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Proactive spectrum handoff protocol for cognitive radio *ad hoc* network and analytical evaluation

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Abstract: Spectrum handoff in cognitive radio technology has been emerged as a new method for improving performance of the cognitive radio networks. The authors propose a proactive spectrum handoff protocol based on a single rendezvous (SRV) coordination scheme without common control channel. This protocol utilises a multi-user greedy channel selection method to select the best channel based on minimum service time for the secondary users to achieve a higher aggregate throughput. The authors proposed a novel theoretical analysis to evaluate the aggregate throughput of the secondary users in the proposed protocol. It uses Markov Chain to model the distributed channel selection scheme. The simulation results show the proposed protocol increases the throughput up to 38.7% in comparison with the study by Song and Xie, for 12 secondary users in the network with transmission rates of primary and secondary users equal to 5 (pkt/s) and 500 (pkt/s), respectively.

1 Introduction

By increasing demand for the spectral resources, cognitive radio network (CRN) emerges as a way to improve the overall spectrum usage by exploiting the spectrum opportunity [1]. CRN allows the secondary users to use the channel whenever the channels are not occupied by the primary users. A successful deployment of CRN requires secondary users to guarantee minimal interference with primary users [2]. There are four important functionalities in CRNs: spectrum sensing, spectrum management, spectrum sharing, and spectrum mobility or handoff [3, 4]. This paper focuses on spectrum handoff in CRNs. Spectrum handoff happens when a primary user appears in a channel being utilised by a secondary user. This allows a secondary user to vacate its using channel and try to migrate to another channel for resuming its unfinished transmission [5, 6].

In general, there are two kinds of spectrum handoff mechanisms in the CRNs. The on demand, called reactive spectrum handoff, occurs at the time of primary user appearance on the channel. Hence, the handoff secondary user will try to migrate to another spectrum after leaving the primary user's channel. This approach does not need the channel usage history information as an advantage but it needs an extra delay of searching for idle channels and then doing hand-shaking to achieve a consensus on the new channel [7]. Proactive spectrum handoff uses channel usage history information by the licensed primary users [8] to find the best channel having larger vacant time with the aim of getting minimum service time and less collision between secondary and primary users [9–11]. However, it requires to have the channel usage history information for a long period of time as its disadvantage.

In this paper, we propose a proactive spectrum handoff protocol for multi user cognitive radio *ad hoc* networks. This protocol results in minimum delay while doing spectrum handoff and less collision than the reactive spectrum handoff. It selects the channel for performing spectrum handoff based on multi-user greedy channel selection (GCS) scheme. This scheme increases the average throughput of the secondary users because the channel selection policy causes minimum service time for packet transmission. Those secondary users who want to perform spectrum handoff or start a communication should coordinate with each other for accessing the channel. In this way, collision between the secondary users in multi user networks is avoided [1]. Furthermore, the proposed scheme enables the transmitting secondary users from the previous phase to continue their transmission without interruption in the next phase. This gives priority to the handoff users to select their channels before the new coming users to decrease service time. Using common control channels (CCC) approach faces several problems like control channel saturation, robustness to primary users' activity, CCC coverage range (scalability), and control channel security in CRNs. Therefore, various coordination schemes without CCC have been proposed in the CRNs [12, 13]. In the proposed scheme in this paper, secondary users coordinate with each other to perform proactive spectrum handoff in cognitive radio *ad hoc* networks by using the single rendezvous (SRV) scheme.

State diagram of the proposed proactive spectrum handoff protocol is used to model behaviours of the proposed scheme. For representing channel selection and cooperation between secondary users in the negotiation state, which is the control phase, a Markov Chain model is proposed [14–17]. It is used to calculate the stochastic probability for channel selection of the secondary users which could successfully communicate in the data phase. At the end, the aggregate throughput of the secondary users is calculated analytically to evaluate the performance of protocol.

In summary, this study includes the following contributions:

- Proposing a novel proactive spectrum handoff SRV coordination protocol without common control channel for a multi-user *ad hoc* CRN.
- Exploiting a multi-user GCS spectrum handoff approach in our proposed split phase coordination protocol.
- Proposing a novel Markov Chain model for our protocol and analysing its theoretical performance aggregate throughput based on it.
- Giving priority to the communicating secondary users than the other secondary users to decrease service times which is significant for the delay sensitive services.

The remainder of this paper is organised as follows. Related works are illustrated in Section 2. In Section 3, a model for proposed proactive spectrum handoff protocols are presented. Section 4 describes the proposed proactive SRV spectrum handoff protocol. In Section 5, aggregate throughput analysis of the secondary users is obtained. In Section 6, performance evaluations and simulation results of the protocol are presented.

2 Related works

A spectrum handoff mechanism can be divided into two major methods. The reactive spectrum handoff in [7] searches the target idle channel based on demand. This scheme imposes an unwanted extra delay to the network because there is a sensing and reconfiguration delay; moreover, it causes collisions between primary and secondary users during the transmission. The proactive spectrum handoff in [18] requires the secondary users to do a spectrum handoff by predicting the appearance of the primary users. Secondary users switch to a new channel before a primary user occupies the channel. The main advantage of this scheme is to decrease collisions between the secondary and primary users [18, 19].

