Joint Integrated Spectrum Handoff Management and routing in CR-MANETs: an analytical modeling

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Abstract. The focus of this paper is on the modeling of joint Integrated Spectrum Handoff MANagement (ISHMAN) and routing in cognitive radio mobile ad hoc networks (CR-MANETs). To model the ISHMAN, we must consider three key factors: (1) channel availability and spectrum usage behaviors of the primary users (PUs); (2) the movements and the motility of the secondary users (SUs); and (3) channel quality degradation. In this paper, we propose a new model for spectrum handoff in CR-MANETs considering the above mentioned factors characterizing the united ISHMAN and routing in these networks.

Keywords*:* Cognitive Radio, Spectrum Mobility, Spectrum handoff, Handoff Management

1 Introduction

In CR networks, the availability of the spectrum bands is arbitrary because of the random appearance of PUs as well as unpredictable SUs' mobility. When the PU reclaims its licensed band, which is preoccupied by the SU, the ongoing data transmission of CR user is transferred to another free spectrum band. The transferring of the SUs' operation frequency to another unused spectrum band is refereed to spectrum handoff. Therefore, the Spectrum handoff occurs when the conditions of the current channel cannot meet QoS or when a PU appears in the preoccupied licensed band. There is also a key relationship between spectrum handoff and routing In CR-MANETs. There must be a strong interaction between spectrum handoff and routing protocol in the CR-MANETs in order to avoid link failure. The established route at the network layer must not lead to any undesirable effect on PU's activities.

In this paper, we analytically model the joint ISHMAN and routing in the CR-MANETs. We also use the Markov chains to illustrate the effect of ISHMAN on the probability of spectrum handoff blocking. To the best of our knowledge, an analytical model for ISHMAN has rarely been seen in the literature.

The rest of this paper is as follows. In section 2, we describe the related works for spectrum handoff management. In section 3, we propose a unified modeling and characterization of channel availability in CR-MANETs. In section 4, we propose an analytical model for spectrum mobility and spectrum handoff in CR-MANETs. Section 5 shows the analytical model of the integrated spectrum handoff management. In section 6, the results and discussion are elaborated. Finally, Section 7 concludes the paper and presents the future work.

2 Related Works

Mobility function is a critical function in CR networks, which depends on the various parameters of the network like channel capacity, connectivity, and coverage [1]. Spectrum handoff management is particularly challenging in CR networks because of the randomness PU activity. It is more challenging in ad hoc networks due to the lack of a central body for managing and controlling the spectrum handoff procedure.

There have been a few works related to spectrum handoff management in CR-MANETs. In [2], a spectrum handoff decision making system is proposed, which uses two fuzzy logic controllers. Each SU calculates the distances between itself and all of the PUs which are active in its neighbouring using the first fuzzy logic controller. The second controller decides whether the SU has to do spectrum handoff or not. There exist some cases in which the SU can avoid doing spectrum handoff by a fair modification of its transmission power. In [3], a handoff management strategy is proposed. This scheme determines the optimal spectrum band based on a multi criteria decision making strategy, which considers the estimated transmission time, the PU presence probability, and spectrum availability time. The authors use a cooperative scheme for spectrum sensing in order to determine the spectrum availability. They also use a geo-location strategy to consider spectrum handoff in the space domain. The simulation results indicate that the proposed spectrum handoff outperforms conventional methods in terms of spectrum handoff delay and transmission efficiency. The authors of [4-5] proposed a proactive spectrum handoff scheme which is based on the statistics of channel utilization. The network coordination issue is solved without using common control channel. The collision among SUs is also deleted using a distributed channel allocation scheme. In [6], the authors have proposed integrated handoff management in CR-MANETs for the first time. They have mentioned the factors and types of mobility, which necessitate integrated mobility and handoff management in CR-MANETs. In this paper, the concept of proposed integrated handoff management in CR-MANET along with a conceptual framework is proposed. The necessary connections and related handoff algorithm are also illustrated in this paper. The authors of [7] have characterized and formulated the availability of spectrum bands in CR-MANETs. They explained and integrated the effects of various events on the spectrum holes availability in CR-MANETs using an analytical model. This integration is necessary to achieve integrated mobility and handoff management.

