channel is random (RSO-MAC).

PRA-MAC. In [20], the authors proposed the parallel sensing with random access MAC (PRA-MAC). PRA-MAC sensing uses parallel sensing of the primary band; however, access of channel is random which is not efficient.

First, we provide the simulation setup and parameters, and in the following subsection, the results and the comparison are discussed.

5.1. Simulation Parameters. For the simulation scenario, we select different values of number of channels (L) ranging from 20 to 100 and the primary traffic load (ρ) is varied from 0 to 1. The number of SUs (M) fluctuates between 2 and 100 in different scenarios. For comparison, the number of groups (N_{g}) is varied from 2 to 50, but the optimum number of groups for PSO-MAC is obtained by determining the point of maxima of $U(N_{\mathrm{g}})$ (5) taking first derivative, applying second derivative test and (10) as elaborated in Section 3.3.

The PSO-MAC protocol is simulated in MATLAB and Monte Carlo simulations have been performed to evaluate the various performance parameters, and results are obtained on averaging 10^6 experiments.

The detailed list of parameters used in the simulation is shown in Table 3.

5.2. Results and Discussions. In this subsection, we analyze the performances of PSO-MAC, PRA-MAC, and RSO-MAC protocols for the considered system model and compare the results in terms of the discovered idle channels, idle channel utilization, and the network throughput.

Figure 4 shows the comparison of the number of idle channels discovered by the proposed PSO-MAC scheme with those in the baseline schemes, i.e., PRA-MAC and RSO-

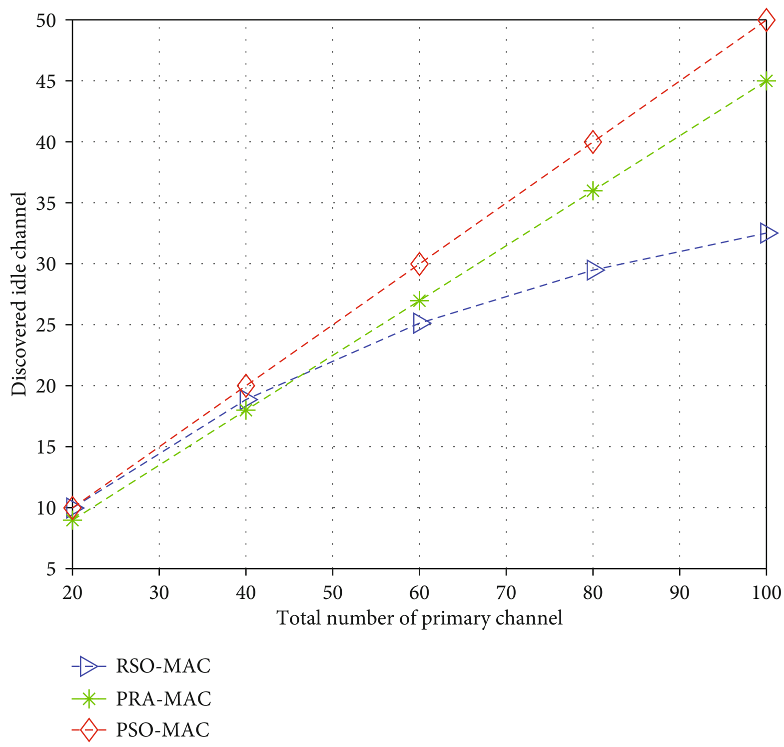


Figure 4: Discovered idle channel with varying primary channels.