In [8], comparison of the reactive spectrum handoff and proactive spectrum handoff has been presented. In [19], secondary users utilise a proactive spectrum handoff scheme based on the GCS method for selecting a channel. In this scheme, the channel is selected based on channel usage information and prediction of service time (time from starting the transmission of a packet until the end of it) for each channel. One major problem of this scheme is that it only considers one pair of the secondary users in the network and in a multi user network it causes inordinate collisions between the secondary users [9].

In [20], a proactive spectrum handoff protocol based on time estimation is proposed which reduces the communication disruption and improves the channel usage. This scheme is proposed for a network with only one pair of secondary users which is a simplified case and is not useful in real networks. In [21], a cumulative probability is introduced to estimate the channel adequacy for transmission or to make a spectrum handoff and it needs the past observation of the channels. The goal is to make a decision between spectrum handoff and staying in the channel. Hence, it reduces the number of unnecessary handoff and improves the secondary user's performance.

In [14], a proactive spectrum handoff protocol is proposed which uses the common hopping coordination scheme. It utilises the channel usage statistics to derive some criteria for doing spectrum handoff; the goal is to decrease the interference between the secondary and primary users and increase the secondary users' throughput. In [15], the authors consider the proposed proactive spectrum handoff criteria in [14] and introduce the common hopping coordination scheme in a multi users' CRN. Moreover, it introduces a distributed channel selection scheme which work with common hopping coordination scheme to improve the performance. The authors in [9] extended the proposed methods in [14, 15]. Moreover, they introduced the multiple rendezvous coordination case, in which more than one pair of secondary users can contend at the same time for accessing the channels.

3 Proposed spectrum handoff model

In our proposed spectrum handoff model, secondary users will do spectrum handoff by the emergence of the primary users. Since secondary users predict the emergence of the primary users by using the channel usage history information, collision between the secondary and primary users is avoided. Handoff secondary users have to compete for accessing the channels by using the proposed multi-user GCS scheme. Using this scheme by multiple users, the first k best channel based the proposed criteria will be accessed by the k competing handoff secondary users, resulting in a higher network throughput.

In this part, initially the required network assumptions are stated. Then, a channel selection scheme for selecting the best channel for performing spectrum handoff is presented. Moreover, the criteria for selecting the best channel are introduced in this part as well.

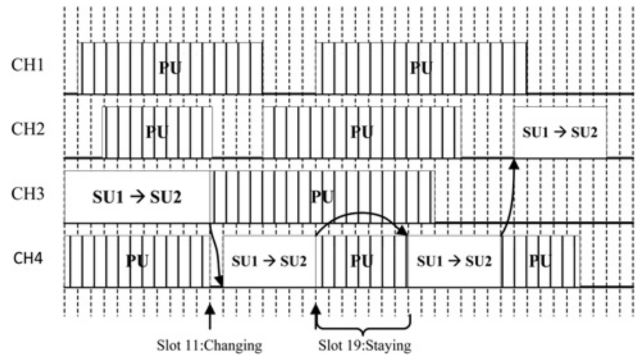

Fig. 1 *Secondary and primary user's packet transmission on different channels*

3.1 Assumption

The channel model is assumed as an ON–OFF process. The hachured rectangles in Fig. 1 show the packet transmission of the primary users as ON processes and other areas as OFF processes which show that primary users do not have any packets for transmission. The primary and secondary users are M/G/1 systems and the packet arrival rates of both secondary and primary users follow the Poisson distribution process [8, 22]. Average arrival rates of the primary and secondary users are λ_p and λ_s, respectively. To make the model tractable, it is assumed that all primary and secondary users utilise the licensed channels. It implies that all the secondary users have the same availability information of the licensed channels.

Considering that the power of the transmitted signal is higher than the received signal, the instantaneous collision detection and transmission is not possible for one radio wireless node. Therefore, in the proposed scheme it is assumed that each secondary user is provided with two radios [23, 24]. The first kind of radio is called the transmitting radio which is used to transmit data and control packets. The second kind of radio is called the scanning radio which is used to scan the channel and gather the channel usage information. Moreover, the scanning radio should sense the selected channel to certify that the selected channel is not occupied by another secondary user.

3.2 Channel selection scheme

In this section, the proposed scheme for proactive spectrum handoff is presented which is based on improved multi-user GCS. In this scheme, all secondary users predict service time on each channel based on the channel usage information. For initiating a spectrum handoff, secondary users should select the best channel based on two criteria: first, minimum service time and second, maximum vacant time which results in lower service time and higher throughput. Fig. 1 shows a sample model of an improved GCS scheme for one pair of secondary users in a CRN. The transmitter of the secondary user selects the best channel based on two proposed criteria.

In Fig. 1, the SU-1 starts the transmission to SU-2 in channel 3 in the first time slot. After 11 time slots, the PU-3 appears in channel 3 and wants to initiate a new transmission. Hence, the secondary user should decide to either change the channel and perform a spectrum handoff or stay in the current channel and resume its unfinished transmission after the primary user vacates the channel. In this sample model, the secondary user changes its channel and resumes the transmission on channel 4, because this channel has maximum vacant time and results in minimum service time. Moreover in time slot 19, a primary user appears in the channel 4 and the secondary user should decide to either stay in the current channel

IET Commun., 2015, Vol. 9, Iss. 15, pp. 1877–1884

or change its channel and performs a spectrum handoff. In this example, the secondary user decides to stay in its channel and continue the unfinished transmission after the primary user finished its transmission.