3 Channel availability in CR-MANETs

In [6], the authors have considered an established route in CR-MANET from a source node S, to destination node D. They introduced two different scenarios, which lead to the handoff initiation in this route. Considering these two events, which are node mobility and spectrum mobility, the authors have introduced a conceptual model for integrated mobility and handoff management in CR-MANETs. They have also explained the model requirements, design consideration, and the algorithm for proposed handoff management.

The authors of [7] have considered the effect of spectrum heterogeneity on the probability of channel availability in CR-MANETs rather than the SUs' mobility and spectrum mobility. In a heterogeneous network, each channel experiences different levels of PU activities, and different transmission range. The authors have supposed that there is the total number of C channels in a heterogeneous network, which are classified into L types according to their different transmission ranges. Different channels occupy different spectrum bands. The number of available channels of each type at each node is c_l in which $l = \{1, 2, \ldots, L\}$. It means that $c = c_1 + c_2 + \ldots + c_L$. The transmission range of channels of type l is R_l. In the initial condition when the nodes are considered fix, different channels will have different transmission range. Channel with lower frequency range needs lower transmission power. Thus, in a heterogeneous network with different channel transmission ranges, the distance between SUs must be considered in the probability of channel availability. Considering this channel classification; channel quality degradation was modeled. Fig. 1 shows this spectrum pool-based heterogeneous CR-MANET scheme. Table 1 shows the notations used in this paper. A pair of SUs transmitter-receiver, who transmit and receive respectively, can use a channel of type T_l for communication when their distance is less than R_l. When the SUs are moving, and their distance exceeds R_l, the communicating nodes must change and choose another channel. In this case, the required channel must have a transmission range longer than R_l (Fig. 2). Based on [7], the $P_{car,c}$, which is defined as the probability that there is at least one common channel among all hops in a route, considering PU's activity, SU's mobility, and channel quality degradation is defined as in (1).

$$P_{car,c} = \left[\sum_{i=1}^{L} \frac{\exp(-\lambda \pi R_{i-1}^{2}/2) - \exp(-\lambda \pi R_{i}^{2}/2)}{1 - e^{-\frac{N}{2}}} \left(1 - \prod_{k=1}^{c - \sum_{j=0}^{i-1} c_j} \left(1 - \left(\frac{\alpha_k}{\alpha_k + \beta_k}\right)^{2}\right)\right) \right]^{n-1} \tag{1}$$

In (1), the PU's activity is considered as alternating renewal two state birth-death processes with a death rate α and birth rate β.