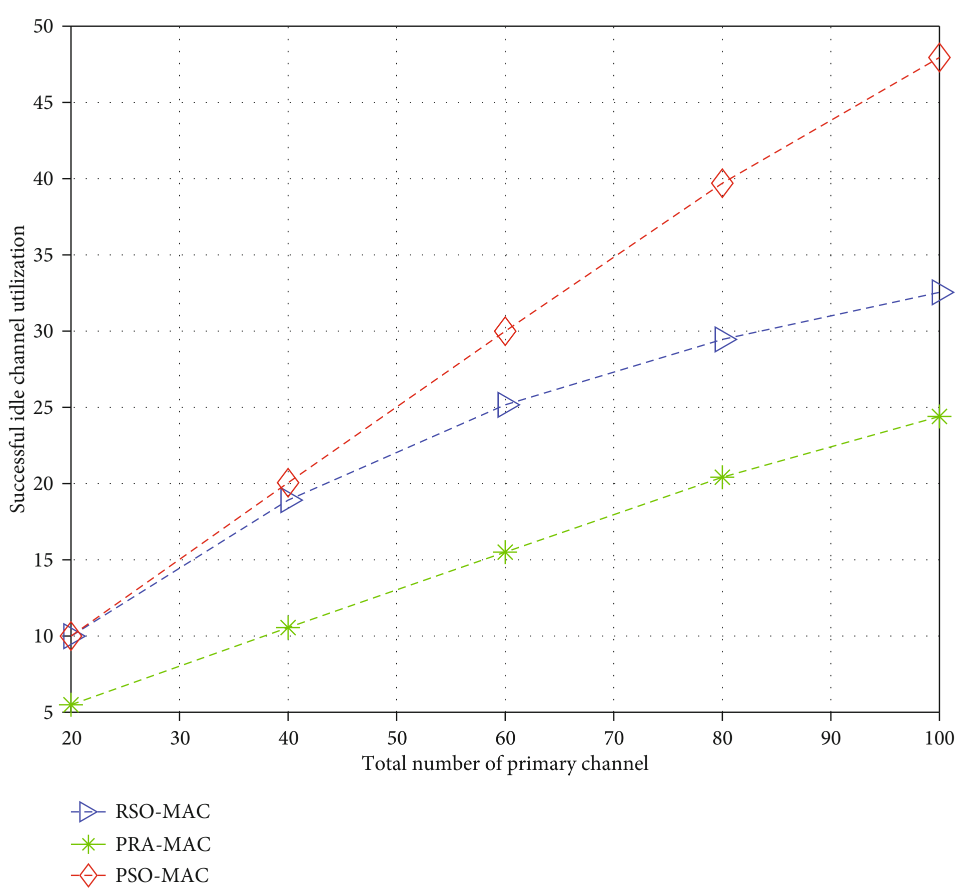


Figure 5: Idle channel utilization with varying primary channels.

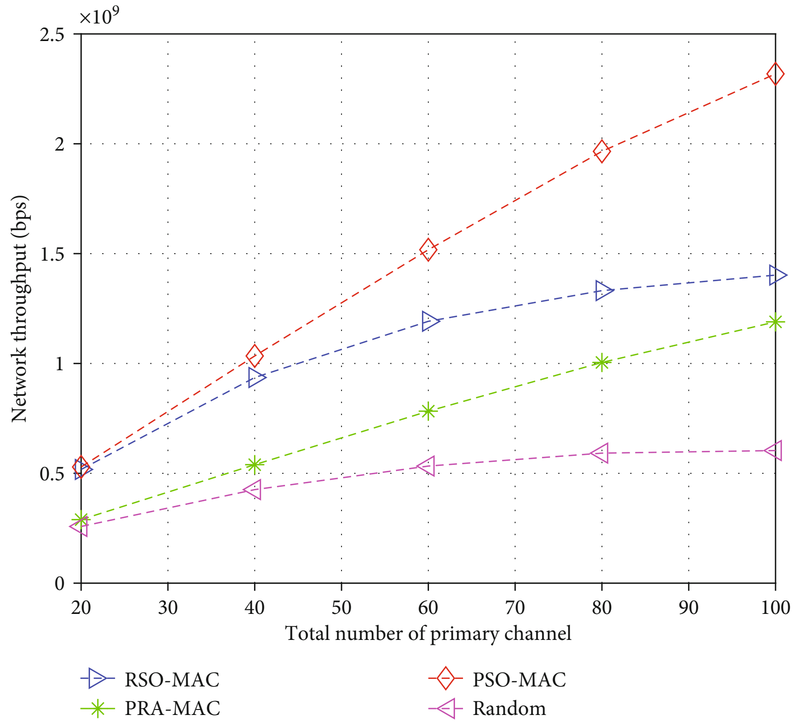


Figure 6: Network throughput with varying primary channels.

MAC. These simulations are conducted at a 50% load on the primary network and $M = 10$. Idle channel discovery performance for PSO-MAC is far better than PRA-MAC and RSO-MAC for the entire range of the number of primary channels. In RSO-MAC, the users randomly pick and sense the channel and its performance quickly degrades, whereas in PRA-MAC, through parallel sensing, the performance remains uniform that results in successfully discovering 90% of the idle channels. PSO-MAC by optimally dividing the sensing task among the SUs gets almost 100% discoveries of the vacant channels. For example, at 50% load on the primary network with 80 channels, there are 40 vacant channels and PSO-MAC has successfully discovered the 40 channels as evident from Figure 4.

Figure 5 shows the variation of idle channel successful utilization with the varying number of the primary channels. Not all the discovered idle channels are successfully utilized by the SUs, and it depends on the access control mechanism. In PSO-MAC, through contention-free access, the waste is negligible; however, this is not the case with other MAC schemes. These results are obtained with simulation parameters set at $M = 10$, the primary traffic load $\rho = 50\%$, and the average number of channels required by each SU to be 5. In PSO-MAC, channels are sensed using parallel sensing and accessed with a self-organized queue in which contention is not required. This leads to the maximum utilization of discovered idle channels and outperforms the PRA-MAC and the RSO-MAC. In PRA-MAC, the parallel sensing improves the discovered resources; however, the random channel access results in wasted opportunities due to collisions and nonattempt. In RSO-MAC, channels are accessed in an organized fashion; thus, despite fewer idle channels being discovered, it performs better than PRA-MAC as all discovered opportunities are tapped. PSO-MAC by virtue of contention-free access successfully utilizes twice as many channels as with PRA-MAC under the identical network conditions. Comparing RSO-MAC with PSO-MAC, initially the gap is small, but it widens as the opportunities for CRN users grow as the discoveries are limited in RSO-MAC.

Network throughput in the CRN can be enhanced by maximizing the discovery of idle channels from the primary band and reducing the overhead in T_c, which extends the transmission time available for the secondary users. Figure 6 illustrates the comparison of the network throughput achieved for the three schemes as well as for the case when both the sensing and access mechanism are random. It is to be noted that the PSO-MAC establishes its superiority, as the network throughput gains are higher with PSO-MAC than the sum of the gains achieved when each one of the other two schemes is employed independently. Considering the IEEE 802.11a channel data rates and the primary network with 80 channels and at $\rho = 50\%$, the network throughput is 1.9 Gbps, 1.35 Gbps, and 1 Gbps for PSO-MAC, RSO-MAC, and PRA-MAC, respectively.