For our CRN with multi-user system, the below equation can be considered. Assume there are N secondary users and M channels in the network. For selecting the channel, secondary users compare stay time in their channels with changing time of other channels

$$ST_i = \begin{cases} S_k & \text{if} \quad S_k < C_j + t_h \\ C_j & \text{if} \quad S_k \geq C_j + t_h \end{cases} \quad (1)$$
$$\text{for} \quad j = 1, \ldots, M \& j \neq k,$$

where S_k denotes the staying time in the current channel of the secondary user (k is the current number of channel for ith secondary user), and C_j is the changing time of the channel which the secondary user can select (j is the number of changing channel for ith secondary user). Let t_h denotes the handoff delay for changing its channel to another channel. ST_i is the minimum time of the selected channel by ith secondary user to continue the transmission. If the staying time is less than the changing time, the secondary user selects current channel and stays in its channel. If the changing time plus the handoff delay is fewer than the staying time, the secondary user decides to change its channel and use the second criterion for the best channel.

As the second criteria, the secondary user should select the channel with maximum vacant time among the whole channels which have zero changing time

$$\underset{m \neq k}{VT_m} = \text{sort}(T_m) \quad \text{for} \quad m = 1, \ldots, M, \quad (2)$$

where T_m is the vacant time of the channels which have zero changing time. It is the time duration from the instant that secondary users perform a spectrum handoff until primary users occupy the channel. In (2), *sort* arranges the vacant time of the secondary users in a decreasing order. VT_m is the vacant time of all channels which is arranged decreasingly. By considering these two criteria, secondary users can select the best channels to continue transmission.

4 SRV spectrum handoff protocol

Split phase protocol in CRN is explained in this section as a SRV coordination scheme. Moreover, proactive spectrum handoff scheme in SRV coordination protocol is illustrated when a primary user wants to occupy the secondary users' channel.

4.1 Split phase coordination protocol

Split phase coordination protocol is used as a SRV coordination scheme [25, 26]. In this approach, time is divided into an alternating sequence of data and control slots. Both of the control and data slots together are called a phase. During a control slot, all the secondary users which want to start transmission or perform spectrum handoff tune to the control channel and try to make agreement to access the channels in the following data exchange slots [26, 27]. In the data slots, secondary users tune to the agreed channel and start data transmission. Fig. 2 shows the operation of the split phase coordination scheme in the CRN.

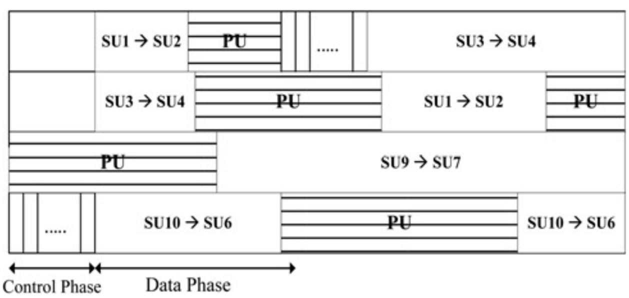

Fig. 2 *Split Phase coordination protocol as a SRV proactive spectrum Handoff protocol*

According to the considered scenario, there are M orthogonal channels in the network and N secondary users who content to access the channel. For accessing a channel, a secondary user should contend with other secondary users in the control phase. For coordinating between the secondary users, the control phase (one slot) is segmented into $2N + 1$ mini slots. First mini slot is to sense the channel and make sure that the rendezvous channel is not occupied by the secondary users. If the channel is free, the secondary user who want to start a new transmission or perform a spectrum handoff, it initially sends a ready-to-send (RTS) packet to the intended receiver in the control phase. If the receiver agreed with the selected channel by the transmitter, replies with clear-to-send (CTS) packet. Then, they hop to the selected channel and start their transmission at the beginning of the data phase. If the secondary users cannot make an agreement for selecting the channel, they should wait until the next control phase. On the other side, if the rendezvous channel is occupied by another secondary user, the users which want to coordinate should go to the next best channel for rendezvous at the same time slot.

In Split Phase coordination protocol, the secondary users need to be synchronised. This method needs time synchronisation between all of the secondary users. Time synchronisation in this protocol can be looser because in this scheme secondary users hop fewer than the other schemes such as common hopping and MMAC. Time synchronisation scheme which is used in this paper is similar to the scheme presented in [28].

4.2 SRV proactive spectrum handoff protocol description

In SRV coordination scheme, when a secondary user wants to start transmission or to carry out a spectrum handoff, it should predict and select the channel based on two proposed criteria. The secondary users should tune to the best channel in each control phase as a rendezvous channel for coordination. Rendezvous channel, which is the best channel, has the minimum delay and maximum vacant time. In the control phase, secondary users which do not want to carry out a spectrum handoff can continue their transmissions. Before sending any RTS/CTS packets at the start of control phase, each competing secondary user should scan the rendezvous channel, because some of the channels are occupied by other secondary users which do not want to perform any spectrum handoff. If the rendezvous channel is occupied by another secondary user, the users which want to coordinate should go to the next best channel for rendezvous at the same time slot. When the channel is not occupied by other secondary users, the considered secondary users can send their RTS/CTS packets.

The secondary users, which want to start packet transmission or perform spectrum handoff, should tune to the rendezvous channel and send a RTS packet on their own corresponding mini slot of the control phase. The RTS packet contains the number of selected channel by transmitter secondary user. Upon receiving the RTS packet, receiver secondary user replies with a CTS packet at the same mini slot of control phase if agrees with the selected channel. If the transmitter secondary user receives the CTS packet, two secondary users tune to the selected channel and will start data transmission in the data phase. If there is no channel that the secondary users can select for transmission, they should wait until the next control phase to select a free channel.