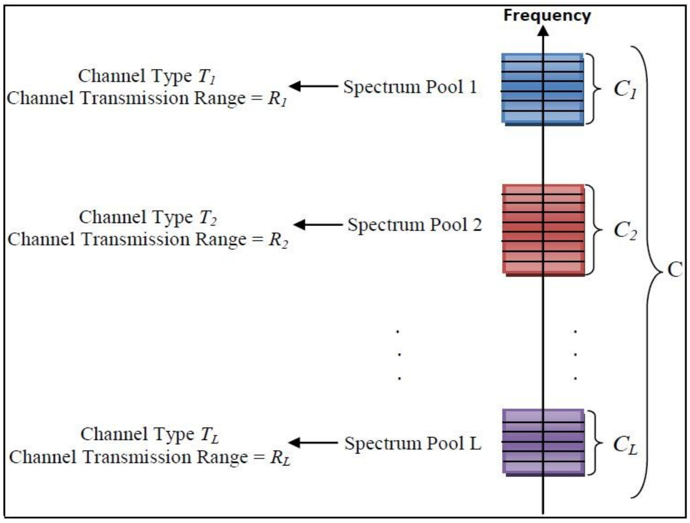

Fig. 1. Spectrum pool based heterogeneous CR-MANET scheme

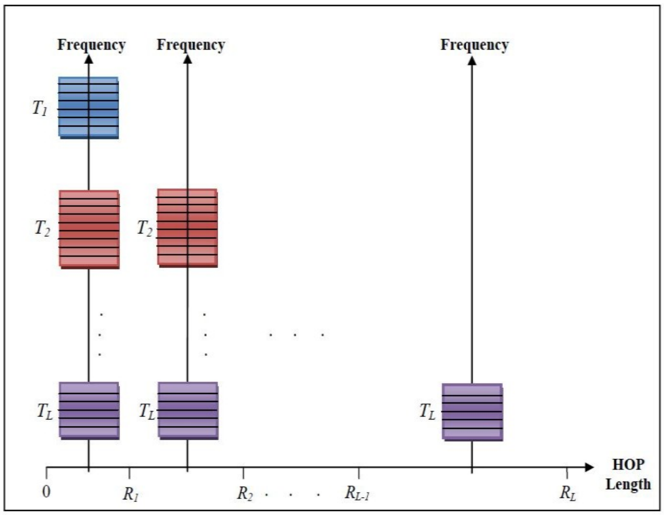

Fig. 2. Choosing the spectrum bands for communication based on the hop length

4 Analytical modeling of mobility and spectrum handoff

In this part, we exploit Markov chains to model the spectrum handoff mechanism in CR-MANETs based on the channel availability modeling above. The spectrum heterogeneity in terms of PER is also considered. The proposed integrated analytical scheme includes different mobility events in CR-MANETs such as spectrum and user mobility. It also considers the channel quality degradation, and topology variations. Once the channel quality declines or PER increases, the probability of successful packet transmission rate is decreased. The SU detects this deterioration throughput QoS and decides to change the channel to achieve a better throughput performance Considering ${P_E}^i$ as the PER of channel of type i and equation (1), the probability of successful packet routing in a route or between n nodes is as in (2).

$$p_{spr,c} = \left[\sum_{i=1}^{L} P_{car,c} (1 - {P_E}^i) \right] =$$

$$\left[\sum_{i=1}^{L} (1 - {P_E}^i) \times \left[\frac{\exp(-\lambda\pi {R^2}_{i-1}/2) - \exp(-\lambda\pi {R^2}_i/2)}{1 - e^{-\frac{N}{2}}} \right] \times \left[1 - \prod_{k=1}^{c - \sum_{j=0}^{i-1} c_j} (1 - (\frac{\alpha_k}{\alpha_k + \beta_k})^2) \right] \right]^{n-1} \tag{2}$$

Table 1. symbols used in this paper and their definitions

Symbol	Meaning
R_T	Node transmission range
C	Total number of available channel
c_l	Number of detected channels of each type at each node
l	Channel type
L	Total number of channel type
c	Total number of detected channels of different types at each node
p	Probability of a particular channel availability at each node
P_{cat,T_l}	Probability that there is at least one channel of type l among c channels between two nodes
$P_{car,c}$	Probability that there is at least one common channel among all hops in a route
λ	Poisson density of nodes' spatial distribution in the network
R_l	Transmission range of channel of type l
n	Total number of nodes in a route
N_N	Total number of the nodes in the network
A_N	Network area
P_{hb}	Probability of spectrum handoff blocking
P_{usrr}	Probability of unsuccessful rerouting
$P_{hb,sh}$	Handoff blocking probability in scheme deploying only spectrum handoff
$P_{hb,\mathrm{l}h}$	Handoff blocking probability in scheme deploying integrated local routing and spectrum handoff management

The probability of successful packet transmission in a hop or between two nodes is also found as

$$p_{spt,c} = p_{spr,c}\Big|_{n=2} \tag{3}$$

The parameter $P_E{}^i$ shows the rate of failed packets sent because of the variable channel conditions caused by factors such as fading and shadowing. The probability of unsuccessful packet transmission in a hop or between two nodes is also found:

$$p_{uspt,c} = 1 - p_{spt,c} \tag{4}$$

The main objective is to calculate the probability distribution of spectrum handoff and also model the spectrum handoff initiation in CR-MANETs. We define the $D_{l\text{-}1\,l}$ as the case in which $R_{l\text{-}1} < d < R_l$, where d is the length of the hop. **P**, which is the Markov matrix, and is written as follows:

$$\mathbf{P} = \begin{bmatrix} P_{T_{11}} & P_{T_{12}} & \cdots & P_{T_{1L}} \\ . & . & & . \\ P_{T_{L1}} & P_{T_{L2}} & \cdots & P_{T_{LL}} \end{bmatrix}$$

Fig. 3 shows the different Markov chains for spectrum handoff modeling based on the length of the hops. The Markov chain has different states based on the different cases for $D_{l\text{-}1\,l}$. As shown in Fig. 2, when the length of the hop is less than R_1, or when the spectrum handoff occurs in the case D_{01}, the two nodes involved in the current hop can select one of the available channels of any L types. In the case D_{01}, the Markov chain is as shown in Fig. 3(a). In the case D_{12}, the nodes involved in spectrum handoff can select one channel among available channels from type k, in which $k\neq 1$, as shown in Fig. 3(b). The other situations can be determined based on the claims above.Suppose that two nodes are communicating in a channel of type k, they can continue communicating in the current spectrum pool under two different conditions. These two conditions, in the case of $D_{i\text{-}1\,i}$, are as follows:

- The packet transmission is successful in the current channel of type k.
- The packet transmission is not successful in the current channel of type k but successful on another channel of only spectrum pool k.

