Backoff Algorithm in Cognitive Radio MAC Protocol for Throughput Enhancement

Shweta Pandit, *Student Member, IEEE*, and Ghanshyam Singh

***Abstract*—In this paper, we have explored a novel concept of the medium access control (MAC) protocol for the distributed cognitive radio network. We have implemented the backoff algorithm in the self-scheduled multichannel cognitive radio MAC (SMC-MAC) protocol for the contention solving among the cognitive users and, hence, reserve the licensed channels for data transmission. In this control channel protocol, the cognitive users share the sensing results with each other, and each channel is divided into four intervals such as idle, sensing–sharing, contention, and data transmission. However, the backoff algorithm has been implemented during the contention interval to enhance the number of successful users and, hence, has increased the throughput of cognitive radio network. The backoff algorithm has significantly minimized the competition and, hence, collision among the cognitive users while reserving the unutilized licensed channels.**

***Index Terms*—Backoff algorithm, cognitive radio, contention, medium access control (MAC) protocol, self-scheduled, sensing and sharing, throughput.**

I. Introduction

RECENTLY, spectrum scarcity has become the bottleneck for the development of wireless communication. As the growing numbers of unlicensed wireless devices have overcrowded the industrial–scientific–medical band of the radio-frequency spectrum, the cognitive radio has tried to alleviate the utilization pressure on affected bands by constantly sensing and utilizing the spectrum opportunities in the radio spectrum. A key challenge in the cognitive radio network is to have an efficient sensing and noninterfering spectrum access decision, which enables the users to reserve chunks of the spectrum for certain periods of time. The problem of allocating spectrum for the cognitive radio network poses new challenges that have not arisen in traditional wireless technologies. The cognitive radio provides the capability of dynamically adjusting both the center frequency and communication bandwidth for each transmission according to the environment. The traditional wireless network uses a fixed channel bandwidth and center frequency for each transmission, and therefore, the spectrum allocation for the channels of predefined bandwidth has been conventionally easy to model as discussed in detail in the fixed allocation [1], [2]. However, the modeling of variable bandwidth communication in the cognitive radio is much more complicated. The limitations of fixed spectrum allocation [2] have been avoided with the help of cognitive radio technology by providing flexible use of the spectrum using two new spectrum allocation methods, namely, dynamic spectrum access (DSA) [3] and opportunistic spectrum access (OSA) [4], [5], which defines a set of techniques and models to support the dynamic management of the frequency bands for wireless communications systems. These new spectrum licensing methods improve the spectrum efficiency and enhance the performance of communication systems. Therefore, the DSA or OSA is the key approach in the cognitive radio communication system, which is adopted by a cognitive radio user to access the radio spectrum opportunistically [2].

First, the cognitive radio should identify the spectrum holes [6] in the licensed user's spectrum band, and second, it should utilize them in a flexible manner, according to the medium access control (MAC) scheme. After identifying the available spectrum resource through spectrum sensing, decision on optimal sensing, transmission time, and proper coordination with other users for the spectrum access are the important characteristics of the MAC protocol. Furthermore, the throughput maximization of a cognitive radio user with the help of a frame structure is demonstrated in [7] and [8]. Moreover, the MAC protocol is responsible for the spectrum sensing and spectrum access decisions, as discussed in [9]–[11]. The main objectives of the cognitive radio MAC (CR-MAC) protocol design are as follows:

1) to optimize the spectrum sensing and spectrum access decision;
2) to control the multiuser access in the multichannel network;
3) to allocate the radio-frequency spectrum and schedule the traffic transmission;
4) to support the spectrum trading function.

In addition to this, another potential method for sharing the licensed user's unutilized spectrum is the game theory [12]–[14]. For DSA-based cognitive radio networks, MAC protocols followed by the traditional wireless networks need to be modified to add the sensing and adaptation functionalities. The design of MAC protocols of the cognitive radios is a very challenging task due to the requirement of the coexistence of unlicensed users with the licensed users. Such protocol of cognitive system needs to achieve the highest spectrum utilization by detecting all the spectrum opportunities and access the spectrum so that the collision with the other cognitive users would be minimized. Some of the cognitive radio MAC protocols have been discussed in [15]–[19]. The hardware-constrained

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The authors are with the Department of Electronics and Communication Engineering, Jaypee University of Information Technology, Solan-173 234, India (e-mail: shweta.pandit@mail.juit.ac.in; ghanshyam.singh@juit.ac.in).

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MAC (HC-MAC) protocol considers the hardware constraints and proposed an efficient spectrum sensing with access/sharing decision [15]. In addition to this, network synchronization is not required in HC-MAC. However, this protocol suffers from a multichannel hidden terminal problem [15]. A distributed spectrum-agile MAC protocol has been proposed in [16], which is a multichannel carrier sense multiple-access-based protocol equipped with a dynamic channel selection algorithm. This model can be used for single or multiple channels and single or multiple users. The protocol discussed in [16] needs two transceivers. One is tuned to the control channel, and the other is tuned to the one of the idle licensed channel; network synchronization is required in the protocol also. In [17], the C-MAC protocol for the distributed cognitive radio network is proposed. However, C-MAC has some technical issues such as nonoverlapping beacon, quiet periods without any central entity, and rendezvous channel availability [17]. In addition to this, network synchronization must be needed in C-MAC, which makes it more complex. Furthermore, a self-scheduled multichannel cognitive-radio MAC (SMC-MAC) protocol has been proposed in [18], in which the cooperation among the cognitive users is incorporated to enhance the throughput by utilizing more idle channels for the data transmission than the idle channels sensed by a single cognitive user. However, the potential technical issues of SMC-MAC are discussed in detail later in this paper. The cognitive-radio-enabled multichannel (CREAM) MAC protocol has been discussed in [19], in which, although there is no hidden terminal problem and can work without network synchronization, there is communication overhead in this protocol. In this paper, we have explored SMC-MAC protocol for the distributed cognitive radio network to improve the throughput of communication system. In SMC-MAC, the less number of contention slots during the contention interval results in significantly more number of collisions among cognitive users. However, the large number of contention slots increases the successful cognitive users and decreases the data transmission interval since the total cycle time is fixed, which is the major limitation of SMC-MAC protocol, as discussed in [18]. Moreover, in SMC-MAC, it has not been possible that the collided cognitive users in the contention interval can once again select a contention slot to be successful in that cycle time because all the cognitive users have selected the contention slot randomly, and once collision is detected in the chosen contention slot, the collided cognitive users wait for the next cycle time for the transmission. In the proposed method, the backoff mechanism has been applied to resolve the contention among the collided cognitive users to increase the number of successful users so that if the collision is detected among cognitive users, the collided cognitive users again attempt to utilize another contention slot in the same cycle time using backoff mechanism to become successful and hence can transmit data during the data transmission interval. In this case, the contention interval is made flexible, which increases and decreases its contention slots according to the number of collisions between cognitive users. For example, the numbers of contention slots are more for large number of collisions compared with less number of collided cognitive users. The remainder of this paper is organized as follows. In Section II, the system model and analysis for the proposed scheme has been described. Furthermore, in Section III, numerical simulation results of the analysis have been discussed. Finally, Section IV concludes this paper.