The secondary users that need to perform spectrum handoff or initiate new transmission at the same control phase should use the distributed channel selection method; because the cognitive radio *ad hoc* network has a distributed characteristic. Since collision among secondary users result in the data transmission failure and hence cause a long spectrum handoff delay, the channel selection algorithm should avoid collision among secondary users [24].

In the distributed channel selection, the secondary users which want to carry out spectrum handoff have priority for channel selection. In delay sensitive applications, spectrum handoff has a deteriorating effect because the transmission of the secondary users should not be stopped and delayed. Therefore, control phase is divided into two parts. In the first part, the secondary users which have carried out a spectrum handoff can send RTS and receive CTS in their corresponding mini slot. In the second part, the secondary users that want to initiate packet transmission can send RTS/CTS for accessing the channel.

Each secondary user which wants to carry out a spectrum handoff or initiating a new transmission should generate a pseudo-random sequence (PRS) for channel selection and follow it to choose the best channel. In each control phase, a pseudo-random selecting sequence is generated in all secondary users should be followed by them. The selecting sequences are also different in various control phases to gain fairness. The secondary users start channel selection based on the pseudo-random channel selecting sequence. The first secondary user in each mini slot selects the best channel. If the first secondary user selects a channel, the other secondary users will remove the selected channel from their lists.

The secondary users should exchange the sensed channel availability information in SRV scheme. Therefore, when a secondary user wants to content to carry out a spectrum handoff, it first broadcasts its own sensed channel availability information to other neighbouring secondary users on its corresponding mini slot in the control phase and then sends RTS/CTS. In this way, collision between secondary users which want to broadcast the sensed channel availability information is avoided.

5 Analysing the aggregate throughput

The secondary users are categorised in four kinds of defined states in the proposed protocol, shown in Fig. 3. First kind is Idle state, in which secondary users do not have any packets to send. Moreover, if a secondary user produces data to send, it will become a ready Idle secondary user who wants to compete in the next control phase. The secondary users which are Communicating currently belong to the second state. They will continue their communication until they finish data transmission or a primary user wants to occupy the channel. The secondary users which want to carry out handoff belong to the third kind of state, Handoff, and will stay in it until the next control phase. They come to the negotiation state in the next coming control phase to negotiate and compete with other secondary users. The fourth kind is the Negotiating state in which secondary users compete with other secondary users [14, 16].

As shown in Fig. 3, after competing at the control phase, if a secondary user selects a channel to communicate, it will go to the communicating state and start to sending data to its intended receiver when there is no other secondary user on the selected channel. In other words, before sending data, secondary users should sense the channel at the start of the data phase to see whether there is another secondary user on that channel from the previous phase or not. When there is a secondary user on the selected channel, it should go to handoff or idle state based on its previous state. Since this sensing time before sending data is very small comparing to the length of a data phase, it can be ignored in the theoretical analysis. At the end of a data phase, a user will be in one of the Idle, Communicating, or Handoff states.

For analysing aggregate throughput of a network utilising our proposed protocol, expected number of secondary users at the communicating state should be calculated. The calculation is divided into two parts; in the first part, aggregate throughput is calculated by multiplying expected number of secondary users who continue their transmission from the previous phase by the channel transmission rate. In the second part, aggregate throughput is computed by multiplying the expected number of secondary users which start their transmission from the Idle state or resume transmission from the Handoff state by the channel transmission rate. The total aggregate throughput is the summation of these two calculated throughput.

All the key parameters for protocol modelling are summarised in Table 1. The number of secondary users who are ready for transmission or reception, all the secondary users in the network except than those in a communicating state, can be calculated as

$$N_r = N - 2(k - v) + h. \quad (3)$$

Table 1 Parameters for the analysing the protocol

Parameters	Description
M	total number of channels
N	number of secondary users in the network
N_r	number of secondary users which are ready for transmission
λ_s	probability of packet generation in idle secondary users
γ	probability of channel utilisation by primary users
μ	probability of finishing data exchange and releasing the channel
k	number of secondary users pair which send data packet in previous data slots
v	number of secondary users pair which finished the data packet transmission in previous data slots
h	number of secondary users pair which their channels occupied by primary users in previous data slots and are ready for resuming the packet transmission in present data phase
w	number of secondary users which generated data packets
z	number of secondary users which can find their intended secondary users receiver
m	number of secondary users pair which send data packet in the present data slots
u	number of secondary users which negotiate successfully and start transmission in present data slots
T_p	length of a phase

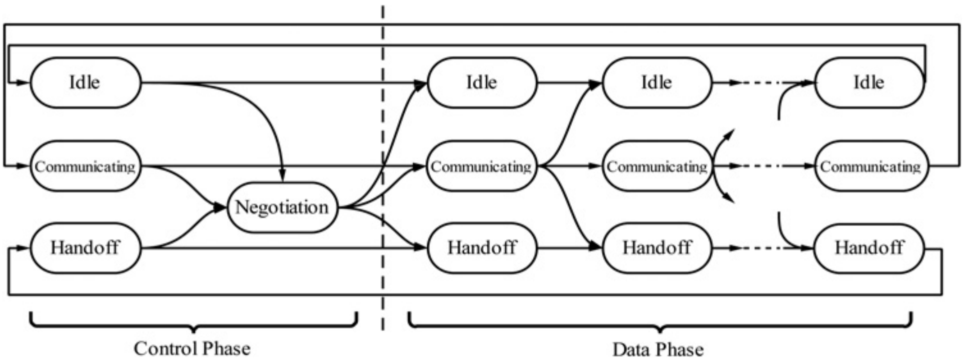

Fig. 3 *Diagram of secondary users' states in a phase slot*

IET Commun., 2015, Vol. 9, Iss. 15, pp. 1877–1884

N_r is used in computing the probability of secondary users who generate packets and probability of finding the intended receiver secondary users in a transmission. Since the geometrical distribution is memory less, the probability that each communicating pair in the previous phase finishes the packet transmission is as below