Thus, the probability of packet transmission $P_{T_{kk}}$ is calculated as follows:

$$P_{T_{kk},D_{i-1\,i}} = p_{spt,c_k} + \prod_{j=1,j\neq k}^{L} p_{uspt,c_j} \tag{5}$$

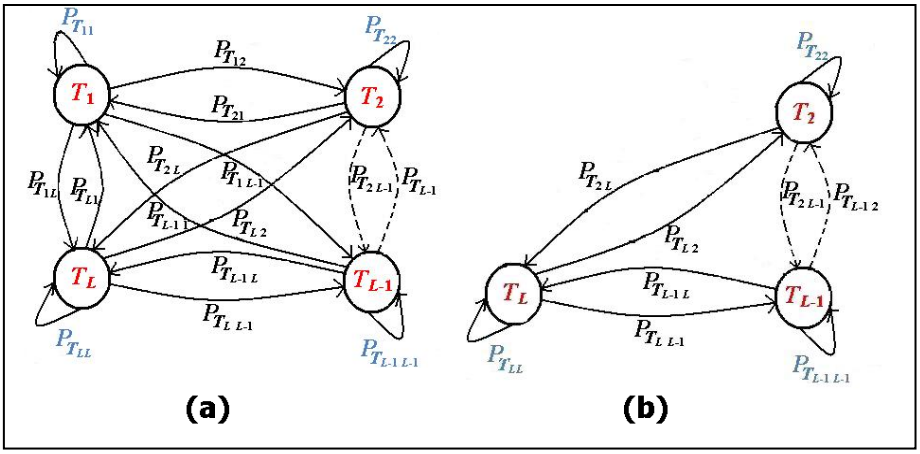

Fig. 3. Markov chains for spectrum handoff modeling based on the distance between SUs or the length of the hops

Based on the proposed claims about different Markov chains, there are two conditions where two nodes, which are communicating on a channel of type e, switch their communicating channel type to another channel of type k such that $k \epsilon \{1,2,\ldots,L\}$, $k \neq e$. These two conditions, in the case of $D_{i\text{-}1\ \mathrm{i}}$, are as follows:

- Unsuccessful packet transmission in a channel of type e, but successful transmission in only channel of type k.
- Unsuccessful packet transmission in a channel of type e, but successful transmission in channel type sets:

$$\mathrm{M}_i \subseteq T, \left|\mathrm{M}_i\right| = L_i \leq L \tag{6}$$

Based on the above Markov chains, there are many possible channel type sets for M_i. The channel of type j can be chosen by an identical probability among the available channel types in the set of M_i. Based on the explanation above, when the probability of channel type changing is $p_{c_{ek}}$, the probability of packet transmission is as follows:

$$P_{T_{ek},D_{i-1i}} = p_{uspt,c_e} \times \left[p_{spt,c_k} \left(\prod_{j=1,j\neq e,k}^{L} p_{uspt,c_j} \right) \right] + \\ \left[p_{uspt,c_e} \sum_{\mathbf{M}_i \subseteq \mathbf{T}} \frac{\prod_{j=1,2,\ldots,i,T_j \in \mathbf{M}_i, j\neq e} p_{\sup,c_j} \prod_{j=1,2,\ldots,i,T_j \notin \mathbf{M}_i, j\neq e} p_{uspt,c_j}}{\left|\mathbf{M}_i\right|} \right] \tag{7}$$

The row vector $\pi^{\mathbf{P}}_{D_{l-1\,l}}$, which is composed of $\pi^{\mathrm{P}}_{D_{l-1l}}(T_i)$, demonstrates the steady state probability for $\mathbf{P}_{D_{l-1l}}$ considering different hop lengths. The value of $\pi^{\mathrm{P}}_{D_{l-1l}}(T_i)$ is calculated using the following equations:

$$\pi^{\mathbf{P}}_{D_{l-1l}}\,\mathbf{P}_{D_{l-1l}} = \pi^{\mathbf{P}}_{D_{l-1l}}\ ,\ \sum_{i=1}^{L} \pi^{\mathrm{P}}_{D_{l-1l}}(T_i) = 1 \tag{8}$$