II. Medium Access Control Protocol and System Design

We have considered the distributed cognitive radio network and its MAC protocol as in SMC-MAC [18]. Here, we have presented the system model, proposed MAC protocol, and its numerical analysis.

A. System Model

We have considered a primary user network, which have N_{ch} licensed channels and a cognitive radio network comprising N_{CU} cognitive users. The primary network is assumed to be a cellular network, and the traffic of cellular network is based on Poisson distribution. The cognitive users of cognitive network will utilize the N_{ch} licensed channels of the primary network for communication applications at the time when they (licensed channels of the primary network) are idle. It is also assumed that the sensing performed by a cognitive user is perfect so that there is no probability of false alarm [7] in the sensing results. In addition to this, there is one control channel for the cognitive users to exchange the control information. This channel is assumed to be always available to the cognitive network, and the cognitive user terminal is equipped with single transceiver (full-duplex mode) that can change frequency to switch among multiple channels. However, if a cognitive user wants to transmit/receive its data on/from different idle channels simultaneously, it should have multiple transceiver systems. In addition, to increase the performance of cognitive system, it is desirable that a cognitive user should sense as many licensed channels as possible. Since we know that there are different sensing techniques in cognitive radio systems and each technique requires some mathematical computation [5] of the received signals to detect the presence or absence of a primary user, therefore, as more and more licensed channels are sensed by a cognitive terminal, there is an increase in the complexity and power consumption of the terminal. This results in the tradeoff between the number of sensed channels and complexity or power consumption. However, based on this consideration, we attempt to reduce the number of sensed channels by each terminal and shared the sensing results with other cognitive users so that more number of licensed channel information is available at each cognitive terminal in comparison with the channels that it has sensed.

B. Proposed MAC Protocol

The proposed MAC protocol consists of the control channel on which the cognitive users share the sensing results of each other and N_{ch} licensed channels, as shown in Fig. 1(a). The control channel cooperation among the cognitive users is performed by presenting all the sensing results of cognitive users on the control channel, and then the idle channel/channels from the pool of the total available idle channels, whose information is available on the control channel, has been selected by the

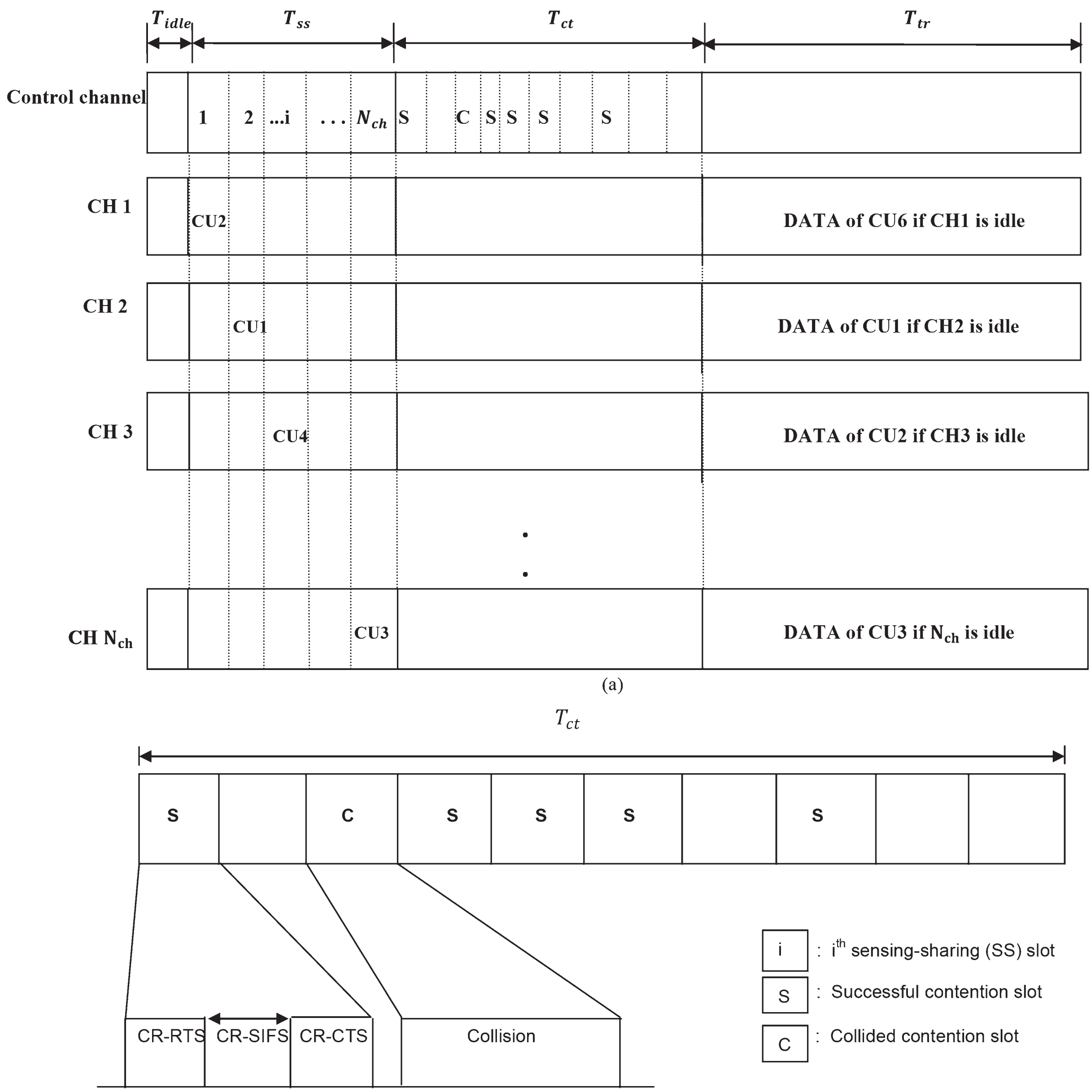

Fig. 1. (a) MAC protocol for distributed cognitive network. (b) Contention slot expansion of MAC protocol.