$$P_{pv} = \sum_{i=1}^{T_p} \mu(1-\mu)^{i-1}. \tag{4}$$

For computing the probability of continuing the transmission by the secondary users from the previous phase, the probability of either finishing transmission or going to handoff state is required to be calculated. In attention to the k number of secondary users which transmit at the previous data phase, v numbers of communicating pairs which finish the transmission in the previous data phase follow the binomial distribution

$$P(v|k) = \binom{k}{v} P_{pv}^{v}\left(1-P_{pv}\right)^{k-v}. \tag{5}$$

Furthermore, h number of secondary users which are stopped their transmission by primary users from sending packet in the previous phase is a conditional probability as below

$$P(h|k,v) = \binom{k-v}{h} P_{ph}^{h}\left(1-P_{ph}\right)^{k-v-h}. \tag{6}$$

Where the probability of primary users' emergence in a channel is a geometric distribution. This event can happen at each slot during a phase which requires to sum the probabilities as below

$$P_{ph} = \sum_{i=1}^{T_p} \gamma(1-\gamma)^{i-1}. \tag{7}$$

Now, it is ready to calculate the probability of existing k, v, and h number of users in the previous phase by using (4)–(7) equations as below

$$P(k,v,h) = P(h|k,v)P(v|k)\pi_k, \tag{8}$$

where π_k in (8) is the steady state vector of transition probability matrix depending on the value of k which can be calculated by the presented Markov Chain model in Fig. 4. Calculating those probabilities, the aggregate throughput of the expected number of the communicating secondary users which have not finished their transmission or not being interrupted by a primary user in the previous phase can be computed as

$$\phi_s = R_d \times \sum_{k=0}^{M}\sum_{v=0}^{k}\sum_{h=0}^{k-v} P(k,v,h)(k-v-h), \tag{9}$$

where the R_d is the channel bit rate. In the following, the aggregate throughput of the secondary users which start their transmission from Idle state or resume transmission from Handoff state in the current phase is going to be analysed.

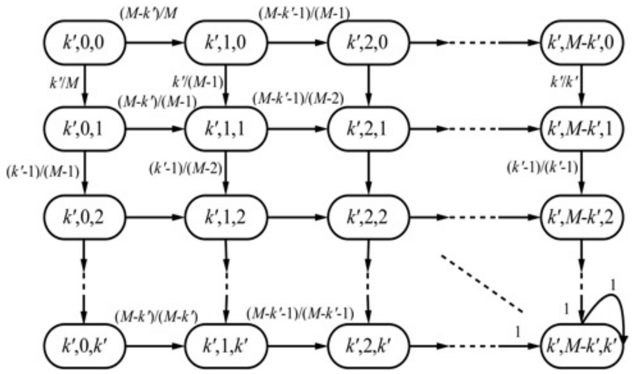

Fig. 4 *Markov Chain model for secondary user's negotiation state*

The number of w secondary users which generate packet follow the binominal distribution which depends on k, v, and h; therefore

$$P(w|k,v,h) = \binom{N_r}{w} \lambda_s^{w}\left(1-\lambda_s\right)^{N_r-w}, \tag{10}$$

which $0 \le w \le N_r$.

All the other Handoff or Idle secondary users in the network are a possible receiver for any transmitter. Hence, the probability that a given transmitter finds its intended receiver among all of the secondary users can be computed as

$$P_{sel} = \frac{N_r - 1}{N-1}. \tag{11}$$

Given k, v, w, and h, the probability that z number of handoff or new starting secondary users find their intended receiver successfully at the present control phase is denoted as

$$P(z|k,v,w,h) = \binom{c}{z} P_{sel}^{z}\left(1-P_{sel}\right)^{c-z}, \tag{12}$$

which $c = \min(M, w+h)$ and $0 \le z \le c$.

After selecting a channel and transmitting RTS/CTS packets, at the beginning of the data phase, secondary users try to send their data packets if there is no secondary user from the previous phase at the selected channel; therefore, the probability is $P(m|k,v,w,h,z)$.

The Markov Chain transition diagram for secondary users' negotiation state is as Fig. 4.