It is also interesting to evaluate the performance with different values of the primary traffic load. We conduct the simulations with parameters $L = 100$, $M = 10$, channels required by the SUs are uniformly distributed between 1 to 10, and the primary traffic load ρ is varied from 0 to 1.

The impact of the primary load on the discovered idle channels is shown in Figure 7 where the PSO-MAC discovered the maximum number of idle channels. The performance is even better than PRA-MAC as not only sensing is done in parallel but the number of groups is adjusted

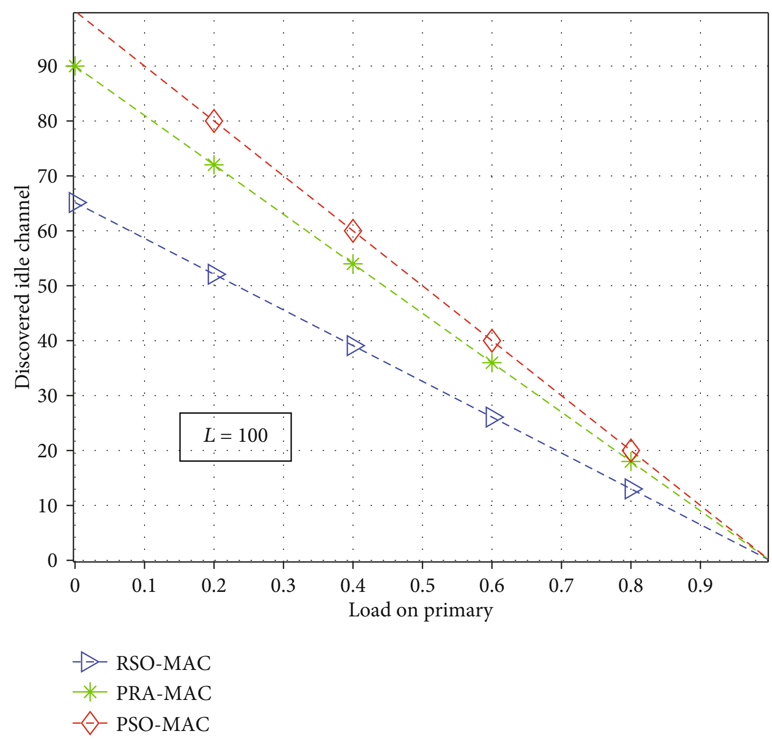


Figure 7: Discovered idle channel with varying primary load.

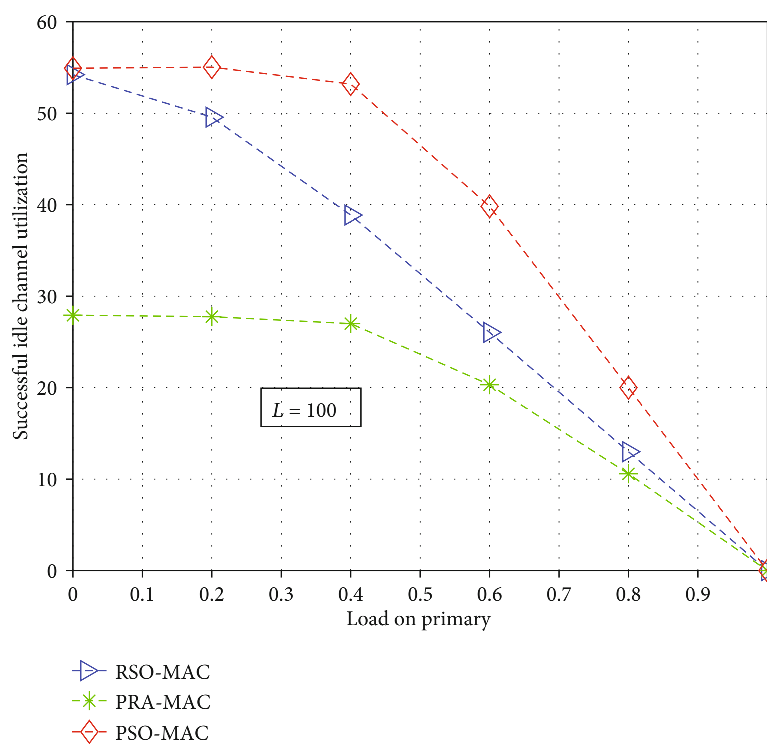


Figure 8: Idle channel utilization with varying primary load.

according to the load on the primary network. The worst performance with respect to idle channel discovery is with RSO-MAC as there is no coordination among the SUs for sensing and is done randomly.

Figure 8 shows the idle channel utilization for the three schemes with a varying load on the primary network. With no load on the primary network $(\rho = 0)$, the performance of RSO-MAC is approximately the same as the PSO-MAC