cognitive users. Each channel is divided into cycle time T_{cycle}, which is further divided into four intervals, i.e., idle T_{idle}, sensing–sharing T_{ss}, contention T_{ct}, and data transmission T_{tr}, as shown in Fig. 1(a). Furthermore, it is assumed that, for the T_{idle} and T_{ss} intervals, all the cognitive users are tuned to the control channel. However, cognitive users compete to reserve the idle licensed channel during T_{ct} interval and then tuned to the selected idle channel/channels. The sensing–sharing and contention intervals are further divided into number of slots [18], as shown in Figs. 1 and 2. The sensing–sharing interval has a number of slots equal to the number of licensed channels, and each cognitive user will randomly select a sensing–sharing slot to sense that particular selected slot number licensed channel during that slot period. Let us consider that there are 20 licensed channels in the network, then the number of sensing–sharing slots will be 20 as well, and out of these 20 slots, whichever slots the cognitive users select, they will start sensing that channel. Suppose a cognitive user has selected the third slot; therefore, that cognitive user will sense the third channel only. However, sensing of the third channel is performed during the first subslot of slot 3, and during the second and third subslots, the sensing information of channel 3 is shared with other users by broadcasting the sensing results, as described in Fig. 3, and all the other cognitive users that are tuned to the control channel will store the broadcasted sensing information. It is also possible that more than one user can sense the same licensed channel during sensing–sharing interval; however, sensing of the same channel by two or more users is not a problem, but broadcasting of the same information by the users on the same channel simultaneously causes corrupted sensing information. Therefore, to avoid this problem, we have considered that the cognitive user, after sensing a channel during the first subslot of the selected sensing–sharing slot, will randomly wait for some time during the second subslot

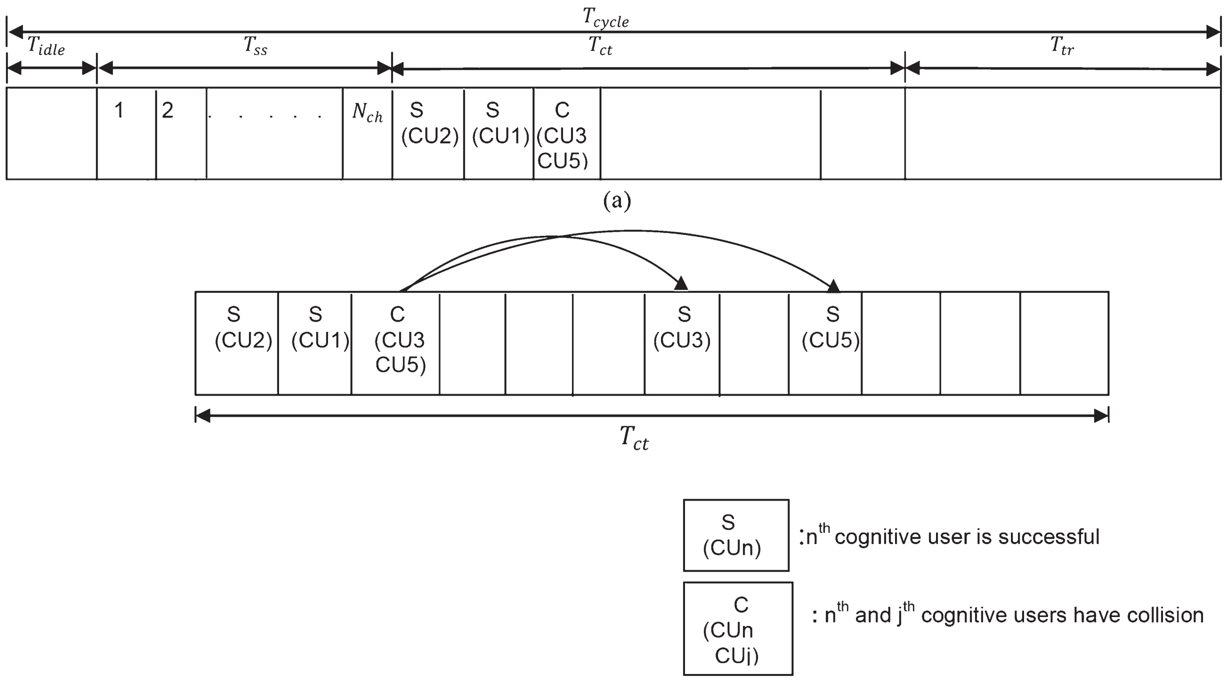

Fig. 2. Control channel structure (a) without the backoff algorithm during the contention interval and (b) with the backoff algorithm during contention interval.

to broadcast sensing information. During this random waiting time of the second subslot, if the cognitive user listens to any transmission, it would know that another user has also selected the same channel for sensing and is broadcasting the sensing information; therefore, the cognitive user will not transmit its own sensing information to avoid collision and will get that channel sensing results from the already broadcasted information. However, it is out of the scope of this paper that how each user will select the time randomly for waiting during the second subslot. This procedure of sensing and sharing is performed by all the cognitive users during their selected slot, and hence, each cognitive user has sensing information of the channels sensed by it and also by the other users, which resulted in the reduced sensing time. A cognitive user is able to send a frame successfully in the transmission interval of the idle licensed channel/channels only if that cognitive user is not having a collision with other cognitive users in the contention interval, which is possible only if each transmitting cognitive user has chosen different contention slots in the contention interval. The collision by a cognitive user is detected by listening to the cognitive radio clear-to-send (CR-CTS) [18] frame that has been sent by the destination cognitive user in response to the cognitive radio ready-to-send (CR-RTS) [18] frame transmitted by the source cognitive user on the selected contention slot in the control channel, and it is clear that if more than one source cognitive user has selected the same contention slot, they will not receive CR-CTS frame correctly, hence detect collision. This probability of collision is significantly high if the number of contention slots is limited and the cognitive users are significantly more. However, the large number of contention slots, although increases the success rate of cognitive users in the cognitive network, simultaneously decreases the data transmission interval and hence the throughput of the cognitive network. Therefore, the number of contention slots should be optimized for the cognitive network MAC protocol so that the throughput of cognitive network will also enhance with the minimum number of contention slots, which has been discussed in Section III in this paper. Since all the cognitive users know the already selected idle channel/channels during the contention slots because of the exchange of CR-RTS and CR-CTS frames on the control channel and will not request to utilize that idle channel/channels on its own CR-RTS frame during its selected contention slot, they have cooperation among each other. On the CR-RTS frame, the source cognitive user sends list of available idle channels to the destination cognitive user. However, it might be possible that at the destination cognitive user location, all those channels are not idle; therefore, the destination user will send the CR-CTS frame with selected list of the idle channel/channels on which source and destination users will transmit data during the data transmission interval. The CR-RTS and CR-CTS frame's structure with different fields has been discussed in detail in [18]. Let us consider that there are six cognitive users in the network and want to transmit data to their respective cognitive receiver. The cooperation of cognitive users is shown in Fig. 1(a), where the data of cognitive user 2 (CU2) are transmitted on channel 3, which is sensed idle by cognitive user 4. However, cognitive user 4 (CU4) is not able to transmit its data because it has collision with another cognitive user 5 in the third contention slot. This collision occurs because cognitive users 4 and 5 have selected the same third contention slot to reserve the idle licensed channels for data transmission; therefore, only four out of six cognitive users are successful. Fig. 1(b) shows the detailed description of contention interval. The interframe spacing between CR-RTS and CR-CTS frame is given by cognitive radio short-interframe-spacing (CR-SIFS) as IEEE 802.11 [20].