This Markov Chain is a three-dimensional process (k', i, j) which is a discrete-time Markov Chain. In this Markov Chain, k' is the number of secondary users from the previous phase that continue their data transmission in the current phase and hence $k' = k - v - h$. Since the secondary users do not have any information about the presence of other secondary users in the channels, they select the channels randomly using their PRS for the competition in the negotiation state. i is the number of secondary users which select unoccupied channels by the secondary users. j is the number of secondary users which select occupied channels by the secondary users. Therefore, one-step state transition probability can be computed as in (13). Now, two-dimensional transition probability matrix $\{P(x, y = i, j)\}_{0 \le x,y,i,j \le M}$ can be computed. For conversion of two-dimensional transition matrix to one-dimensional transition probability matrix denoted by $Q = \{q_{m,n}\}_{(M-k'+1)(k'+1)\times(M-k'+1)(k'+1)}$,

$$\begin{cases} P(i+1,j|i,j) = \dfrac{M-k'-i}{M-i-j} & 0 \le i \le M-k'-1,\ 0 \le j \le k' \\ P(i,j+1|i,j) = \dfrac{k'-j}{M-i-j} & 0 \le i \le M-k',\quad 0 \le j \le k'-1 \\ P(x,y|i,j) = 0 & |x-i| \ge 2 \quad \text{or} \quad |y-j| \ge 2 \quad \text{or} \quad x = i \quad \text{or} \quad y = j \\ P(i,j|i,j) = 1 & i = M-k',\quad j = k' \end{cases}. \tag{13}$$

the below equation could be used

$$q_{m,n} = p(x, y|i, j), \tag{14}$$

which m and n can be considered as

$$\begin{cases} m = (k' + 1)i + j \\ n = (k' + 1)x + y \end{cases}. \tag{15}$$

Thus, the conditional probability of the number of newly secondary users which select the unoccupied channel at the current phase can be obtained by

$$P(u|k, v, w, h, z) = \sum_{r=(k'+1)u}^{(k'+1)u+k'} Q^z|_{(0,r)}. \tag{16}$$

Since $u = m - k'$, the below equation can be considered as

$$P(m|k, v, w, h, z) = P(u|k, v, w, h, z). \tag{17}$$

By using the (5), (6), (10), (12) and (17), the conditional probability denoted by $P(m|k)$ of the m pairs of secondary users which communicate in the present phase given k can be written as

$$P(m|k) = \sum_{v=0}^{k}\sum_{h=0}^{k-v}\sum_{w=0}^{N_r}\sum_{z=0}^{c} P(m|k, v, w, h, z) \times P(z|k, v, w, h) P(w|k, v, h)P(h|k, v)P(v|k). \tag{18}$$

For calculating the aggregate throughput of the newly negotiated secondary users which want to start or resume data transmission, the expected number of them is required; hence, below equation is computed

$$\phi_n = R_d \times \sum_{k=0}^{M}\sum_{m=0}^{M}\sum_{v=0}^{k}\sum_{h=0}^{k-v} P(k, v, h, m)(m - (k - v - h)). \tag{19}$$

The inner used probability can be written as

$$\begin{aligned} P(k, v, h, m) &= P(h|k, v, m)P(v|k, m)P(m|k)P(k) \\ &= P(h|k, v)P(v|k)P(m|k)\pi_k, \end{aligned} \tag{20}$$

where π_k in (20) is the steady state vector of the transition probability matrix depending on the value of k which can be calculated by the presented Markov Chain model in Fig. 4. Since newly negotiated secondary users just transmit in the data phase, the aggregate throughput (ϕ_n) is normalised by $T_p - 1/T_p$. Total aggregate throughput of the continued secondary users from the previous phase and the newly started secondary users in the present phase can be calculated as

$$\phi_{\text{total}} = \phi_s + \left(\frac{T_p - 1}{T_p}\right)\phi_n. \tag{21}$$

6 Proactive spectrum handoff performance evaluation and simulation results

In this part, to evaluate performance and effectiveness of the proposed proactive spectrum handoff model, average aggregate throughput of the secondary users based on different parameters is computed. Moreover, some simulations are presented to demonstrate performance of the proposed protocol compared with the other existing proactive spectrum handoff protocols.

Table 2 Theoretical analysis parameters

Parameters	Values
the channel bit rate	$R_d = 1$ Mbps
the length of the time slot	$T_s = 2$ ms
number of the channels	$M = 6$
the number of secondary users	$N = 20$

To evaluate the average aggregate throughput of the protocol the required parameters in Table 2 is considered.

For calculating aggregate throughput of the secondary users (21) is utilised and the required parameters are given in Table 2. In Fig. 5, aggregate throughput of the secondary users is shown under packet generation rate (λ_s) with different channel utilisation of the primary users (γ). Moreover, the probability of finishing data exchange in this simulation is $\mu = 0.3$ and length of a phase is $T_p = 11$ (slots). It is shown in Fig. 5 that by increasing λ_s, aggregate throughput of the secondary users increases and it finally reaches maximum available network throughput. By increasing γ, expected number of unused channels by the primary users decreases which causes smaller throughput by the secondary users. When the $\lambda_s = 0$, the aggregate throughput of the secondary users is equal to zero because no packet is generated. On the other

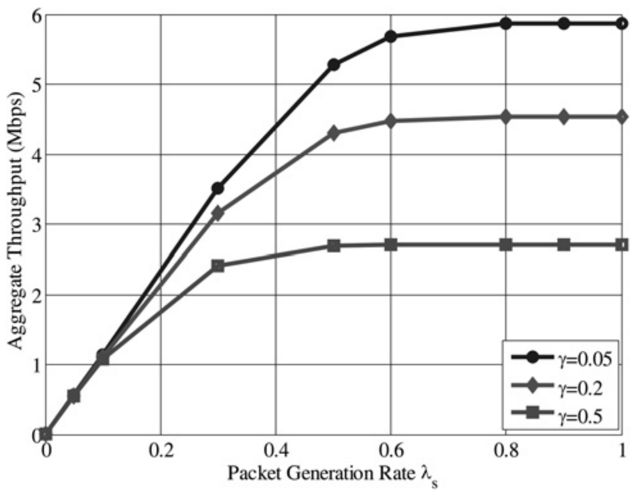

Fig. 5 *Aggregate throughput of the secondary users under packet generation rate of the secondary users*

