Spectrum Handoff Management in Cognitive HetNet Systems Overlaid With Femtocells

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***Abstract*—Cognitive radio networks can facilitate seamless mobility to users considering their effective use of the dynamic spectrum access. This is performed by proactive/reactive adaptation of transmission operations in response to the wireless environment changes. One of these operations includes handoff between various wireless domains. The handoff here is not just a registration with a new base station, but it is also a negotiation to get access to the available channels locally in coexistence with the primary users. This dynamic adaptation between channels, known as spectrum handoff (SH), significantly impacts the time of handoff reconnection, which raises many questions about the functioning of the cognitive radio solution in the next generation of network systems. Therefore, it is necessary to develop a new method for roaming mobile users, particularly networks that employ small cells such as femtocells in order to reduce the unnecessary channel adaptations. This paper proposes a new entity, namely, channel assigning agent for managing SH, operator database, and channel access authentication. The goal of this mechanism is to retain the same channel used by a mobile user whenever possible to improve network performance by reducing the unnecessary SHs. The modeling and efficiency of the proposed scheme are validated through simulation results. The proposed solution improves the accessibility of resources and stability of mobile radio connections that benefits mobile users as well as operators.**

***Index Terms*—Cognitive radio, femtocell, mobility management, spectrum handoff (SH), throughput.**

I. Introduction

COGNITIVE radio users may encounter multiple connections interruptions when channels become unavailable due to the primary user transmissions or normal handoff operations. These interruptions trigger in a series of *spectrum handoffs (SHs)* to restore cognitive communications whenever an interruption event occurs [1], [2]. Clearly, SHs will increase the time required for reconnecting the new arrival mobile users in any cognitive transmission domain while reallocating channels. This new factor of time delay increases the time required for data delivery, particularly in cognitive networks that employ small cells such as femtocells. The main concern for such model of networks is that interruption may occur for unpredicted time intervals, leading to significant signaling overhead and degradation in the whole system performance.

It is reasonable to incorporate any new mobility functionality with the IP layer in order to solve the problem of spectrum handover. This is due to the fact that the IP layer is generic enough to serve all underlying technologies [3]. Also, it is widely accepted that there is a strong need to migrate the technology-specific core infrastructures toward all-IP networks [4]. The mobile IP working group within the Internet Engineering Task Force proposed a packet-based mobility management protocol, namely, Mobile Internet Protocol (MIP) in order to support global mobility in IP networks. This was upgraded later on to MIPv6 in response to the emergence of IPv6. In MIP, each mobile node (MN) is identified using two different IP addresses: a permanent home address and a temporary care of address (CoA). The CoA is provided to the MN as it roams in a foreign network other than its home network. The CoA is given to the MN by the visiting subnet after issuing a router solicitation message to its foreign agent [5].

Even with the flexibility in performing IP handover, developing a solution for SH in cognitive radio networks is still a complex challenge as it needs to answer the following two questions: How to transfer the updated state information of the mobile users' used channel from the MIP to the Mobility Management Entity (MME)? What entities should be involved to allocate a certain channel for a mobile user that is moving between two cognitive access points (APs)? Considering the motivation to avoid the impacts of spectrum handover and the complexity of the aforementioned challenges, we propose a new scheme that can allocate the same channel to a cognitive mobile user moving between various APs as long as this channel is vacant in these domains. The goals that we intend to achieve here are as follows:

1) reducing the number of unnecessary SHs and improving the cognitive communications stability;
2) minimizing the time latency incurred during the data delivery;
3) improving spectrum coordination and avoiding channel scattering due to unnecessary SH.

Therefore, the main contribution of this paper is to propose a solution to the SH problem in cognitive radio networks overlaid with femtocells. We propose a new channel assigning agent (CAA) entity at the IP protocol layers. The CAA retains the same channel in use by a mobile unit when it moves to a new macro-/femtotransmission domain whenever the requested channel is available. The CAA is coupled with the MME to

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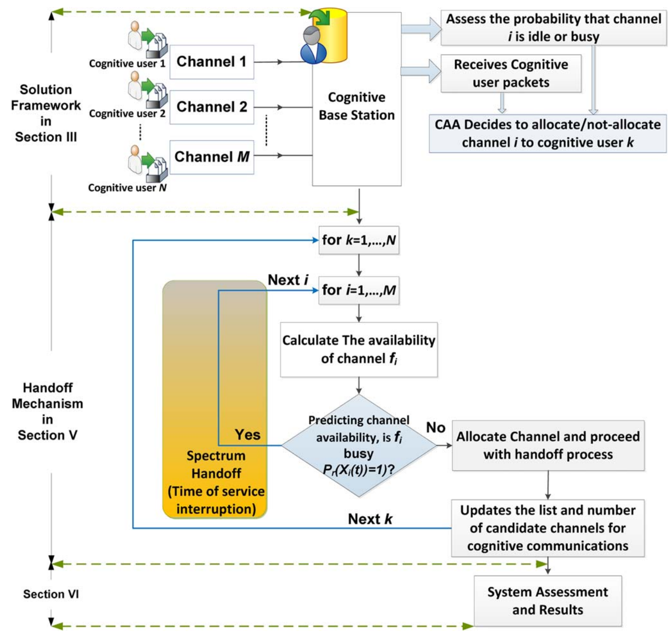

Fig. 1. Overview of contents in this paper.

allow centralized management of the channel allocation during handoff in large cognitive networks. This can minimize or eliminate the time consumed during SH in a cognitive radio network that employs femtocells. Our simulation results demonstrate that the proposed scheme reduces the total handoff latency, end-to-end data time delay, and number of handoffs and improves the overall system throughput. The contents of this paper are arranged into stages in order to develop the CAA system model, as shown in Fig. 1.

The remainder of this paper is organized as follows. Section II discusses related studies. Section III overviews the IPv6 system model and the flow diagrams of the proposed scheme. Section IV describes the protocol of spectrum mobility and handoff in cognitive networks. The algorithms of SH management are given in Section V. Simulation evaluations and performance analyses are presented in Section VI. Finally, our conclusions are presented in Section VII.

II. Related Studies

There is no literature that solves the problem of SH using MIP according to the author's knowledge. Keeping in mind that there are few studies addressing solutions to the SH issue, we will start by showing the most prominent solutions for SH, and then, we show how MIP is used to solve the handoff latency. Our goal is to establish the necessary background for a solution that incorporates both SH and MIP, as shown in the following sections. Some of the most related studies to our work are described in the following.