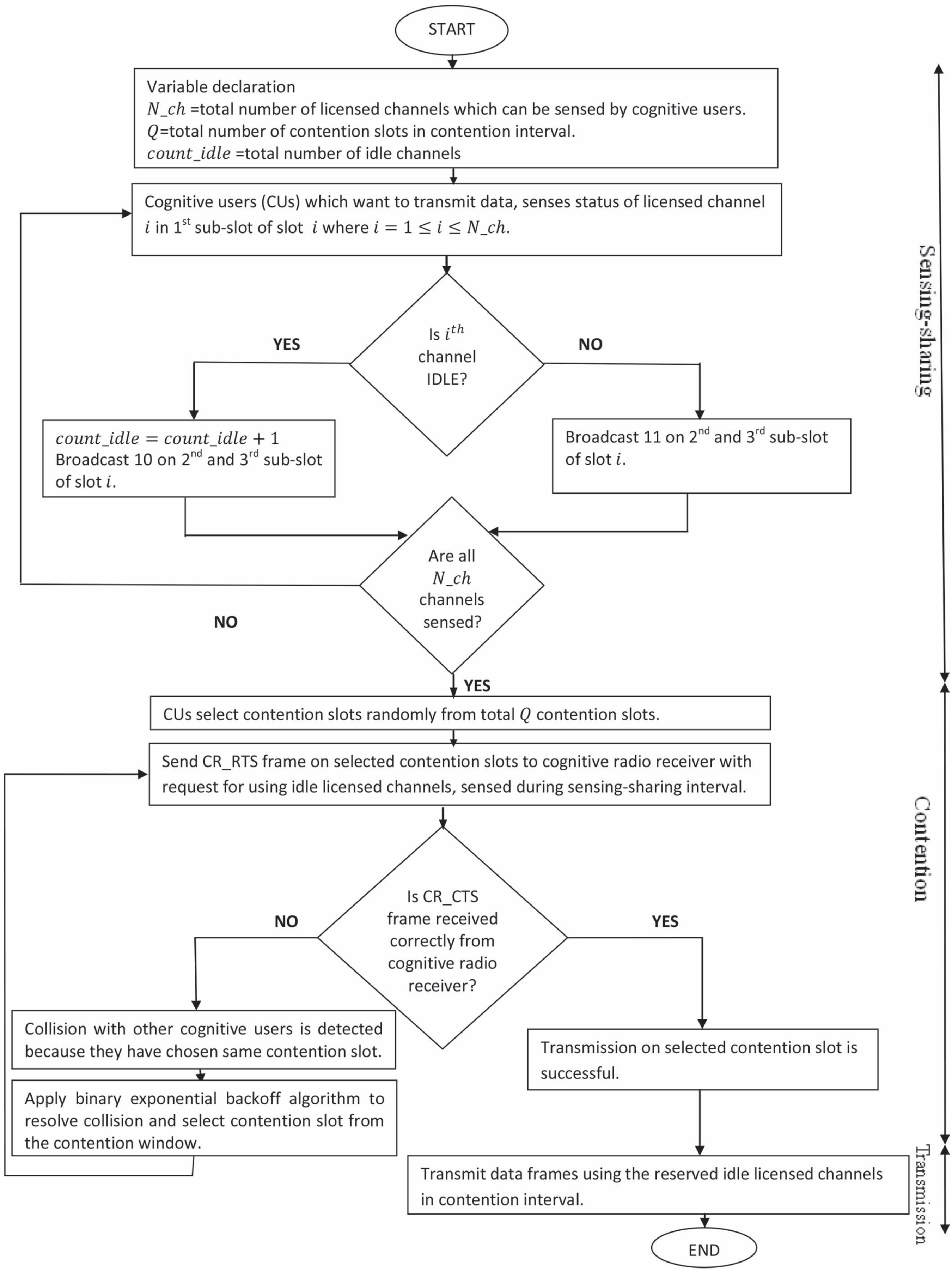

Fig. 3. Flow diagram of the proposed MAC protocol.

Since we have considered that the cognitive user is having full-duplex capability, a cognitive node can simultaneously transmit and receive. The selection of licensed idle channel by the cognitive user during the contention interval will switch cognitive node to the selected channel, and after this, on the selected licensed channel, if the primary user signal has been sensed by the cognitive node, the node will stop transmission of its own signal to protect the primary user on that channel. Since sensing is performed almost throughout the cycle time by cognitive node, however, during sensing–sharing interval, the sensing results are also shared with other users to incorporate cooperation and enhance performance of the cognitive network. Moreover, in SMC-MAC [18], it has been proposed that each cognitive user randomly chooses a contention slot, which makes it more vulnerable to collision among the cognitive users. Therefore, to reduce the number of collisions, we have modified the control channel's contention interval, as shown in Fig. 2(b), by using the backoff algorithm in the contention interval. By taking an example, it has been shown in Fig. 2(a) that cognitive user 3 (CU3) and cognitive user 5 (CU5) are having collision during $T_{\rm ct}$ in SMC-MAC and hence cannot reserve the licensed channels during the current $T_{\rm cycle}$. However, in the proposed method, the performance can be improved by modifying the control channel, as shown in Fig. 2(b), which again allows collided cognitive users to select another contention slot in the same $T_{\rm cycle}$. As shown in Fig. 2(b), cognitive user 3 (CU3) and cognitive user 5 (CU5) after collision again select a contention slot from contention window with the help of backoff algorithm, and if the selected contention slots are different, both the cognitive users become successful otherwise; if there is collision again, then the contention window size is increased and the same procedure is followed. However, this whole procedure has been presented with the help of a flow diagram, as shown in Fig. 3.