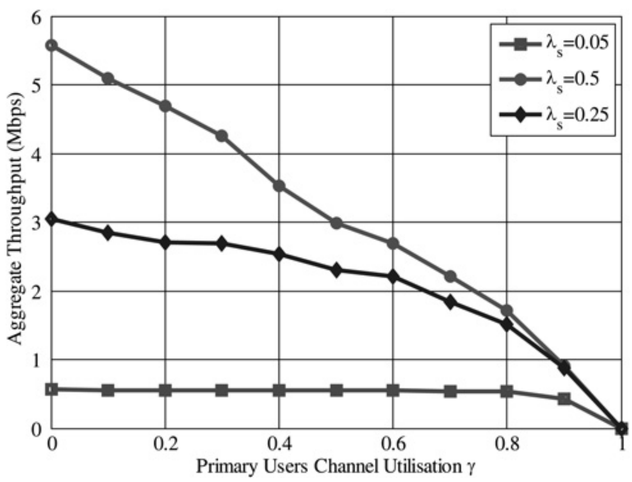

Fig. 6 *Aggregate throughput of the secondary users against channel utilisation of primary users*

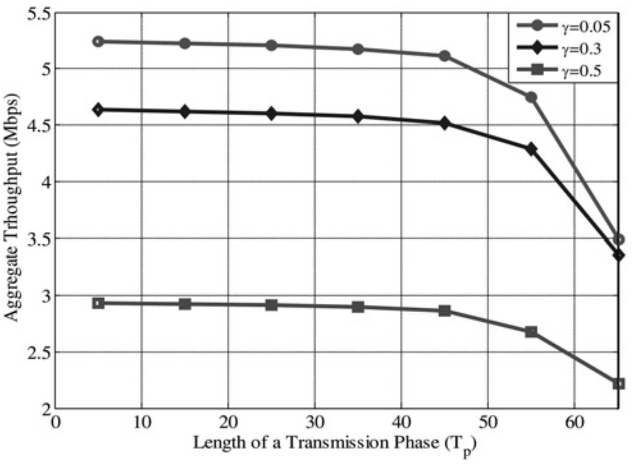

Fig. 7 *Aggregate throughput of the secondary users for different length of a phase*

side when $\lambda_s = 1$, all of the secondary users are generating packets, which increases aggregate throughput.

In Fig. 6, the average aggregate throughput of the secondary users is shown under different channel utilisation of the primary users. Probability of finishing data exchange is $\mu = 0.3$. By increasing channel utilisation of the primary users, aggregate throughput of the secondary users decreases; because it leads to fewer unoccupied channels which can be utilised by the secondary users. By increasing the probability of packet generation by the secondary users, λ_s, they produce more packets for transmission and hence compete more for transmitting. As a result, secondary users can utilise more of the unused channels in the network which increase aggregate throughput.

In Fig. 7, the impact of a phase length on aggregate throughput is presented. In this simulation, finishing data exchange probability and packet generation rates are $\mu = 0.3$ and $\lambda_s = 0.5$, respectively. By increasing T_p, aggregate throughput decreases because cooperation between the secondary users for accessing the channel decreases. In fact, as T_p increases, the secondary users which want to perform spectrum handoff or start a new transmission should wait for a longer period to the next control phase. Therefore, the secondary users cannot access the channels and the capacities of the channels are remained unused. Whatever the length of a phase increases, the aggregate throughput decreases. For different channel utilisation of the primary users, γ, it results in having different unused channels in the network and it causes different aggregate throughputs for the secondary users; where in all cases they follow the same behaviour of the aggregate throughput by increasing data phase length.

The simulation parameters of the proposed protocol are presented in Table 3.

Fig. 8*a* shows the comparison between throughput of the proposed protocol and those of the random channel selection and probability based spectrum handoff [9] protocols. The number of channels and secondary users are 6 and 12, respectively. This figure illustrates the proposed protocol outperforms both other protocols under different primary users traffic load; the reason is that in both other protocols there is a possibility of collision between the

Table 3 Simulation parameters

Parameters	Values
the channel bit rate	$R_d = 1$ Mbps
the length of the time slot	$T_s = 2$ ms
number of the channels	$M = 6$
the number of secondary users	$N = 12$
data packet length of primary user	10^5 (bits)
data packet length of secondary user	6×10^4 (bits)
packet generation rate secondary user	500 (pkt/s)