An optimization problem was formulated in [6] for a proactive determination of target channel selection with the objective of minimizing the cumulative delay per connection. This allows a newly arriving secondary user to avoid multiple SHs due to the high-priority primary users and the traffic statistics of both primary and secondary users. This process takes into account the time required for channel switching and the transmission delay time resulting from accessing unsuitable channels. In contrast to a proactive assignment before accessing the channel, channel-switching policies and a proactive SH protocol in [7] were proposed to let cognitive users vacate a channel before the primary user accesses it to avoid interference. This means that the cognitive user is using the channel and it acts before the primary user returns to occupy the space. Once the cognitive user is driven into conducting an SH, a distributed channel selection scheme is activated to avoid collisions among cognitive users in a multiuser SH scenario. A further application of the optimal target channel sequence selection in proactive-decision SH is given in [8] with a Poisson arriving of primary users. The theoretical analysis has shown a minimum probability of SH failure using the proposed scheme. The authors in [9] considered the channel handoff agility limitations for a cognitive radio user with a dynamic multichannel-access capability. The channel handoff agility was modeled as a continuous-time Markov process in order to analytically derive the forced access termination and blocking probabilities of cognitive users. Although the paper assumptions accept that SHs can only be performed to vacant channels that are immediate neighbors of the cognitive users' current channels, however, they do not show how this scenario can reduce the numbers of SHs or proactively prevent them. Clearly, the SH studies investigate methods that can host the arrival of a cognitive user in the spectrum or the ways to respond to subsequent changes in the spectrum availability without being able to prevent SH occurrence.

The handling of handoff operations with the MIP has a very different prospective from the SH prospective that we mentioned earlier due to the operation management. The MIP features allow investigating the connection latency and state information of the mobile users and unifying technologies using the IP layer. For example, the authors in [10] proposed an optimized handoff scheme using an adaptive retransmission timer that is proportional to the size of the messages involved in the transactions of the handoff process. This local mobility management, which was placed in the Fast MIPv6 (FMIPv6) and Hierarchical Mobile IPv6, has shown a major support to handle network layer mobility for Voice over IP (VoIP) traffic. This also allowed a minimum disruption for interaccess router movements, which are the most expected cases, and avoided triangular routing, which can harm VoIP services in mobile systems. The focus on IPv6 approach to provide solutions for mobility was also investigated in [11], where a generic framework for handoff techniques was combined with mobility management mechanisms at the IP layer in order to replace the well-performing soft handoff capabilities of the Universal Mobile Telecommunications System/wireless local area network (WLAN) radio technologies. Although the IP handover mechanism was employed to manage the restoration of radio communication as well as proactively take actions and establish state information, the given analysis of the MIPv6 and FMIPv6 protocol operation focused only on handoff delays. A very similar solution using IPv6 can be also seen in [12] and [13] to support dynamic location changes of MNs and propose solutions for the impact of mobility. Analytical and simulation evaluations in [14], [15], and [16] addressed seamless mobility management by transferring the features of the Session Initiation Protocol (SIP) of a separate location management function to the MIPv4. One of the advantages of such modeling is the support of a global seamless handover between homogeneous or heterogeneous networks (HetNets). However, mobility management becomes more challenging when migrating from macro-only to HetNet environments. This is due to the more challenging interference conditions, small cells appearing and disappearing more quickly as MN devices move, macrocells and small cells deployed at different carrier frequencies, and so on [17]. All this literature on network-based mobility management protocols has not considered SH over IP layer.

In contrast to the aforementioned literature, this paper develops a long-term solution for the challenging SH. Our solution aims at significantly reducing the number of SHs in cognitive HetNets. This is performed by directly connecting the MIPv6 to the MME using a new entity that can stabilize the mobile user connections with fewer or no SH events. The solution couples the correspondence node, target node, and network management entity using IPv6 protocol, as discussed in the next section.

III. Solution Framework for SH

The HetNet has more small coverage cells, such as femtocells, than that of cellular systems. Hence, it is reasonable to predict that handoffs will be more frequent than that in macro-only networks. In a cognitive radio network, this becomes more complicated with SHs and the tremendous need for frequency adaptations when moving among various transmission domains. Therefore, any solution framework should enable to update in MIP networks with the channel used by an MN in order to maintain connection continuity of ongoing connections when the MN moves into a new domain. Our choice is to use MIPv6 for two reasons: First, it enables an MN to keep the network connectivity even if the MN changes its point of attachment to the network [18], which is essential for HetNets with different technologies, and second, MIPv6 has minimized control traffic [19], which is essential for an effective mobility management and dynamic wireless environment. The framework of the CAA solution suggests that the information on MN operative cognitive channel is exchanged among the MN, the source AP, and the target AP for channel allocation. In the following sections, we show how the CAA integrated with the MIPv6 for HetNet SH management. Then, we show the control signals for a mobility scheme that scans the channel availability and allocate channels between multiple domains. We also identify the conditions for channel assessment that can trigger SH whenever necessary. These will formulate the basis for the CAA algorithms given in the following sections.

A. Introducing the CAA

In order to reduce or revoke the interruption time that occurs from frequent SHs of a mobile user moving between different cognitive APs, we proposed in our earlier work in [20] to create a new agent, namely, CAA-based IPv4 for WLAN technologies. Although the functionality of the proposed CAA was to allocate channels for cognitive users, it cannot provide roaming for an MN moving between different technologies/HetNet domains. In this paper, we develop further the CAA to allow the Long-Term Evolution (LTE)/WLAN systems to use the same agent to control SH between variety of macro- and femtodomains. In this extended new application, the CAA is incorporated within the MIPv6 to support roaming option as well as SH control signaling. The current known mobility management in cognitive radio network does not support channel allocation; therefore, it is necessary to incorporate such functionality in order to be able to deal with the SH problem. As CAA is integrated to the IPv6 protocol, IP–Dynamic Host Configuration Protocol is used to create the global interface for all cognitive radio clients in motion. This simplifies the process of registration and allows a central management for channel allocation as proposed by the CAA. To perform a seamless handoff, we allow mobile user to communicate directly with its correspondent nodes (CNs) instead of tunneling the traffic via a home-agent node, particularly inside femtocells. This utilizes local transmission opportunities efficiently in small-cell communications as one of our main goals in this paper. In addition, a two-way handshake (solicit/reply) is used instead of the usual four-way handshake (solicit/advertise, request/reply) to reduce the time of response while adapting performing handoff and/or SH operations. This is a very essential requirement for mobile users moving at high speeds.