C. Performance Analysis

Here, the numerical analysis of the proposed MAC protocol is performed, and different parameters of the cognitive network are discussed.

1) Sensing–Sharing Analysis: In [21], the behavior of cellular communication system subscribers, which follows the Poisson distribution and the exponential distributed arrival time between two calls, is shown. The Poisson process is a Markov process with state transitions limited to the next higher state or to the same state and having a constant transition rate. Therefore, for the given Poisson distribution of primary network cellular calls, with interarrival time T and average rate λ, the distribution of waiting times between successive calls is computed using the cumulative distribution function [21]

$$p_i = P(T \leq T_{\rm cycle}) = 1 - P(T \geq T_{\rm cycle}) = 1 - \exp(-\lambda T_{\rm cycle})$$

where p_i is the given probability of cognitive user interfering with the primary user, and $T_{\rm cycle}$ is the maximum interference time a cognitive user is allowed to interfere with the primary user. Hence, T_{cycle} is calculated as $T_{cycle} = -\ln(1-p_i)/\lambda$. In this paper, it has been assumed that all the licensed channels have same utilization probability α. Therefore, the probability $p(l)$ that the number of idle licensed channels is l, which follows the binomial distribution as given by [18] is expressed as follows:

$$p(l) = \binom{N_{\rm ch}}{l} (1-\alpha)^l \alpha^{N_{\rm ch}-l}, 0 \leq l \leq N_{\rm ch} \qquad (1)$$

where $N_{\rm ch}$ is the total number of licensed channels, and the average number of licensed idle channels is [18]

$$E[L] = \sum_{l=0}^{N_{\rm ch}} l p(l) \qquad (2)$$

where $p(l)$ is from (1). Let us assume that the cognitive user can sense only $Ch_{\max}$ channels randomly among the total $N_{\rm ch}$ licensed channels. Then the probability distribution of the number of sensed idle channels m among the maximum sensed licensed channels $Ch_{\max}$ by a single cognitive user is [18]

$$p(m) = \binom{Ch_{\max}}{m} (1-\alpha)^m \alpha^{Ch_{\max}-m}, 0 \leq m \leq Ch_{\max}. \qquad (3)$$

Thus, the average number of sensed idle channels by a cognitive user is

$$E[M] = \sum_{m=0}^{Ch_{\max}} m p(m) \qquad (4)$$

where $p(m)$ is from (3). Then, the probability that a channel is being sensed by a cognitive user is given by

$$\mu = \frac{\text{Number of channels each cognitive user would sense}}{\text{Total number of licensed channels}}$$

or

$$\mu = \frac{Ch_{\max}}{N_{\rm ch}}. \qquad (5)$$

Now, the probability distribution that a channel is sensed by j cognitive users among total $N_{\rm CU}$ cognitive users follows the binomial distribution as given by

$$p(j) = \binom{N_{\rm CU}}{j} \mu^j (1-\mu) N^{\rm CU} - j, 0 \leq j \leq N_{\rm CU}.$$

From (5), we can obtain the probability that a channel is not sensed by any $N_{\rm CU}$ number of cognitive users, which is given by

$$p_{\rm nosensed} = (1-\mu)^{N_{\rm CU}}. \qquad (6)$$

From (6), the probability that a channel is sensed by at least one cognitive user is

$$p_{\rm sensed} = 1 - p_{\rm nosensed}. \qquad (7)$$

The probability distribution of the number of sensed idle channels n among $E[L]$ idle licensed channels by $N_{\rm CU}$ cognitive users is determined using (2) and (7) as

$$p(n) = \binom{E[L]}{n} (p_{\rm sensed})^n (1-p_{\rm sensed})^{E[L]-n}, 0 \leq n \leq E[L]. \qquad (8)$$

From (8), the average number of sensed idle channels by N_{CU} cognitive users is calculated as

$$E[N] = \sum_{n=0}^{E[L]} np(n) \tag{9}$$

where $p(n)$ is from (8).

2) Contention Analysis: After sensing the licensed channels and sharing the results of sensing among N_{CU} cognitive users during the sensing–sharing interval, the cognitive users compete with each other to reserve the idle licensed channels during the contention interval. Each cognitive user, which has data to send to its intended receiver, randomly selects a contention slot among total number of contention slots Q in the contention interval. Now, the following two cases are considered, i.e., one in which without backoff (without contention resolving) method is applied and the other in which the backoff algorithm is applied. The case without the backoff algorithm is for the existing SMC-MAC protocol, which has been already discussed in [18].

a) Without backoff algorithm: Since the contention slot selection by each cognitive user is random, it is possible that two or more cognitive users have selected the same contention slot, which results in collision and collided cognitive users cannot reserve idle licensed channels for the data transmission during data transmission interval. However, the case in which a contention slot is selected by a single cognitive user results in the successful contention slot and the data are transmitted over the reserved idle licensed channel/channels during the transmission interval by the successful cognitive user. Since we have Q number of contention slots, the probability of selecting each contention slot is $r = 1/Q$. The number of cognitive users that select a given contention slot is denoted by random variable s, which follows the binomial distribution

$$p(s) = \binom{N_{\mathrm{CU}}}{s} r^s (1-r)^{N_{\mathrm{CU}}-s}, 0 \le s \le N_{\mathrm{CU}}. \tag{10}$$

The probability of a contention slot being successful is determined from (10) when $s = 1$, i.e., when the single cognitive user has selected a given contention slot. Therefore, the probability of success from (10) is given as

$$\begin{aligned} p_{\mathrm{success}} &= p(1) = \binom{N_{\mathrm{CU}}}{1} r^1 (1-r)^{N_{\mathrm{CU}}-1} \\ &= N_{\mathrm{CU}} r (1-r)^{N_{\mathrm{CU}}-1}. \end{aligned} \tag{11}$$