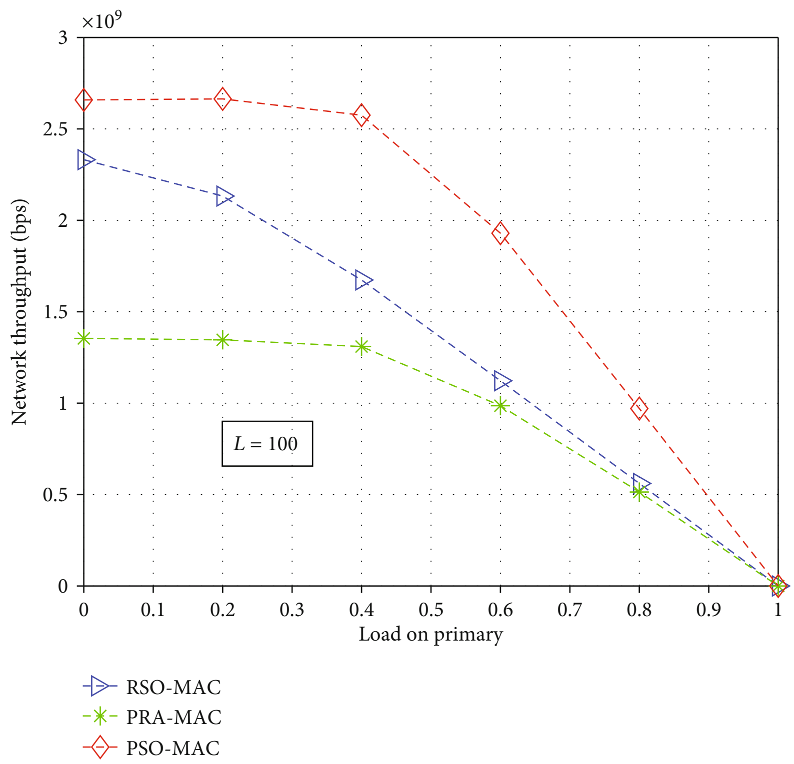


Figure 9: Network throughput with varying primary load.

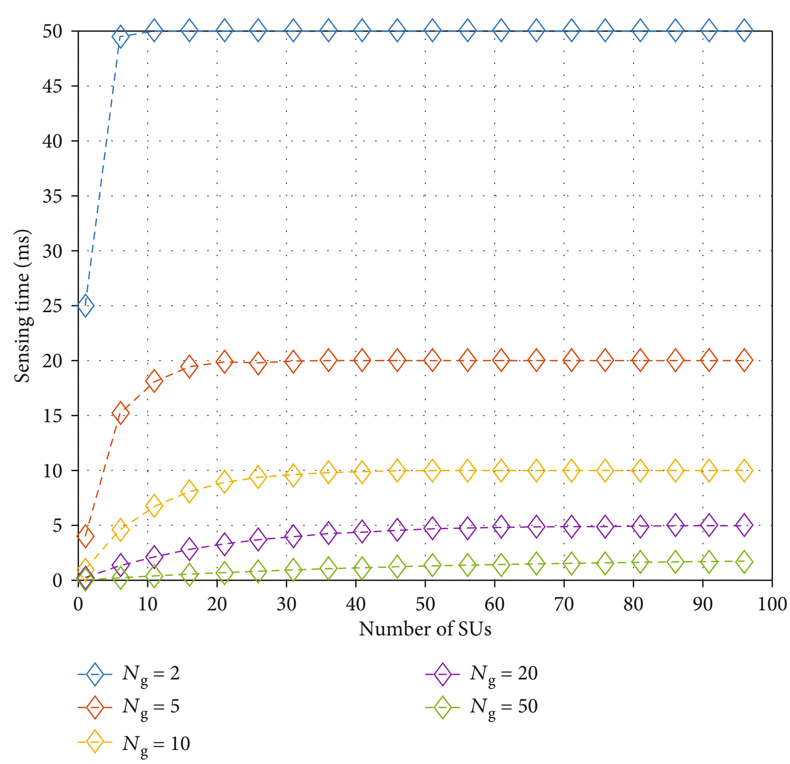
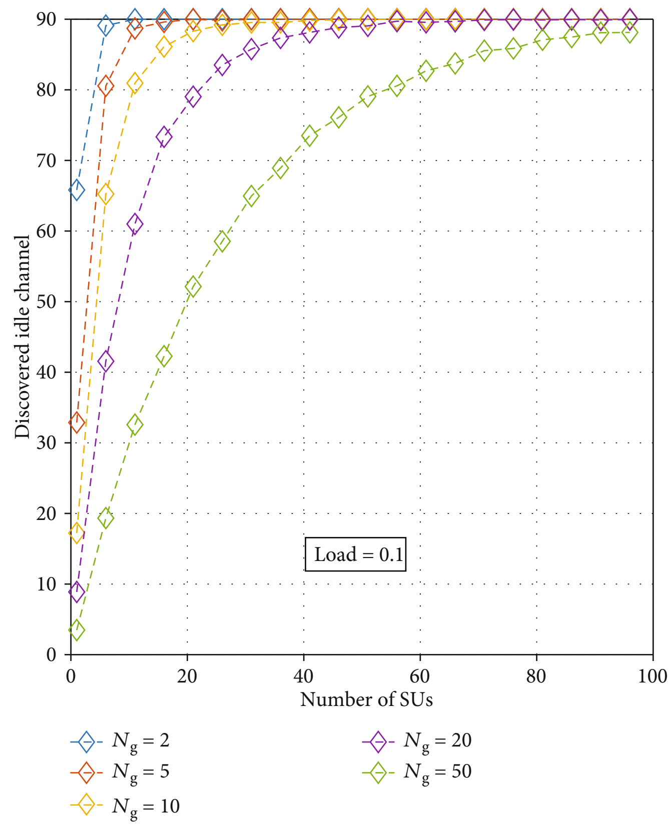
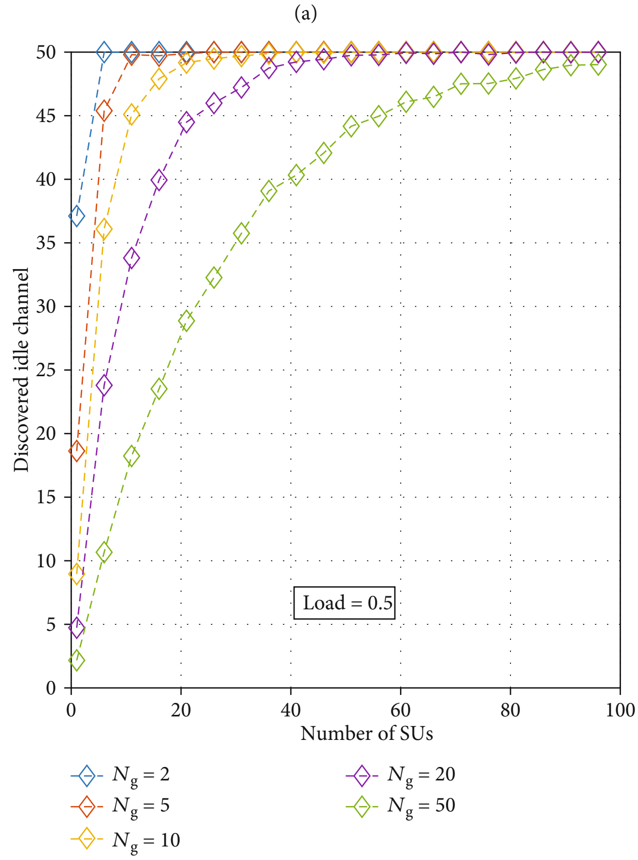