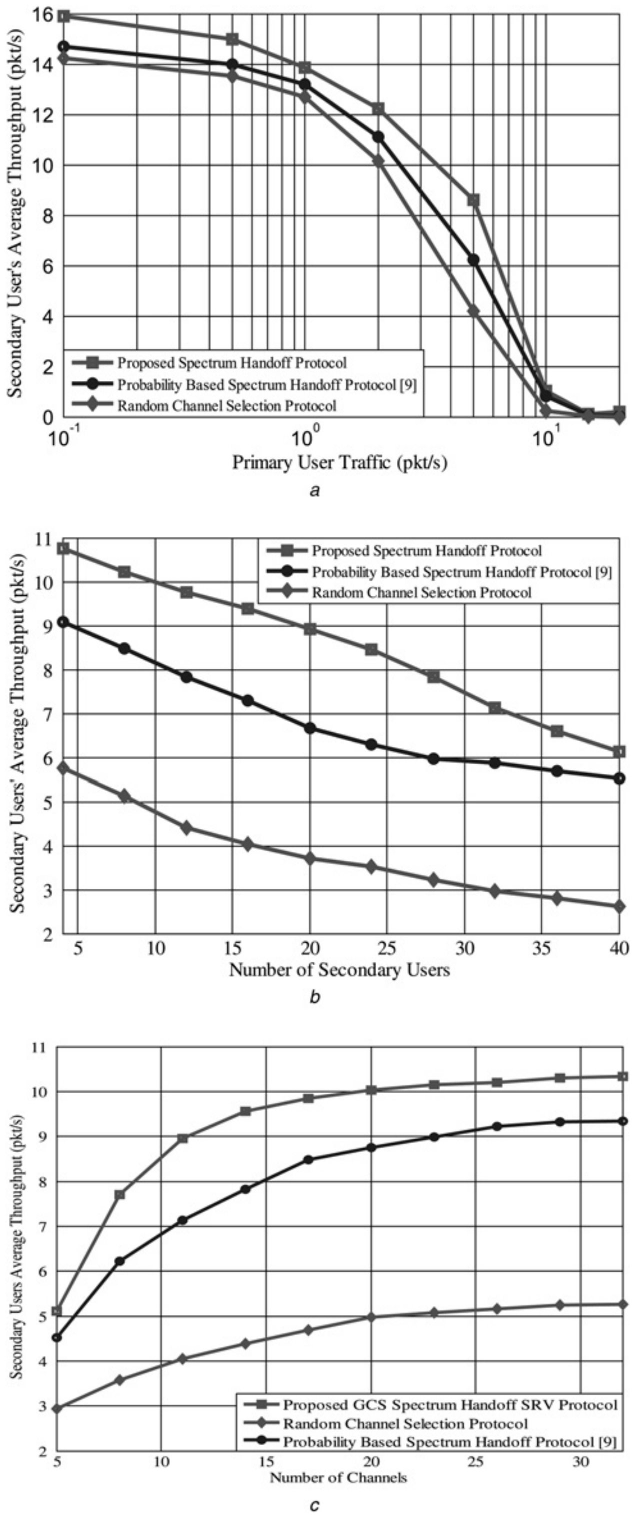

Fig. 8 *Simulation results of the proposed protocol in comparison with other protocols*

a Average throughput of the secondary users under different traffic load of the primary users
b Average throughput of the secondary users via different number of secondary users
c Average throughput of the secondary users via different number of channels

secondary and primary users. In random channel selection scheme, secondary users select their channels randomly and probabilistically in probability based spectrum handoff protocol which can cause a collision between secondary and primary users. With primary users' transmission rate of 5(pkt/s), the proposed protocol shows 38.7% and 91.1% improvement in comparison with probability based spectrum handoff [9] and random channel selection scheme, respectively.

In Fig. 8*b*, throughput of the proposed protocol is compared with those of the random channel selection and probability based spectrum handoff protocols. In this figure, the number of the channels is set to 20. By increasing the number of the secondary users, the average throughput of each secondary user will decline because of fair share of the channel usage by the secondary users. The proposed protocol has maximum improvement in throughput up to 34.4% compared with the probability based spectrum handoff [9], when there are 20 secondary users in the network. Moreover, proposed protocol has maximum increment of 143.2% compare with the random channel selection scheme for 20 secondary users in the network.

Fig. 8*c* shows the average throughput of the secondary users under different number of channels in the network. It's assumed that there are 10 secondary users in the network, the packet transmission rate of the secondary and primary users are 500 (pkt/s) and 5 (pkt/s), respectively. By increasing the number of the channels, the average throughput of the secondary users increases because of increasing the expected number of the vacant channels. After a certain point, the average throughput leads to its saturation point because increasing the number of the channels does not provide more opportunity for the secondary users to access the channel. In a larger scale with 35 channels in a network, our proposed method shows performance improvement of 11% and 96% compared with the probability based spectrum handoff and random channel selection methods, respectively.

7 Conclusion

This paper proposes a proactive spectrum handoff SRV protocol based on a multi-user GCS scheme. This protocol uses a split phase channel coordination scheme along with a distributed channel selection algorithm to perform channel selection. By using the SRV coordination scheme, all secondary users go to the rendezvous channel for negotiation; therefore, there is no need to use a CCC. This protocol reduces the collision not only between the secondary and primary users, but also between secondary users themselves. In addition, it gives priority to the handoff secondary users than the new entering secondary users to achieve a better service time. A theoretical analysis for calculating aggregate throughput to evaluate protocol performance of the secondary users based on a Markov Chain model is proposed.

The results from our simulations indicate that the proposed protocol for 12 secondary users in the network increases the throughput up to 38.7% compared with [9] while the transmission rates of primary and secondary users are equal to 5(pkt/s) and 500 (pkt/s); respectively. It is worth mentioning that this improvement is achieved while the network is highly congested by the primary users. In addition, considering the effect of changing the number of secondary users in the network showed 34.4% improvement of throughput for 20 secondary users in the network in comparison with [9].

Back-up channel reservation of the secondary users can be considered as a future work. Moreover, a new multiple rendezvous proactive spectrum handoff protocol can be considered with computing the theoretical analysis.

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