Let t be the random variable that denotes the number of successful cognitive users and the probability of cognitive t users being successful as

$$p(t) = \binom{Q}{t} (p_{\mathrm{success}})^t (1-p_{\mathrm{success}})^{Q-t}, 0 \le t \le Q. \tag{12}$$

The average number of successful cognitive users is calculated from (12) and is defined as

$$E[T] = \sum_{t=0}^{Q} tp(t). \tag{13}$$

From (12), the average number of collided cognitive users is

$$E[C] = N_{\mathrm{CU}} - \sum_{t=0}^{Q} tp(t) \tag{14}$$

where $p(t)$ is from (12).

b) With backoff algorithm: In the proposed scheme, after the first instant detecting the collision during contention interval, the contention window size will increase according to the backoff algorithm, and then, the cognitive user again selects another contention slot from the increased contention window; now, if there is collision again, we further increase the contention window size. In this case, the contention interval is made flexible, and when there are more collided cognitive users, the contention slots are increased to minimize the collision. Therefore, it is evident that with the increase in the number of cognitive users, the congestion problem arises, and to solve this problem, we have to increase the contention window size; hence, the number of contention slots in the contention interval will significantly increase. In the numerical simulation section, we have achieved the optimized number of the contention slots using the proposed MAC protocol with the backoff algorithm at which all the users become successful. Therefore, in the proposed method, there is an implementation of the backoff algorithm in the control channel's contention interval, and its algorithm is described as follows:

Algorithm:

Step 1: Variable declaration
N_CU $= Number\ of\ cognitive\ users$
CW $= No.\ of\ contention\ slots\ initially$
CW_new = CW + 2^4 *which is selected initially by cognitive users which undergoes collision for the first time during contention interval //taken by default*
Count $= number\ of\ collided\ cognitive\ users$
N $= Number\ of\ successful\ cognitive\ users$
$\mathbf{T_{tr}}$ $= transmission\ time$
$\mathbf{Ch_{idle}}$ $= average\ number\ of\ idle\ licensed\ channels$ *used by each cognitive user*
$\mathbf{T_{cycle}}$ $= cycle\ time$
R $=$ *data rate per channel*
Step 2: *Count the number of collided cognitive users in the contention interval*
FOR N_CU = *10 to 50 //taken by default*
  N_CU *cognitive users randomly select contention slots between 1 and* CW
  IF *N_CU cognitive users have selected different contention slots*
    N_CU cognitive users are successful
  ELSE
    $Count$ = *count the number of cognitive users which have selected the same contention slots*
    N = N_CU-$Count$
  END

Step 3: Solve contention among collided cognitive users with the help of backoff algorithm
$X = the\ number\ of\ cognitive\ users\ which\ have\ selected\ the\ same\ contention\ slot$
X *cognitive users selects randomly a contention slot between* CW *and* CW_new
IF X *cognitive users have selected different contention slots*
$N = N + X$
ELSE
CW_new = 2*CW_new
Follow step 3 again
END
Step 3 is followed for all N_CU *cognitive users, which have selected the same contention slot during step 1*
END

3) Data Transmission and Throughput Analysis: The successful cognitive users transmit their data in the data transmission interval on the idle channels selected during contention interval. The data transmission interval $T_{\rm tr}$ is defined by subtracting the idle time $T_{\rm idle}$, the sensing–sharing time $T_{\rm ss}$, and the contention time $T_{\rm ct}$ from the cycle time $T_{\rm cycle}$ [18]. This transmission interval is utilized for the computation of the throughput of cognitive users [18]. However, the maximum achievable throughput is the throughput for the case when all the sensed idle channels are utilized by total $N_{\rm CU}$ cognitive users. Therefore, the maximum achievable throughput is defined as the product of the average number of sensed idle channels $E[N]$, amount of time available for the data transmission per cycle interval $(T_{\rm tr}/T_{\rm cycle})$, and data rate per sensed idle channel R. Hence, the maximum throughput is given as [18]

$$Th_{\max} = \frac{E[N]T_{\rm tr}R}{T_{\rm cycle}} \tag{15}$$

where $E[N]$ is from (9). However, the throughput without the backoff algorithm $Th_{\rm wo\_bo}$ in the contention interval of the successful users is the minimum of the $Ch_{\rm idle} \times S$ and the average number of sensed idle channels in (9). Therefore, the throughput of cognitive users is given as [18]

$$Th_{\rm wo\_bo} = \frac{E\left[\min\left(Ch_{\rm idle} \times S, E[N]\right)\right] T_{\rm tr}R}{T_{\rm cycle}} \tag{16}$$

where $Ch_{\rm idle}$ is the number of idle channels that a cognitive user is allowed to use, and S is the number of successful cognitive users during the contention interval. Therefore, $(Ch_{\rm idle} \times S)$ defines the total number of idle channels in which all successful cognitive users transmit data. The throughput with backoff algorithm $Th_{\rm w\_bo}$ in the contention interval of the successful users is given as

$$Th_{w\_bo} = \frac{N * Ch_{\rm idle} * T_{\rm tr} * {\rm R}}{T_{\rm cycle}} \tag{17}$$

where N is the number of successful users after the backoff algorithm in the contention interval.

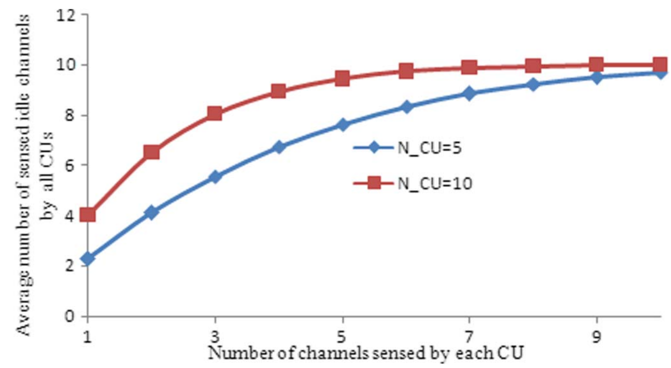

Fig. 4. Response of the average number of sensed idle channels by all cognitive users to the number of channels sensed by each cognitive user for the 5 and 10 cognitive user network.