Figure 10: Sensing time with varying number of SUs.

as the entire band is available for the SUs. However, as the load increases, the performance of RSO-MAC declines sharply due to the poor discovery mechanism. The performance of PRA-MAC remains below par despite having better sensing and discovery process. This is due to the unorganized, contention-based random access on the vacant

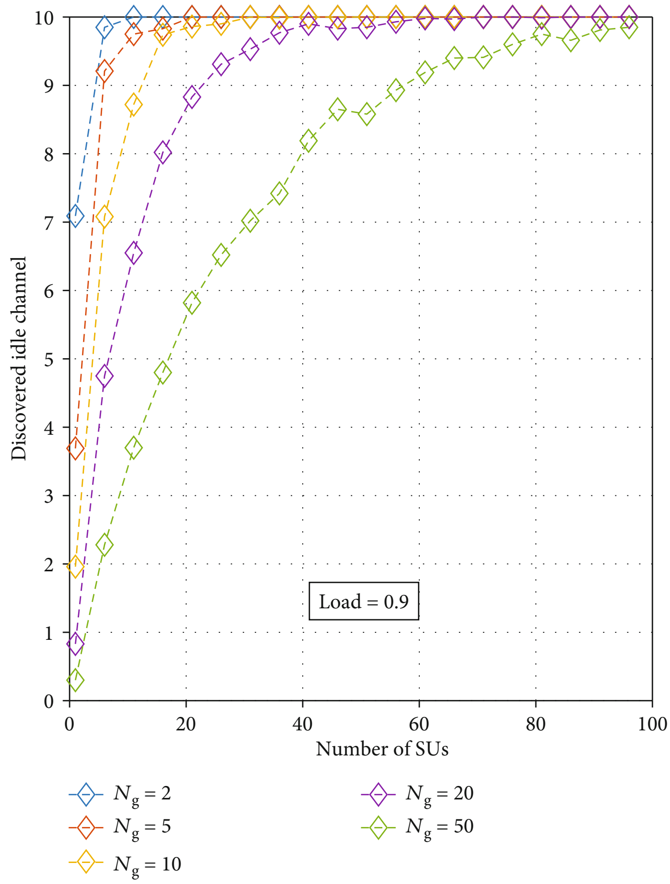


(a)



(b)

Figure 11: Continued.



(c)

Figure 11: Discovered idle channel with varying numbers of SUs.

primary channels. The utilization is best with PSO-MAC due to optimized sensing and organized access; however, as the load on the primary network increases, the utilization drops as the available opportunities are limited.

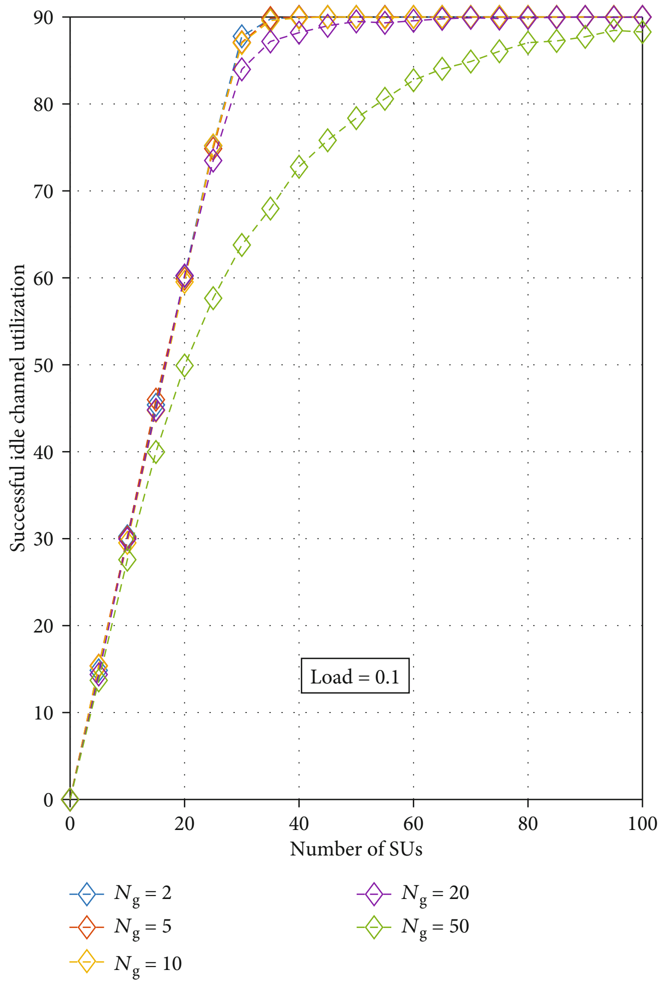
The network throughput with variation in primary traffic load is shown in Figure 9. The PSO-MAC achieves the highest network throughput throughout the entire range of primary traffic load. This is by the virtue of optimized parallel sensing and organized contention-free access.