Ultimately, the steady state probabilities for various hop lengths for channel type *i* are calculated as below:

$$\pi^{\mathrm{P}}(T_i) = \sum_{l=1}^{L} \Pr(R_{l-1} < d < R_l)\,\pi^{\mathrm{P}}_{D_{l-1l}}(T_i) \tag{9}$$

where $\Pr(R_{l-1} < d < R_l)$ is defined as [7]:

$$\begin{aligned}\Pr(R_{l-1} < d < R_l) &= \left[\frac{1-\exp(-\lambda\pi R_l^{2}/2)}{1-e^{-\frac{N}{2}}}\right] - \left[\frac{1-\exp(-\lambda\pi R_{l-1}^{2}/2)}{1-e^{-\frac{N}{2}}}\right]\\ &= \left[\frac{\exp(-\lambda\pi R_{l-1}^{2}/2)-\exp(-\lambda\pi R_l^{2}/2)}{1-e^{-\frac{N}{2}}}\right]\end{aligned} \tag{10}$$

$$,\ 0 < R_{l-1} < R_l < R_T \ \ \&\ \ R_0 = 0$$

5 Integrated mobility and spectrum handoff management

To propose the integrated spectrum handoff management, we introduce the different scenarios which cause spectrum handoff initiation through an established route in a CR-MANET.

In CR-MANETs, the available spectrum bands vary over time. On the other hand, during the movement of an intermediate node, which is a member of an active route, the route may be broken and has to be repaired. To avoid route breaking, the local routing must be efficient enough. Suppose that, based on Fig. 4, a route from a source node S to the destination node D has been established. There are three different scenarios that initiate the spectrum handoff in this route, which are as follows:

SU mobility:

According to Fig 4(a), link failure happens when either node B or node F moves such that there is no channel that can support their data transmissions. Before the link breaks, rerouting must be performed. Fig. 4(b) shows that a local routing can be from node A to node E and finally joining node F. The finding of the new route and channel requires a common channel between node A, E and node F which is within the transmission range limit. In this scenario, only the links and channels between A and F will be changed, and the unified routing and spectrum handoff management system tries to solve the problem by finding a node in within the neighboring area of the damaged links.

To perform local routing, a certain amount of overlapping of the transmission range between node A, node F and the node that will take responsibility for routing the packets is necessary. To consider these two nodes as a hop counts, the maximum overlapping between these two nodes is shown in Fig. 5. The maximum overlapping area is $1.23R_T^2$. In a topology where nodes are uniformly distributed over the network area, the following condition guarantees the presence of at least η nodes in the overlapping area [8]:

$$N_n \geq \frac{\eta A_N}{1.23 R_T^2} \tag{11}$$

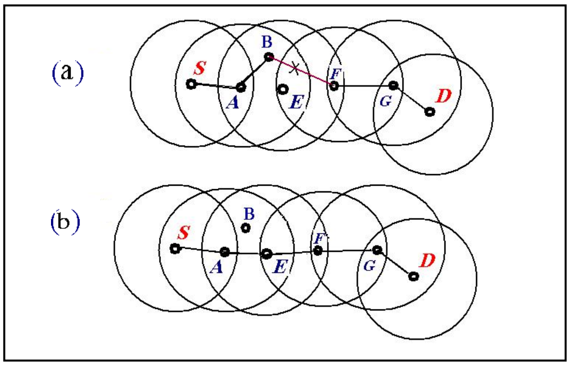

Fig. 4. Node mobility and local rerouting

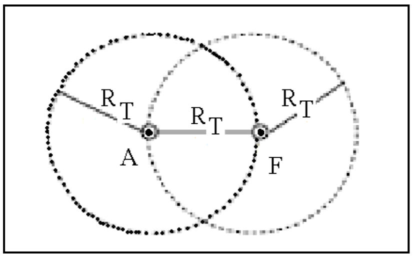

Fig. 5. Maximum overlapping between nodes A and F

To guarantee the overlapping of the transmission range of node A and node F, the following requirement must be satisfied:

$$N_n > \frac{A_N}{R_T^2} \tag{12}$$

This equation is in accordance with (11).