As mentioned earlier, the framework solution incorporates the CAA at the IP network layer to assign certain channels prior to any handoff actions. This assumes that the CAA is aware of the channel used by the MN and it can determine the availability of the same channel at the target subcell domain prior to any new handoff request. This means that the CAA is also aware of the mobile user route of movement. As such information is very hard to be predicated, we assume that the CAA in real applications can learn from long-term monitoring of MNs. For example, the CAA can predict the route of a certain mobile user who is used to take the same highway street to commute to work at early morning and at the end of the working day. Such long-term data of monitored users and the location registrations obtained from the access router allow the CAA to allocate channels in collaboration with the MME, as shown in Fig. 2. Hence, the CAA operation procedures include the following. First is informing the target node to assign a certain channel(f_i) at the time of arrival of an MN in order to interface communications immediately and eliminate any need to perform SH. Second, the CAA determines the obtained channel sensing reports to manage the allocation of another channel (f_i') and adopt this new channel as the new operative channel for this MN to avoid further SH actions. The last scenario is very likely to occur in cognitive HetNets, but the CAA functionality keeps the handoff mostly as a horizontal handoff over a series of connections rather than a vertical handoff where an MN adapts rapidly between various channels.

Considering Fig. 2, when an MN moves from domain 1 to domain 2, tunnel 1 is terminated at the time of MN registration with the AP at domain 2. Using the CAA, we should be able to revoke the impacts of interruption time that is likely to occur due to the SH operation. This advantage of CAA application

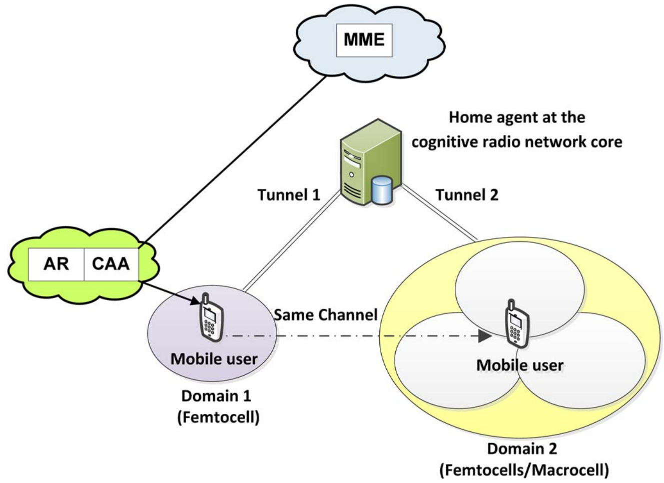

Fig. 2. CAA entity as part of IP.

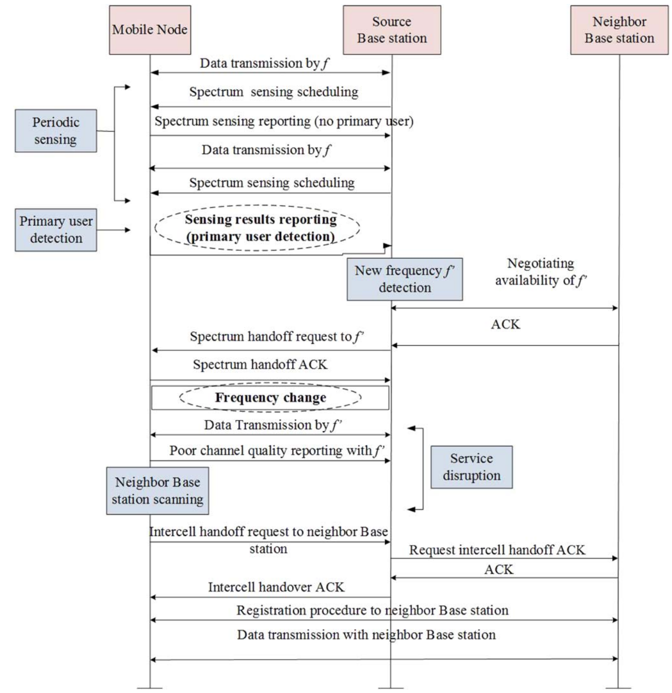

Fig. 3. Operation of intercell SH [21].

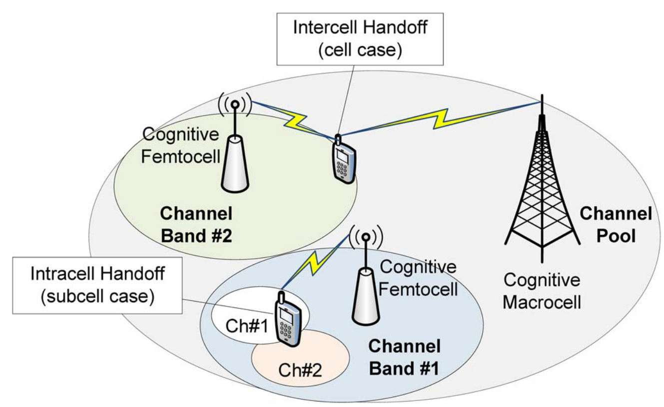

Fig. 4. Inter-/intracell SHs.

does not eliminate the other usual handoff time latencies that occur due to the normal mobility registration and signaling operations. Although this solution is designed to be a general application to all size cognitive radio network domains, this study will focus on femtocell-to-macrocell network scenario model. This limitation allows us to develop the SH signal control flow for a network management of a macrocell of LTE technology overlaid with femtocells of WLAN technologies. This SH solution is further developed into a channel assignment protocol that can retain mobile user channel during handoff between different wireless domains. These contributions are proposed in the following sections of this paper.

B. Model Formulation

We investigate the SH problem that is likely to occur for an MN traveling between two cognitive base stations. Our intention is to develop the necessary control signal scheme for channel allocation for HetNet. From the literature, the authors in [21] proposed an intercell SH scheme as shown in Fig. 3. In this scheme, the mobile user senses the spectrum periodically to detect the presence of any primary user. The sensing results are exchanged with CN, which may decide to allocate another channel to the MN. In this case, the availability of the new channel will be negotiated with neighbor nodes to prevent interference. If it was decided to adapt to a new channel, there will be a distribution in the services during the time of frequency adaptation. This disrupted mobile user needs to carry out additional intercell handoff to maintain a connection. In the worst case, the mobile users must carry out a new network entry procedure due to the connection loss. Clearly, this was developed to solve the problem when a primary user reclaims its channel and the cognitive MN has to look for another channel to maintain cognitive communications. We think that this scheme is an initial step to generate the signal control scheme for the SH, and we expand this work by incorporating a channel reservation mechanism that can reduce not only the probability of service interruption but also the total number of potential handoffs.

Considering Fig. 4, there are two potential cases for SHs: inter-SH within the cell and intra-SH within the subcell. In fact, all of them can be treated as the same using one SH procedure in a spectrum pool model. Thus, the channel reservation concept can be generalized to all users subject to the channel availability and accessibility at any of the wireless domains. Specifically, the goal is to reduce/eliminate unnecessary SHs for active radio connections. Although such channel reservation model can impact the way of assigning the spectrum between cognitive users, we will justify this proposal in the following sections by showing the improvement in performance of active connections. Therefore, we generalize the conditions to enforce or cease SH operations to all MNs moving between any two domains, as shown in Fig. 3, as follows.