The effect of parallel grouping on duration of sensing phase has also been investigated further. In Figure 10, when the number of SUs increases in the CRN, the probability of a group having no member is reduced. As a result, less number of portions of the primary band is skipped in sensing and the sensing time is increased. However, it becomes constant after the CRN has a certain number of SUs (divided into N_g groups) as the probability of a group having no members approaches 0. It also shows the favorable effect of increasing the number of groups on sensing time. With number of primary channels $L = 100$, the sensing time is 50 ms, 20 ms, 10 ms, 5 ms, and 2 ms for $N_g = 2$, $N_g = 5$, $N_g = 10$, $N_g = 20$, and $N_g = 50$, respectively. However, this is at the cost of reduced number of discovered resources as revealed in Figure 11. This reduction in discovered resources with increase in number of groups is primarily due to the fact that with large number of groups, the probability of a group with no members in it increases. The portion of spectrum assigned to be sensed by a group with no members is not covered during the sensing phase, and consequently, all opportunities of this band are lost.

The comparison of the three subplots in Figure 11 shows that as the load on the primary network increases, the number of discovered resources for each of the groups of SUs decreases (depicted in scaling of y-axis in the three subplots where the limits are 0-90, 0-50, and 0-10, respectively). This behavior call for adjustments in the number of groups in parallel sensing phase so that the overall sensing time is reduced while discoveries are not compromised at the same time. In PSO-MAC, the number of parallel groups is dynamically adjusted according to equations (5) and (9), which is dependent on the load on the primary network and number of secondary users.

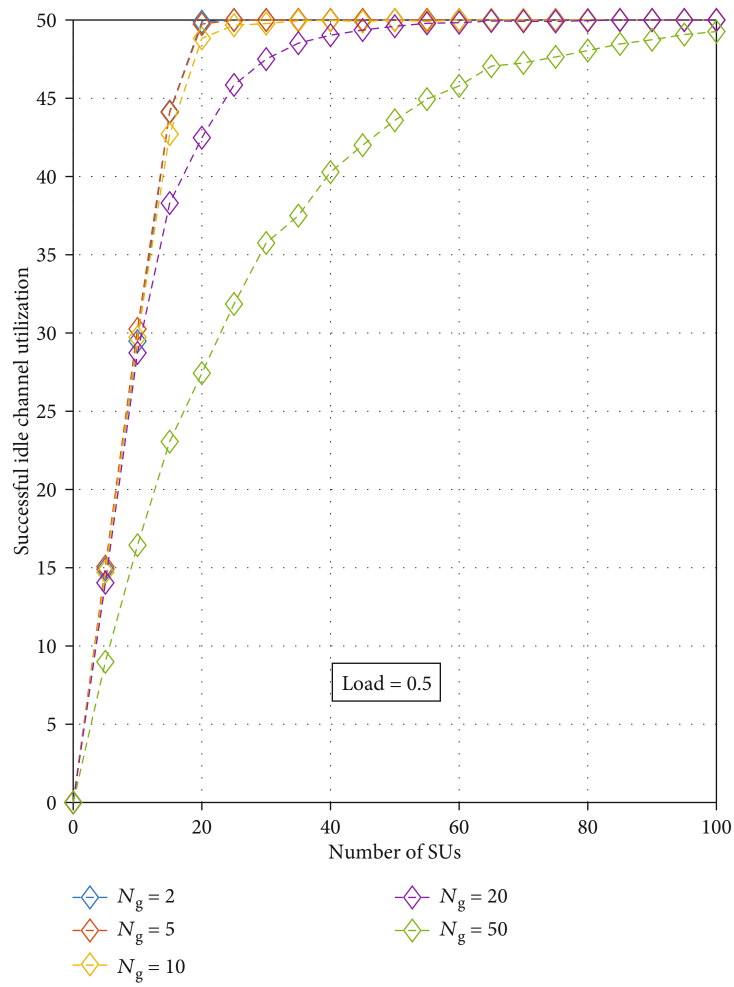
The utilization of idle channels for three values of primary traffic loads, i.e., 0.1, 0.5, and 0.9, is shown in Figures 12(a)–12(c), respectively. It can be seen that when the primary traffic is low, the higher number of SU groups provides better utilization. And as the load on the primary network increases, the number of groups should be smaller for the same number of SUs.