PU activity dominates:

This problem happens when PU starts its activity or node E, which is a member of an active route, enters the activity area of the PU during its movement. Before the link breaks, node E must perform rerouting. In this scenario, the node E can perform spectrum handoff considering common channel availability, or it can do the local rerouting considering the mentioned conditions in the first scenario.

Spectrum heterogeneity and different channel transmission range:

The mobility of the CR user can also lead to spectrum handoff because of spectrum heterogeneity and different channel transmission ranges. Suppose that two nodes, with a distance less than R_l, are involved in an active route. Also suppose that these nodes are using a channel of type l for their data transmission. When they are moving, and their distance exceeds the R_l, they must change their communicating channel to a channel with a transmission range longer than R_l.

Consider the possibility of that the entire available channels are not able to support the successful packet transmission based on spectrum handoff, the probability of spectrum handoff is equal to:

$$P_{sh} = \sum_{i=1}^{L} \pi(T_i)(p_{uspt,c_i} - \prod_{j=1}^{L} p_{uspt,c_j}) \tag{13}$$

In such a case, the troubled nodes do not perform spectrum handoff. These nodes have two choices. In such a case, the troubled nodes do not perform spectrum handoff; they perform local flow handoff. In (13), the term $\sum_{i=1}^{L} \pi(T_i) \prod_{j=1}^{L} p_{uspt,c_j}$ is the probability that the entire available channel cannot support the successful packet transmission. This term can be defined as the probability of local rerouting:

$$P_{lh} = \sum_{i=1}^{L} \pi(T_i) \prod_{j=1}^{L} p_{uspt,c_j} \tag{14}$$

The probability of successful spectrum handoff (P_{ssh}) depends on the probability of successful packet transmission in a hop $p_{spt,c}$. However, to perform local flow handoff, equations (11) and (12) must be satisfied.

We define the link maintenance probability (P_{LM}) as the probability that the link is successfully maintained during unsuccessful packet transmission in a hop or between troubled nodes, which is dependent on the probability of channel availability between two nodes. Thus, the link maintenance probability, considering only spectrum handoff, can be written as follows:

$$P_{LM,sh} = P_{sh} P_{spt,c} \tag{15}$$

When the link maintenance is not successful, despite the spectrum handoff, local rerouting is performed. In this case, the probability of link maintenance is as follows:

$$P_{LM,lh} = \left(\frac{N-2}{N} \right) (1 - P_{LM,sh}) P_{lh} P_{spt,c} \tag{16}$$

Finally, the probability of link maintenance considering the integrated routing and spectrum handoff management can be written as follows:

$$P_{LM,Ih} = P_{LM,sh} + P_{LM,lh} \tag{17}$$

6 Results and Discussion

Spectrum heterogeneity and SU mobility have a significant effect on the handoff blocking probability in the integrated routing and spectrum handoff management scheme. We define the probability of unsuccessful link maintenance as the probability of spectrum handoff blocking (P_{hb}). Fig. 6 compares the probability of unsuccessful rerouting (P_{usrr}), the handoff blocking probability deploying only spectrum handoff ($P_{hb,sh}$) and the handoff blocking probability deploying integrated routing and spectrum handoff management ($P_{hb,Ih}$), considering various number of SU nodes in the network. In the following figures, L=2, p=0.5, R_1=75 m, R_2=125 m, R_T=150 m, C=10, c_1=5, c_2=5, and the number of hops is equal to 14. Based on this figure, the integrated routing and spectrum handoff management scheme outperforms the scheme only deploying spectrum handoff in terms of link maintenance probability and spectrum handoff blocking probability. The probability of link maintenance in the integrated routing and spectrum handoff scheme is also significantly higher than the probability of successful rerouting. As the number of SUs in the network increases, the probability of handoff blocking decreases because the probability of finding the proper nodes to perform local rerouting increases.

Based on [9], with an area network of A_N=1000 m^2 and R_T=150 m, the number of expected hop count in the network is equal to 5. Fig. 7 compares the proposed parameters in Fig .6 with an expected hop count in the network equal to five. Comparing Fig. 6 and Fig. 7, we conclude that the probability of handoff blocking decreases when the number of hops decreases. This results shows that the proposed integrated spectrum handoff management and routing scheme achieves more actual data transmission opportunities.