Condition 1: Enforcing SH

$$\{Q\left(f_i'\right) < \delta_{\text{th1}}\} \cap \{l, \text{s.t. } Q(\ddot{f}_i) > \delta_{\text{th2}}\}. \tag{1}$$

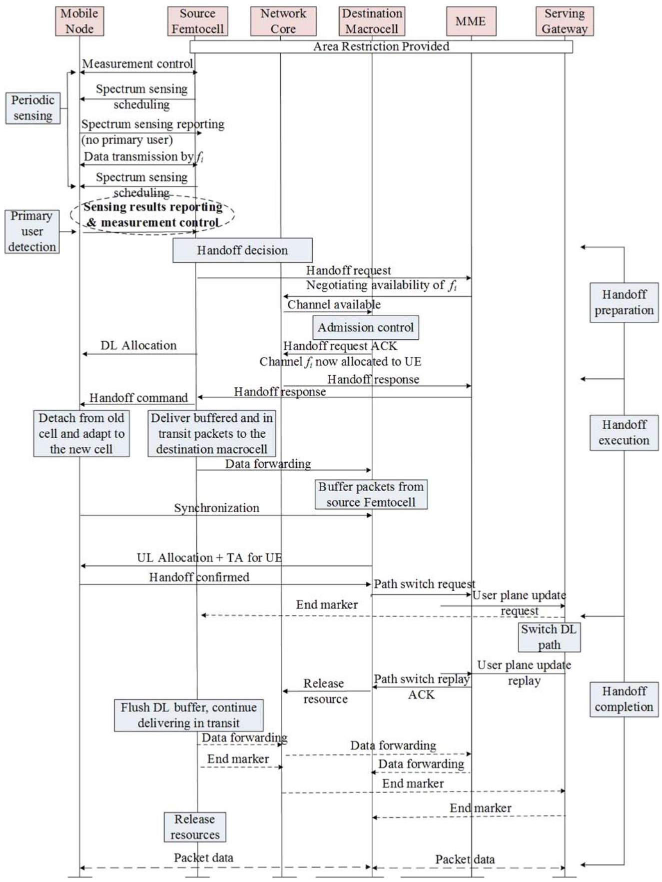

Fig. 5. Scheme for SH while changing to (f_i').

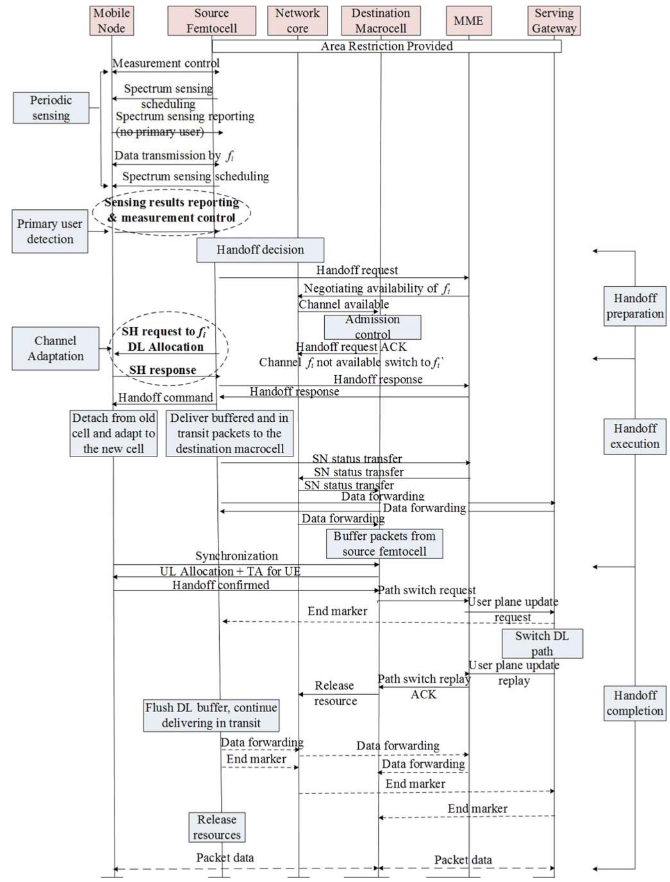

Fig. 6. Scheme for SH using (f_i).

Condition 2: Ceasing SH

$$\{Q(f_i) < \delta_{\mathrm{th1}}\} \cap \{Q(f_i') > \delta_{\mathrm{th2}}\} \tag{2}$$

where f_i is the original frequency of serving base station, f_i' is the new frequency of the target base station after SH, $f_\imath$ is the frequency of the neighbor base station indexed by l, δ_{th1} is the threshold for triggering SH, δ_{th2} is the threshold for determining SH, and Q is defined as the received signal-to-noise ratio for each frequency channel.

Since the handoff model given in Fig. 3 is not able to meet the requirements of large-size networks due to the absence of a central management unit that allocates channels between various domains, we provide a new SH scheme that is extendable to cognitive HetNets that employ small cells of femtocells. The new signal flow diagrams for channel allocation are given in the following section.

C. New Handoff Scheme

The SH scheme for a mobile user traveling from femto- to macrodomain is given in Fig. 5. The scheme determines the availability of the frequency (f_i) for the new arrival mobile user in order to maintain the same channel in the new target domain.

If the enforcing condition of SH given in (1) is satisfied, the detailed procedure shown in Fig. 6 is carried out. When a cognitive user is moving toward the macrocell domain, a control message is reported with the latest updates of the periodic spectrum sensing. Then, a handoff request is made to the next base station provided by the frequency of operation (f_i) to negotiate the availability of this channel at the new domain.

If the channel is not available at the target base station, a channel scanning is performed to identify a new available channel (f_i'). Once (f_i') becomes available, a channel adaption request is sent back to the MN to change to (f_i'). Before adapting to a new frequency, the MN buffers the data and halts any transmission. Similarly, the femtocell buffers and directs any packets to the macrocell unit in order to resume normal transmissions. Thus, a path switch request is issued to the cognitive radio network core which acts as the serving gateway to redirect future communications to the new route of connections as well as update the user profile of the new location and frequency.

Fig. 6 shows the SH scheme in case of frequency (f_i) is available at the macrocell for the newly arrived MN. Comparing Figs. 5 and 6, we can see clearly the differences in the control signals and the additional operations required for the frequency adaptation scenario. This confirms the impact of SH that adds an extra delay time to the reconnection time incurred during normal handoff action. There are other time delays incurred in cognitive systems due to the SH, such as the time required for scanning the spectrum, channel assignment, and frequency reconfiguration.