Finally, we compare the actual utilization of the vacant resources of the primary network by the CRN taking into consideration the overhead of the scheme, discovered



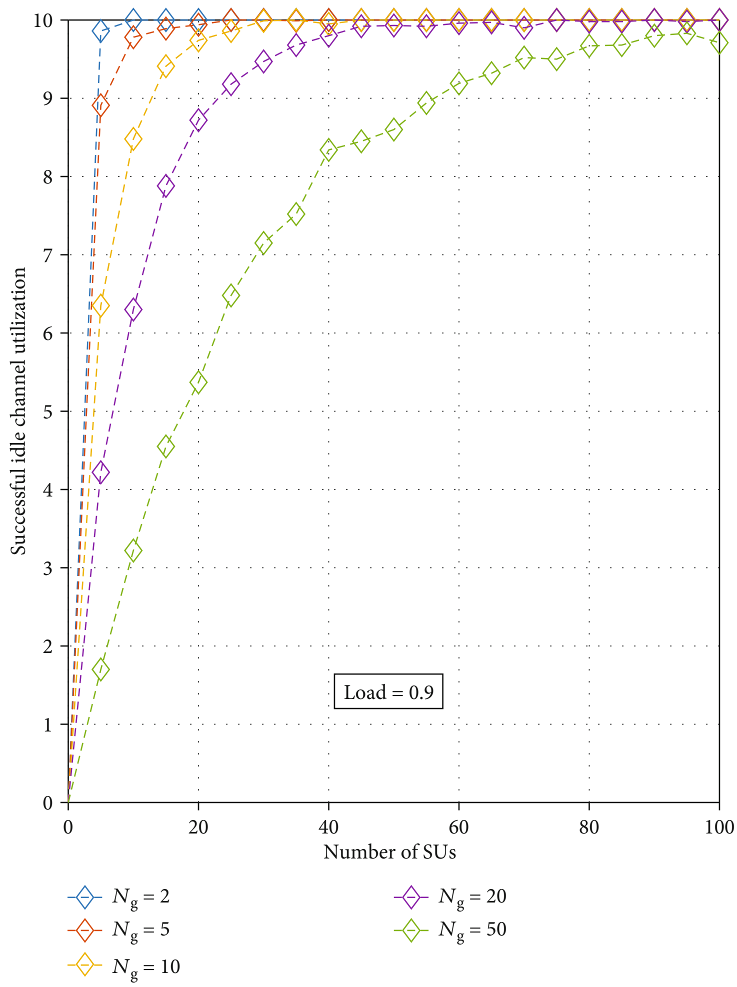
(a)

Figure 12: Continued.



(b)

Figure 12: Continued.



(c)

Figure 12: Idle channel utilization with varying numbers of SUs.

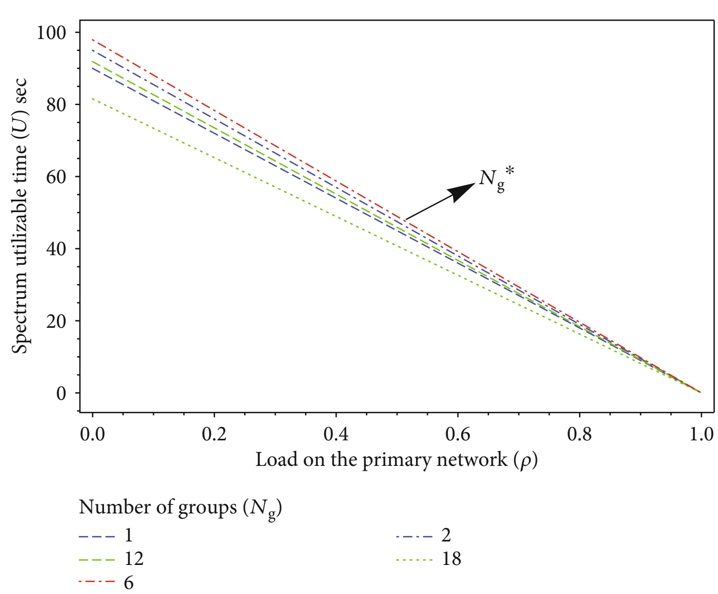


Figure 13: Utilizable time for the CRN with different numbers of groups.