Fig. 8 compares the effect of channel heterogeneity and channel homogeneity on handoff blocking probability *(P_{hb})*. This figure implies that, in contrast to homogenous channel condition, the node density in the network with the heterogeneous channel must be high to have an acceptable P_{hb}. Hence, we must consider channel heterogeneity in terms of transmission range and path loss.

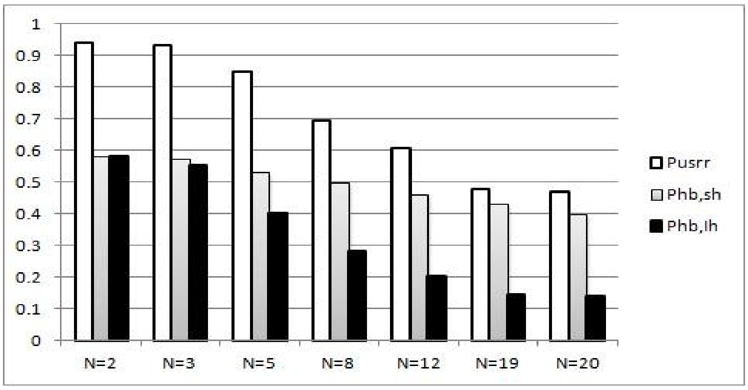

Fig. 6. Comparison of different handoff management schemes and routing performance with a hop count of 14.

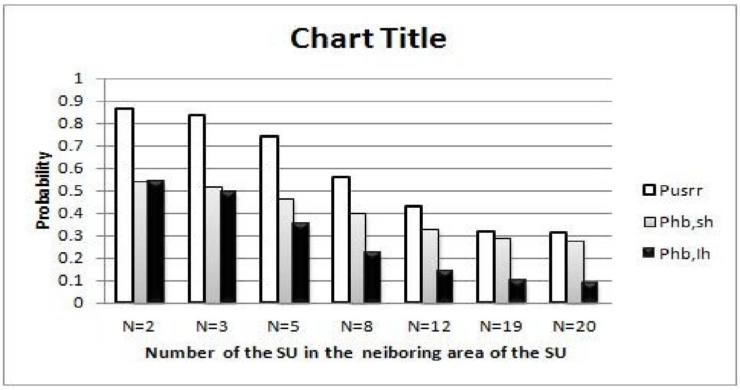

Fig. 7. Comparison of different handoff management schemes and routing performance with an expected hop count of 5.

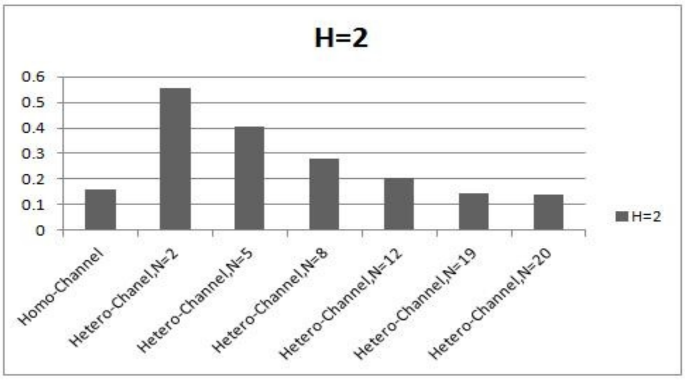

Fig. 8. Effect of channel heterogeneity on integrated handoff blocking probability

7 Conclusion

Spectrum handoff management is still an open issue in CR networks. It is particularly challenging in CR-MANETs. In CR-MANETs, the available spectrum bands vary over time and space, while they are distributed non-adjacently over a broad frequency range. However, in CR-MANETs, the fluctuation of PU activity and the SU mobility make the issue of maintaining optimal routes more complex. In this work, we present an integrated spectrum handoff management and routing scheme that considers spectrum mobility in the time and space domains and considers the network topology variations. We propose a network architecture that considers the heterogeneous spectrum availability and its variation over time and space and distributed nodes. Then, we formalise the probability of channel availability in this dynamic radio environment. Based on this unified architecture, an integrated routing and spectrum handoff management scheme is proposed. The proposed scheme considers the CR-MANETs spectrum handoff problem and incorporates the routing issue. It is a step towards a comprehensive management system for CR-MANETs.

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