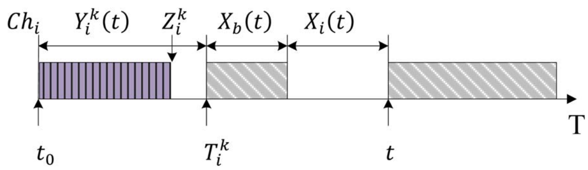

Fig. 7. Primary user traffic activity on channel f_i.

TABLE I
MYTHOLOGY

$Y_i^k(t)$	Number of successfully transmitted packets of a number of cognitive user k over channel i
$Y_f^k(t)$	Number of failed transmitted packets of a number of cognitive user k over channel i
T_i^k	Packets arrival time of a number of cognitive user k over channel i
$X_b(t)$	Number of slot times that channel i is busy in a future time interval t
$X_i(t)$	Number of slot times that channel i is idle in a future time interval t
k^{th}	Number of cognitive users
i^{th}	Number of channels available to cognitive users
Z_i^k	Packet length of a cognitive user k over channel i

In the next section, we provide the mechanism for the CAA functionality to verify the given solution of holding or adapting channels between various cognitive base stations.

IV. SH Mechanism

The framework for SH solution proposed in this paper assumes that the MN sends its location data, used channel, and sensing data message during handoff request. Upon receiving, the MME starts making predictions of the channel availability before the current transmission frame ends. Based on these predictions, the MME decides whether to allocate the same channel to the MN, to switch to a new channel, or to terminate the ongoing transmission. In this section, we develop a new assessment model that can determine the channel availability and use these data to help the MME making decisions on SH requests. We propose two criterion for channel assessment: 1) the forecast probability that the current candidate channel (i.e., a channel that can be selected for continuing the current data transmission) is busy or idle and 2) the expected length of the channel idle period. Based on these measures, we design SH policies that are used to assign channels between various cognitive users.

To estimate the probability that a channel is idle, it is necessary to identify the time intervals of busy and idle states of random transmission durations. Considering Fig. 7 (Table I) and using a Bayesian learning algorithm [22], the probability that channel i is idle can be given as follows:

$$P_{f_i}^{\text{idle}}(t) = \frac{X_i(t)+1}{X_b(t)+X_i(t)+2} \tag{3}$$

where $X_b(t)$ and $X_i(t)$ are the numbers of slot times that channel i is busy or idle in a future time interval t.

Therefore, the criterion for channel ith to become a candidate channel at time interval t is given by

$$\begin{cases} P_{f_i}^{\text{success}}(t) = \frac{Y_i^k(t)+1}{Y_i^k(t)+Y_f^k(t)+2} & T_i^k \le t \\ Z_i^k \le \tau_z \end{cases} \tag{4}$$

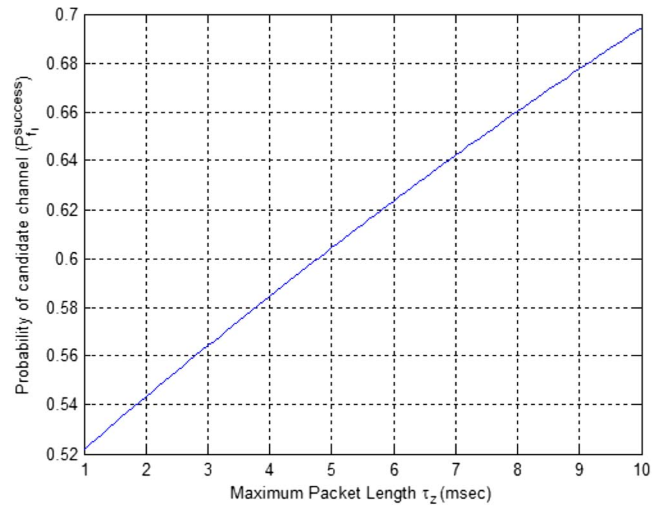

Fig. 8. Probability of successful candidate channel for cognitive transmission over interval time t.

where $Y_i^k(t)$ and $Y_f^k(t)$ are the numbers of successful and failed cognitive radio slot transmissions over channel i, Z_i^k represents the packet length of the a number kth of cognitive users on channel i, and τ_z is the maximum packet length that can be conveyed over a link ($\tau_z = 10$ ms for SIP).

Therefore, the probability of successful cognitive transmission over a certain link using (4) can be shown in Fig. 8.

In this case, there is no need to perform an SH operation, and the cognitive user is being facilitated easily in coexistence with the primary user. The condition in (4) means that, in order to support at least one cognitive user frame, the probability that the duration of the idleness of the ith channel has to be longer than a frame size must be higher than or equal to τ^z.

This means that an SH action will be necessary whenever

$$\begin{aligned} &\left(P_{f_i}^{\text{success}}(t)=0\right), \quad \text{if } T_i^k < t; \quad T_i^k + Z_i^k \ge t; \quad k \ge 1 \\ &\left(P_{f_i}^{\text{success}}(t)=0\right), \quad \text{if } T_i^k + Z_i^k < t; \quad T_i^k \ge t; \quad k \ge 1 \\ &T_i^{k+1} \ge t, \quad k = 0. \end{aligned} \tag{5}$$

In this case, it is necessary to perform SH provided by scanning other channels in the available band to identify a new candidate channel in order to resume transmission. It should also be noticed that a cognitive user should switch to a new channel if

$$Z_i^k \ge \tau_z. \tag{6}$$

The aforementioned policies are used to develop the probe for channel assignment in SH model. This is performed in the CAA protocol given in the following section.

V. Protocol Modeling

A. Channel Availability Algorithm

We propose a protocol that conducts an SH using the channel assessment model that was given in the previous section. The protocol has two parts. The first part, namely, Algorithm 1 (the pseudocode highlights the channel allocation scheme in

Fig. 5), describes how a cognitive user initiates a handoff request. Regardless of the transmission domain, if a handoff request arrives at the base station, the MME uses the channel availability predications to allocate a certain channel as reported by CAA. Based on the prediction results, if the channel satisfies the policies in (4) for data transmissions, the MME sends acknowledgment (ACK) that frequency channel f_i is available to the MN, and the transmission resumes at the beginning of the next time frame. Upon allocating the channel, the MN detached from the prior base station performs the normal handoff and starts the data transmission using the same channel.