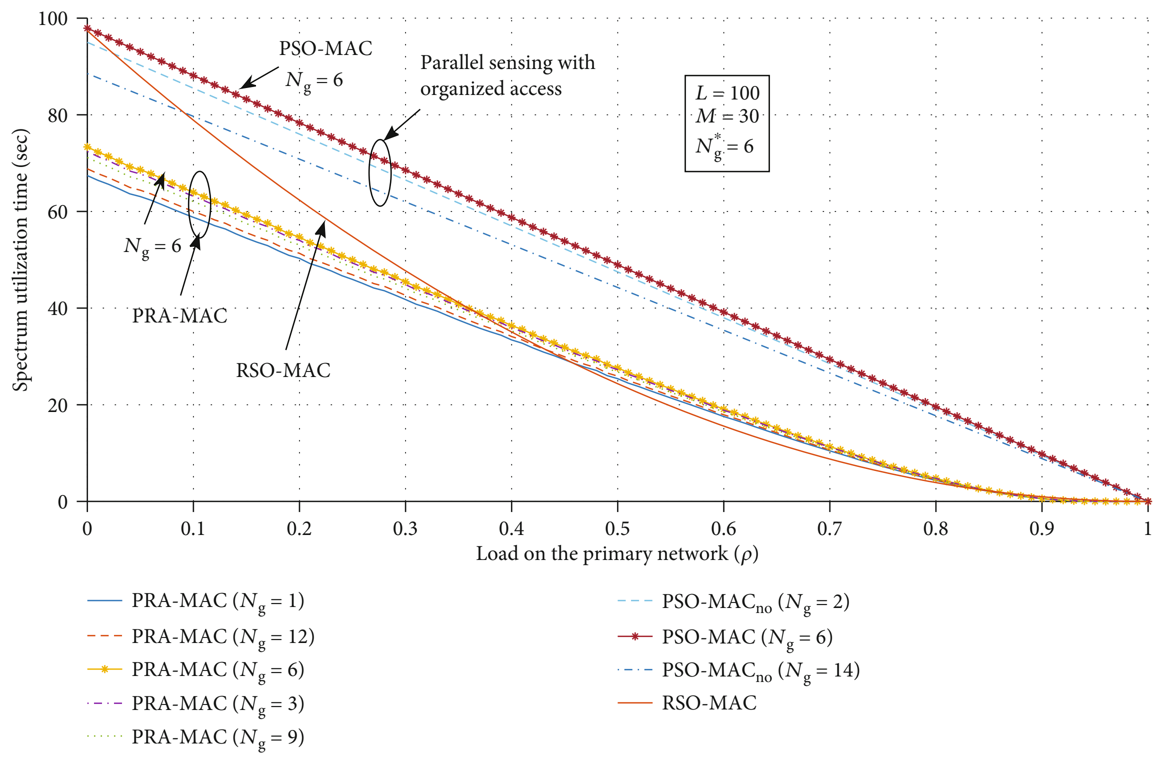


FIGURE 14: Successful spectrum utilization time.

resources, and successful utilization of these resources. For PSO-MAC, the optimal number of groups is determined as elaborated in the algorithm; in order to demonstrate the advantage of dividing the SUs into an optimal number of groups, we include the plots with nonoptimal number of groups, i.e., parallel sensing, organized access but number of groups randomly chosen.

Considering $M = 30$ and $L = 100$, the optimum number of groups as obtained through (10) is $N_g^* = 6$. Figure 13 demonstrates that the PSO-MAC maximizes the utilizable time from the primary network to the CRN by using the optimum number of groups. Any other value of N_g, smaller or greater, as used in PRA-MAC, reduces the utilizable time for the CRN. With 6 groups of SUs, each SU is required to sense $100/6 \approx 16$ channels. In order for a fair comparison of PSO-MAC with RSO-MAC, which employs the random sensing, each SU in RSO-MAC is also required to sense 16 channels, i.e., the value of j in (13) is 16.

The successful utilization of this spectrum utilizable time, acquired for SUs through sensing, depends upon the access scheme. In PSO-MAC and RSO-MAC schemes, where there is no contention, the successful utilization is very high. However, when these acquired resources are accessed through random access, as in PRA-MAC, the utilization drops sharply with the increase in load on the primary network.

As shown in Figure 14, the PRA-MAC despite accumulating large resources through parallel sensing wastes a lot of opportunities for data transmission due to random access. RSO-MAC by virtue of organized access does not miss too many opportunities, but since the sensing is performed randomly, the resources that it manages to accumulate a limited set of resources for its users in CRN are very limited. As a result, the successful utilization of the resources falls sharply with an increase in load on the primary network. By combining the parallel sensing with organized access, the utilization is significantly improved even for PSO-MAC$_{no}$, even for the case where the number of groups is randomly chosen and is a nonoptimal value. However, when the number of groups is optimized in PSO-MAC, the results clearly demonstrate its superior performance in comparison to other schemes.

6. Conclusions and Future Work

In this work, parallel sensing with self-organizing medium access control (PSO-MAC) has been proposed for an ad hoc CRN. Parallel sensing not only reduces the overhead time but also makes the discovery of idle channels more efficient through the division of the sensing task among the secondary users; this minimizes duplication as well as channel skipping. The self-organization of the secondary users in an ad hoc network maximizes the utilization of the discovered opportunities by reducing collisions and nonattempts on any discovered idle channel. Both these schemes, the parallel sensing and the self-organization MAC, require coordinated efforts among the secondary users which could result in significant overhead. This overhead decreases the valuable time available to the secondary users to use for the transmission of data.

To minimize this overhead and to maximize the useful time in a transmission cycle, an enhanced frame structure has been designed that unifies these two mechanisms while keeping the overhead to a minimum. This improved frame structure enables to achieve the synergy where the gain of this unified approach is more than the sum of the gains of the two schemes working in isolation. This is clearly evident from the comparison of the network throughput achieved with the unified scheme to that for each of the two approaches separately. It can be noticed that the performance gains with the proposed PSO-MAC increase with the increase in the number of channels for the given load on the primary network and given the number of secondary users. This is primarily due to the careful design of the frame structure which includes a sequence of different phases, provision of dynamic adjustment of the frame according to the load on the primary network, and the number of secondary users. Another contributing factor is the optimization of the parallel sensing phase wherein the number of groups is dynamically adjusted according to the load on the primary network and the number of secondary users of the cognitive radio network. This dynamic adjustment makes the best compromise between the sensing duration in the frame and the portion of the primary band to be sensed so that the utilization is maximized.

There are several possible directions to extend this work further. For this work, the channel is considered busy if there are conflicting reports about the channel to provide the maximum protection to the primary user against interference from the CRN; other schemes such as the majority decision can increase the probability of finding a vacant channel, albeit at the cost of some interference to the primary network. Another challenging possibility could be to incorporate fairness guarantees in the self-organization scheme. Other possible extensions may include location-based grouping in parallel sensing and channel allocation using machine learning techniques such as reinforcement learning and deep learning.

Data Availability

Data is available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

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