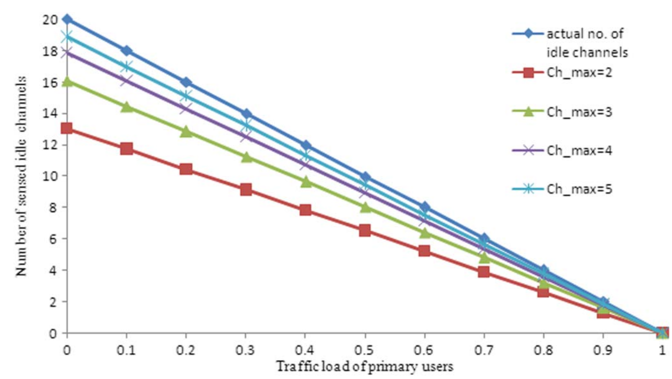

Fig. 5. Response of the number of sensed idle channels with respect to the traffic load of primary users for $N_{\rm CU} = 10$.

III. Simulation Results

The MAC protocol parameters for cognitive user network are employed from IEEE 802.11a [20]. The simulation parameters are the following: Single slot time is 9 μs and CR-RTS, CR-CTS, and CR-SIFS frame times are 24 μs, 24 μs, and 16 μs, respectively. The data rate of each channel is 54 Mb/s, $T_{\rm idle} =$ CR-SIFS $+ 2 \times$ single slot time, $T_{\rm ss} = 3 \times N_{\rm ch} \times$ single slot time, and $T_{\rm ct} = Q \times (({\rm CR\text{-}RTS}) + ({\rm CR\text{-}SIFS}) + ({\rm CR\text{-}CTS}))$. The simulation results of the sensing–sharing analysis, which is discussed in Section II-C1, have been presented in Figs. 4 and 5. The total number of licensed channels is assumed to be $N_{\rm ch} = 20$ and $Ch_{\rm idle} = 1$. In Fig. 4, the numerical results are presented using (9) for the case when the total number of cognitive users is $N_{\rm CU} = 5$, $N_{\rm CU} = 10$, and the traffic load α is assumed to be 0.5.Since a cognitive user is able to sense only the fixed number of channels given by $Ch_{\max}$, Fig. 4 shows that, as the number of channels sensed by each cognitive user increases, the number of idle channels detected by $N_{\rm CU}$ (number of cognitive users) also increases. However, more mathematical computations are required for sensing with the increase in $Ch_{\max}$, and it makes the cognitive radio terminal less energy efficient. Furthermore, Fig. 5 demonstrated the actual number of idle channels and number of idle channels sensed by $N_{\rm CU} = 10$ cognitive users for different values of $Ch_{\max}$ and its dependency over α. Fig. 5 reveals that there is a gap between the actual number of idle channels and the number of sensed idle channels when $Ch_{\max} = 2$, which is due to the small number of channels sensed by the individual cognitive

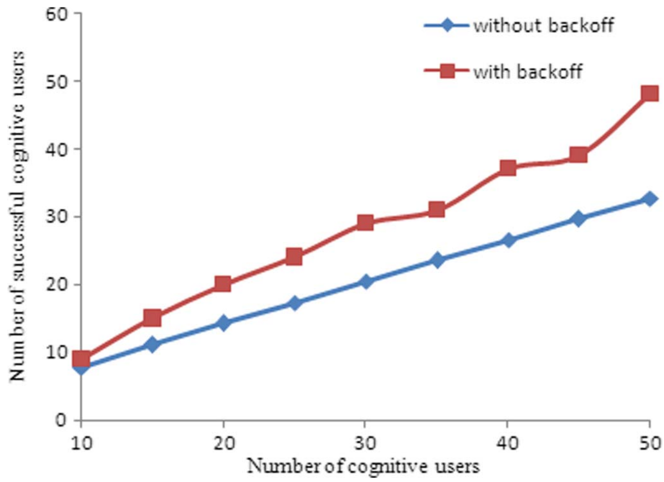

Fig. 6. Total number of successful cognitive users with and without backoff algorithm with parameters CR-RTS $= 24\ \mu$s and CR-CTS $= 24\ \mu$s.

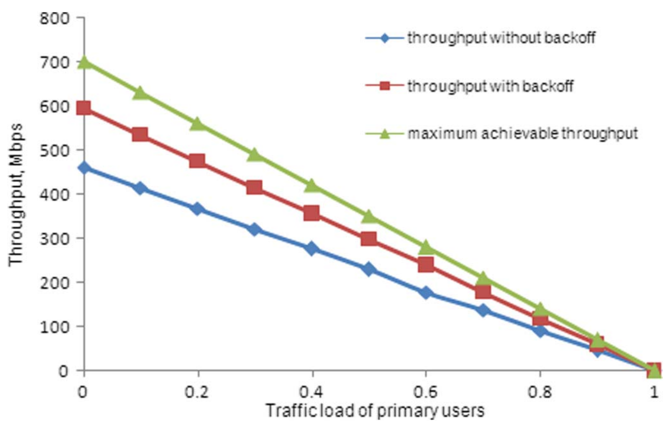

Fig. 7. Throughput comparison with varying traffic load of the licensed channels with parameters $T_{\text{cycle}} = 1$ s, $Ch_{\max} = 2$, CR-RTS $= 24\ \mu$s, and CR-CTS $= 24\ \mu$s.

user. However, it has been demonstrated in Fig. 5 that, as the cognitive user's ability to sense the licensed channels increases, i.e., as the value of parameter $Ch_{\max}$ increases, the total number of idle channels sensed by all the cognitive users approaches to the total number of available idle channels. Moreover, there are some limitations of the SMC-MAC [18], which is discussed through the numerical simulation, and the proposed scheme has avoided these limitations as demonstrated in Figs. 6 and 7. Thus, it is clear that the large number of contention slots increases the successful cognitive users but decreases the data transmission interval due to the fixed cycle time, which is one of the major limitations of SMC-MAC protocol, as discussed in [18]. In addition, in SMC-MAC, it has not been possible that the collided cognitive users in the contention interval can once again select the contention slot in that cycle time. Therefore, data transmission could not be possible in the same cycle because all the cognitive users have selected the contention slots randomly, and once collision is detected in the chosen contention slot, the collided cognitive users will have to wait for the next cycle time for the data transmission. However, in the proposed method, when the binary exponential backoff mechanism is applied to resolve the contention among collided cognitive users, more users become