//** ***Algorithm 1: Starting A Handoff Request***: f_i ***is available*** **//

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1 *MN arrives at new base station domain*
2 *Handoff request: CAA reports used channel* $\mathrm{Ch}_i = f_i$, $\mathrm{HO} = 0$ request $= 0$
3 *Scanning for* (f_i): *frequency and time duration* (4)
4 ***{***
5 ***If*** (f_i) *is available*
6 *MME allocates* f_i *at the new destination* (2)
7 ***Else*** *switch to Algorithm 2*
8 ***End if***
9 HO request $= 1$
10 *Sending ACK*
11 ***Upon*** receiving ACK
12 *Performing handoff*
13 ***If*** *handoff completed*
14 *Resume transmission*
15 HO request $= 0$ *when transmission ends*
16 ***End if***
17 ***}***

B. Channel Adaptation Algorithm

The second part, namely, Algorithm 2 (the pseudocode highlights the algorithm in Fig. 6), is an SH when channel f_i is not available for MN transmission at the target base station. This protocol determines the process for MN to carry out an SH as in (1) and then switch to a new channel by the time the current frame in transmission ends. This should happen when the channel sensing information satisfies the policies in (5) and (6) for a potential SH. If the condition is not fulfilled, then the used channel will be available for the next frame transmission, and we will switch to use Algorithm 1. Once the condition is fulfilled and an SH is necessary, the MME evaluates the set of channels available for cognitive transmission.

The algorithm maintains two functions of (NUC) and (LSC) as the number and the list of the candidate channels for cognitive transmissions, respectively, similar to [7]. The MME evaluates the next candidate channel on the LSC using (4). Then, the MME sends a channel-adaptation-request (CAR) packet containing the updated chosen channel information in the next time slot. Upon receiving the CAR packet, the cognitive MN replies with an ACK packet. As the ACK packet is successfully received by the source base station, the MN performs an SH by the end of the frame to avoid any interference to the primary user. A connection is established between the MN and the target base station while data communications are rerouted to the next linked base station.

//***** ***Algorithm 2: SH***: f_i ***is not available*** *****//

---

1 *Initialize operation*
2 $\mathrm{CAR} = 0, \mathrm{HO} = 0, \mathrm{NUC} = 0, \mathrm{LSC} = 0$
3 ***{***
4 ***For*** $(i = 0, i \leq M)$ *do*
5 *Predicting the availability of* Ch_i *(channels other than* (f_i)*): frequency and time duration*
6 ***End for***
7 ***If*** $(\mathrm{CH}_i,\ 0 \leq i \leq M)$ *available: frequency and time duration* (4) *acceptable*
8 $\mathrm{NUC} = \mathrm{NUC} + 1$
9 $\mathrm{LSC(NUC)} = i$
10 ***End if***
11 ***If*** $\mathrm{LSC} = 0$
12 *Go to step 4*
13 ***End if***
14 ***Upon*** *receiving CAR* ***then*** Send ACK
15 *Performing complete handoff (including SH)*
16 *Start scanning the channel*
17 ***If*** *the channel gets busy*
18 *Transmission stops*
19 *Go to step 4*
20 ***Else*** HO request $= 1$
21 ***End if***
22 ***If*** HO request $= 1$
23 *Transmitting data*
24 HO request $= 0$ *when transmission ends*
25 ***End if***
26 ***}***
27 *Go to Algorithm 1*

The time delay of the SH is defined as the interval from the time a cognitive user leaves its used channel to the time it resumes the transmission on a new channel. There is also a possibility that the allocation is not appropriate as the primary user resumes transmission over the new channel. Therefore, it is necessary for the cognitive mobile user to scan the channel and make sure that it is idle at the beginning of any frame transmission. If the channel is sensed busy, Algorithm 2 is launched again to search for another channel.

VI. PERFORMANCE EVALUATION

A. Simulation Setup

The developed SH scheme is compared with the conventional handoff management model using the designed OPNET

TABLE II
SIMULATION PARAMETER VALUES

Parameter	Value
Cell layout	Sectors: 1 macrocell, 3 femtocells, and 14 primary units
Users active per sector	2
Minimum distance to BS	35 meters
Propagation model	Hata-large city
Number of available channels i^{th}	14
Packet inter-arrival time Y_i^K	10ms
Voice packet length Z_i^k	80 bytes
t_{OFF}	variable
Application Layer	
Encoder Scheme	G.711 (silence)
Voice Frames Per Packet	1
Type of Service	Best Effort (0)
Signaling	SIP
Max. ACK Delay	0.2 sec
Max. ACK Segments	2
Fast Recovery	Reno
Cognitive Network	
Physical characteristics	OFDM (802.11a)
Data rate	48Mbps
maximum transmission power	1mW
Route request rate limit	10 pkts/sec
Node Traversal Time	0.04sec
Primary Network	
Physical characteristics	Direct sequence
Data rate	11Mbps
Channel bandwidth	22MHz
Max. Receive lifetime	0.5 secs

models. The choice for using this software is due to the fact that examining the performance of higher level layers such as the Transmission Control Protocol/IP is a complex challenge that needs to be solved with a very powerful computing processing system. The OPNET is capable of simulating complex HetNets of multiple numbers of nodes provided by the capability to mimic real-time network operations [23]. The channel allocation algorithms are coded and incorporated within the functions of the simulator. The simulations integrate cognitive radio network models with the primary network to create dynamic channel selectivity similar to what a cognitive network experiences in real operations. The network parameters for the designed simulations are shown in Table II.

The proposed algorithms are set up to have no frequency channel overlap. Therefore, transmissions from an instance of one model can only be received by instances of the same model. Hence, instead of trying all receiver channels every time, we filtered these out by the prior information on the users' channels. There are two primary places to do that filtering: the receiver group pipeline stage and the channel match pipeline stage. In the receiver group, the code access, channel minimum frequency, and bandwidth attributes for the transmitter/receiver channels use the information on channels to accept or reject the pair between base station and MN. The default receiver group pipeline stage does not pay attention to frequency or bandwidth attributes.

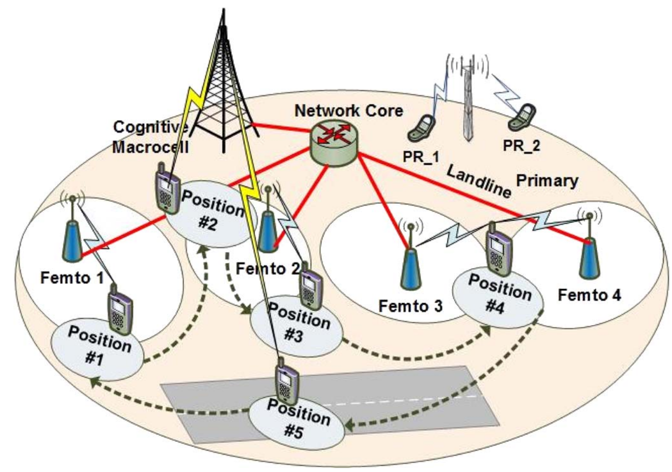

Fig. 9. SHs events for a cognitive mobile station moves between different femto- and macrodomains.

We use the attribute dra_chanmatch, which is a compiled pipeline procedure to dynamically compute the type of interaction that can occur between a radio transmitter channel and a radio receiver channel. The default model can dictate that a transmission be viewed by a radio receiver channel as a valid and potentially receivable signal. This allows us to avoid any interference or an irrelevant signal. If the latter outcome occurs, the remainder of the pipeline is not executed for the given transmitter–receiver pair.

B. Simulation Steps

SH is another source besides traditional handoff for providing mobility in cognitive radio network architecture. Considering SH, this dynamic process of adaptation between channels may occur to fixed and moving nodes at the same time. However, splitting the effects of conventional handoff schemes from the new SH is a new topic for discussion in secondary networks. Our goal is to reduce/eliminate the time of interruption in services that can occur during the adaptation of a cognitive MN between different channels. The evaluation setup of the proposed SH method is performed by allowing the MN shown in Fig. 9 to use the same channel when moving between positions #1-to-#2, #3, #4, #5, and then back to #1. This was compared to the conventional model where MN may be forced to adapt to another frequency channel when performing normal handoff between two wireless domains.

Considering the system in Fig. 9, the MN experiences five different events of handoff as it moves along the trajectory shown in the figure. These handoffs occur when the following events happen.

1) The MN moves out of the femtocell coverage area (position #1) where service capacity is much higher because

TABLE III
SIMULATED MOBILE USER SPEEDS

Speed (mph)	Description
2.877	Pedestrian
20	Cars speed in urban areas
30	Cars speed in urban areas & villages
40	Cars speed in non-built areas
50	Cars speed in non-built areas
70	National speed limit

of the stable and short-range communications toward macrocell coverage zone.

2) The MN arrives at the femtocell coverage area (position #2), leaving the macrocell service area.
3) The mobile mode heads directly to the macrocell area (position #3), leaving the femtocell zone of node 2.
4) The MN moves to the fully covered area by three transmission sources: the macrocell and two femtocells (position #4).
5) The MN moves along the motorway (position #5), returning to its initial point (position #1).

To examine the performance of the new SH scheme using the aforementioned scenario, the MN is set to use different speeds of movement along the route shown in the figure. These speeds were set according to Table III that presents the vehicular speed limits.

An IP telephony and silence suppressed signals are generated to test the system performance. The reason to choose this kind of application is that normal phone calls are actually composed of different times of activity where the user is either talking or silent. The IP networks transmit packets only when the data and control information are in action. Therefore, there is no usage for the channel if the clients are not sending anything. Thus, such application is very useful in analyzing the cognitive networks and the dynamic spectrum access models. The reason for this is that transmissions occur temporarily and when it is needed only, which is the same principles of the cognitive radio systems.

The simulation setup includes two networks, namely, primary and secondary networks, that coexist with each other. Primary users are transmitting using all channels while secondary systems are accessing the available band on temporary basis whenever there are no primary activities. In order to simulate the performance of the new model precisely, the number of mobile users is set to 1, 3, and 7, respectively. In each case study, an evaluation for the system improvement with no SH is compared to the traditional case where the SH is happening along the movement route.

C. Results

In this section, the simulation results are presented to validate the proposed scheme.

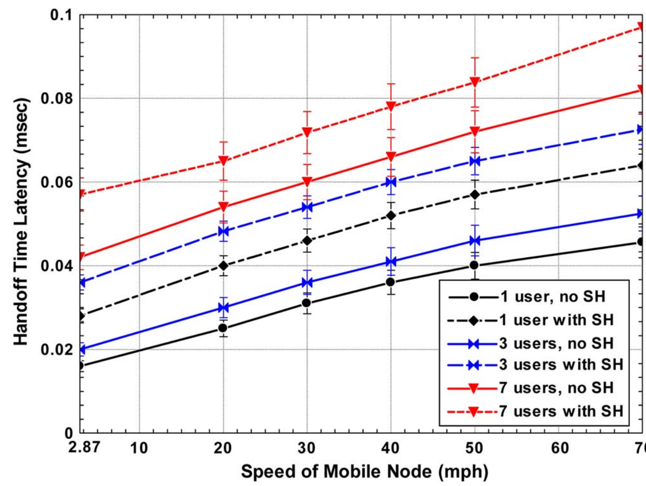

Fig. 10. Handoff time latency as a function for the mobile speed.

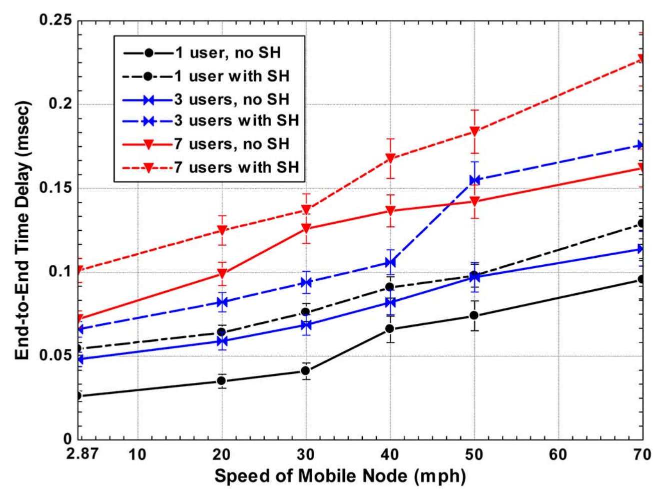

Fig. 11. End-to end time delays as a function for the mobile speed.

In Fig. 10, handoff time latency is shown for all simulated numbers of MNs as a function of the mobile speed. The figure depicts that there are considerable time savings using the new scheme of CAA compared to the conventional model of handoff. The figure shows that the savings in handoff time latency increase as the number of MNs increases. This signifies the importance and success of the proposed solution in practical applications that employ large numbers of cell and subcell domains. This reduction in time latency during handoff shows that a mobile user can quickly be reconnected to the destination base station and services can be maintained without interruptions.

Fig. 11 compares the end-to-end time delays for the different numbers of users who with and without are experiencing the SH events. In all of the aforementioned cases, the end-to-end delay time is increasing with higher mobile user speeds. The reason for this is that major time delays are incurred as the speeds of cognitive MNs increase, causing more handoffs to occur as users move between various femto- and macrodomains. However, the cancellation of SH that results from the installation of CAA entity provides in much lower time delays, as depicted by the figure for all simulated cases.