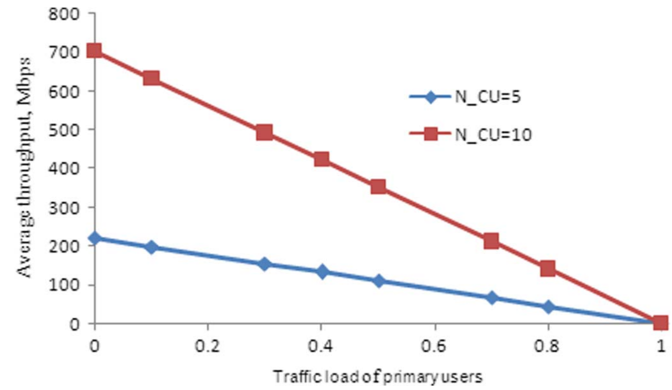

Fig. 8. Average throughput variation with the traffic load for the parameters: $Ch_{\max} = 2$, $T_{\text{cycle}} = 1$ s, $Q = 10$, CR-RTS $= 24\ \mu$s, and CR-CTS $= 24\ \mu$s.

successful, as shown in Fig. 6, which reveals the total number of successful users with and without the backoff algorithm for the same number of contention slots. The SMC-MAC protocol is without the contention resolving algorithm, as discussed in detail in [18], and it is clearly shown in Fig. 6 that the total number of successful cognitive users is significantly more in the case when the backoff algorithm is applied. Furthermore, Fig. 7 shows the comparison of several throughputs, as presented in Section II-C3 with the traffic load of the primary users for the same number of contention slots, and it is clear that the throughput is significantly more for the backoff contention algorithm case, as compared to the without backoff algorithm. It is clear in Fig. 7 that the throughput with the backoff algorithm is close to the maximum achievable throughput. Therefore, it is necessary that when the number of cognitive users is more, the contention slots required are also more. Since, in the wireless communication system, the number of transmitting cognitive users is randomly changing, having a fixed number of contention slots is not practical. However, the number of contention slots must vary according to the number of cognitive users to enhance the performance. The data transmission and throughput analysis has been numerically simulated and discussed further in Fig. 8,which shows the average throughput variation with the traffic load for cognitive users 5 and 10 with $Ch_{\max} = 2$, $T_{\text{cycle}} = 1$ s, and $Q = 10$. Therefore, all the idle channels among $N_{\text{ch}} = 20$ are not utilized for the transmission of data, and hence, the average throughput for $N_{\text{CU}} = 5$ is significantly less, as compared with that for $N_{\text{CU}} = 10$. Furthermore, in Fig. 9, we have obtained the optimized number of contention slots required in the proposed MAC protocol for which all the cognitive users become successful. For example, the optimum number of contention slots for $N_{\text{CU}} = 10$ and 20 is 30 and 60, respectively, because at this value of the contention slots, all the cognitive users are successful and hence the throughput will be maximized. However, if we further increase the contention slots from 30, the throughput will start reducing, as shown in Fig. 10. Moreover, it is clear in Fig. 9 that as the number of cognitive users in the network increases, the MAC protocol will need more contention slots to make all the users successful, as compared with the network having fewer users. Therefore, to resolve the congestion among the increased number of cognitive users, we have to increase the contention window size and hence the number of the

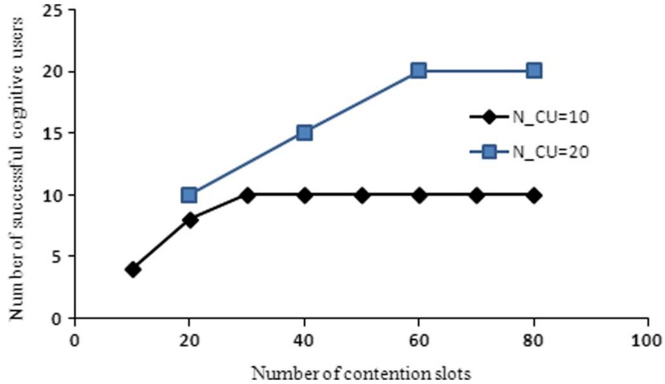

Fig. 9. Optimized number of the contention slots for $N_{\mathrm{CU}} = 10$ and $N_{\mathrm{CU}} = 20$ with parameters CR-RTS $= 24\ \mu$s and CR-CTS $= 24\ \mu$s.

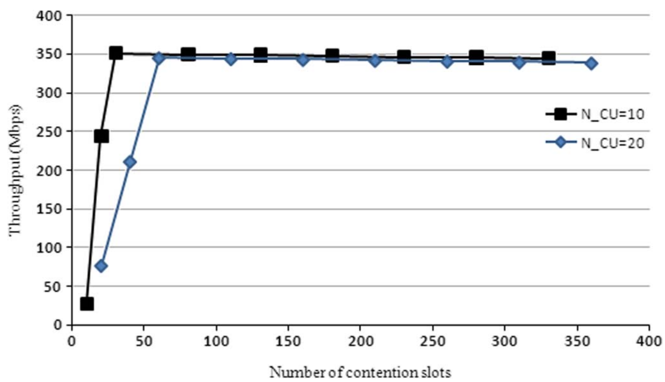

Fig. 10. Throughput variation in the proposed MAC protocol with number of contention slots for $N_{\mathrm{CU}} = 10$, $N_{\mathrm{CU}} = 20$, and $\alpha = 0.5$.

contention slots in the contention interval, which is clear in Fig. 9 where for $N_{\mathrm{CU}} = 10$, the optimized contention slots required are 30; however, for $N_{\mathrm{CU}} = 20$, this value is 60 to make all users in the network successful.

IV. Conclusion

In this paper, the SMC-MAC protocol for the distributed cognitive radio communication system with backoff algorithm has been proposed. The proposed method has significantly enhanced the performance of cognitive communication systems by increasing the number of successful cognitive users for the data transmission. Hence, the proposed method has enhanced the throughput compared with the existing SMC-MAC protocol, as reported in [18] for the distributed cognitive network, which is demonstrated by the numerical simulation results. The proposed MAC protocol has contention slots, which depends upon the number of cognitive users compare with the fixed slots in SMC-MAC.

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Shweta Pandit (S'13) received the B.Tech. (Honours) degree in 2010 from Himachal Pradesh University, Shimla, India, and the M.Tech. degree in electronics and communication engineering from Jaypee University of Information Technology, Solan, India, where she is currently working toward the Ph.D. degree.

Her areas of research interest are next-generation communication systems, cognitive radio, wireless networks, and capacity enhancement and interference reduction in wireless channels.

Ghanshyam Singh, photograph and biography not available at the time of publication.