The throughput in Fig. 12 shows also a major improvement with the application of CAA and no SH events. For all

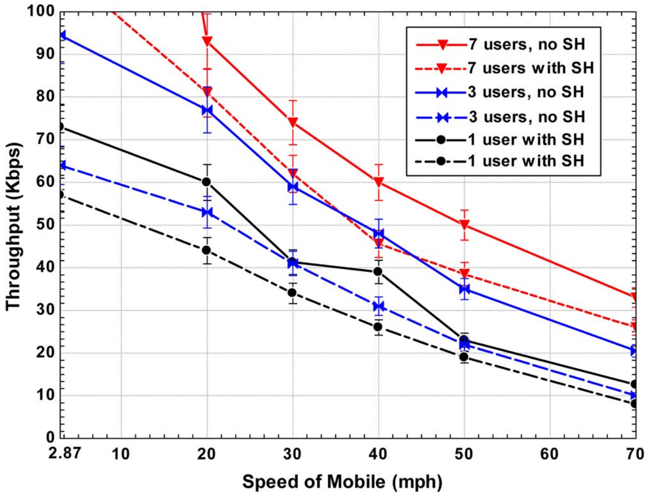

Fig. 12. Throughput as a function for the mobile speed.

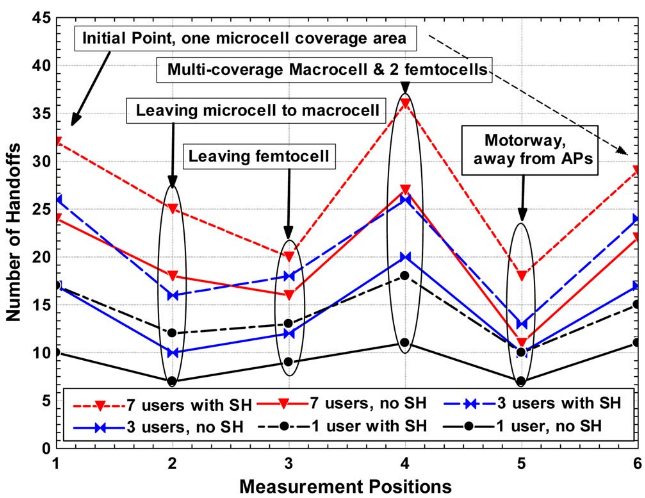

Fig. 13. Number of handoffs versus mobile locations as shown in Fig. 9.

simulated cases, the throughput is higher than the case for the traditional SH. The explanation for this is that the time spent in the adaptation between various channels reduces the performance of the system. This interruption time impacts the overall time delay in Fig. 11 and the throughput in Fig. 12. It can be noticed also that the performance of the simulated system is declining slowly with the increment of the MN speeds. This is due to the fact that a speedy MN loses some local transmission opportunities that are available at scattered locations in the macro- and femtodomains. Therefore, the faster the MNs become, the lowest the ability to attain local transmission opportunities.

Fig. 13 shows the reduction in the number of handoffs due to the CAA installation. Clearly, there is lower number of handoffs occurring when MNs travel between the different coverage areas, as shown in Fig. 8. The measurement points were selected to show the improvement in performance at the most prominent points of SH events. It can be noticed that the number of handoffs is increasing as the MNs move toward the macrocell base station (position #1 to position #2). The maximum value can be seen when MNs are within the coverage area of three sources: macrocell and two femtocells at position #4. Afterward, the handoff shows the lowest values as the MNs travel along the motorway within macrocell coverage at position #5. At the end, the handoff values increase again as the MNs return home to the initial point of their journey (position #1). Generally, more handoffs occur while moving between heterogeneous domains rather than homogeneous domains or one domain scenario.

In summary, the CAA entity that maintains channels to cognitive MNs improves the performance in accessing the spectrum and reduces the numbers of handoffs incurred due to the frequency adaptations.

VII. Conclusion

A new scheme has been proposed to reduce the SH in future cognitive radio networks that employ small cells such as femtocells. A new entity named CAA is introduced at the mobile IP to allocate the same channel used by a cognitive mobile user as it moves between subcell areas. The main goal of this design is to reduce the interruption time that occurs during frequency adaptation and the redundant unnecessary SHs for a mobile user traveling at various speeds. The solution involved the design of handoff algorithms that scan the available band for the channel in operation before any decision of adapting to other frequencies. Then, a comprehensive assessment was conducted to evaluate the suitability of the free time interval within the selected channel to host the cognitive MN packets. Results show considerable improvement in throughput with less number of handoffs and major savings in time delay using the proposed scheme.

References

[1] C.-W. Wang and L.-C. Wang, "Analysis of reactive spectrum handoff in cognitive radio networks," *IEEE J. Sel. Areas Commun.*, vol. 30, no. 10, pp. 2016–2028, Nov. 2012.

[2] Y.-S. Chen and J.-S. Hong, "A relay-assisted protocol for spectrum mobility and handover in cognitive LTE networks," *IEEE Syst. J.*, vol. 7, no. 1, pp. 77–91, Mar. 2013.

[3] Z. Yan and J.-H. Lee, "State-aware pointer forwarding scheme with fast handover support in a PMIPv6 domain," *IEEE Syst. J.*, vol. 7, no. 1, pp. 92–101, Mar. 2013.

[4] C. Makaya and S. Pierre, "An architecture for seamless mobility support in IP-based next-generation wireless networks," *IEEE Trans. Veh. Technol.*, vol. 57, no. 2, pp. 1209–1225, Mar. 2008.

[5] T. Taleb and K. Letaief, "A cooperative diversity based handoff management scheme," *IEEE Trans. Wireless Commun.*, vol. 9, no. 4, pp. 1462–1471, Apr. 2010.

[6] L.-C. Wang, C.-W. Wang, and C.-J. Chang, "Optimal target channel sequence design for multiple spectrum handoffs in cognitive radio networks," *IEEE Trans. Commun.*, vol. 60, no. 9, pp. 2444–2455, Sep. 2012.

[7] Y. Song and J. Xie, "ProSpect: A proactive spectrum handoff framework for cognitive radio *ad hoc* networks without common control channel," *IEEE Trans. Mobile Comput.*, vol. 11, no. 7, pp. 1127–1139, Jul. 2012.

[8] S. Zheng, X. Yang, S. Chen, and C. Lou, "Target channel sequence selection scheme for proactive-decision spectrum handoff," *IEEE Commun. Lett.*, vol. 15, no. 12, pp. 1332–1334, Dec. 2011.

[9] M. NoroozOliaee, B. Hamdaoui, X. Cheng, T. Znati, and M. Guizani, "Analyzing cognitive network access efficiency under limited spectrum handoff agility," *IEEE Trans. Veh. Technol.*, vol. 63, no. 3, pp. 1402–1407, Mar. 2014.

[10] H. Fathi, S. S. Chakraborty, and R. Prasad, "Optimization of mobile IPv6-based handovers to support VoIP services in wireless heterogeneous networks," *IEEE Trans. Veh. Technol.*, vol. 56, no. 1, pp. 260–270, Jan. 2007.

[11] L. Dimopoulou, G. Leoleis, and I. S. Venieris, "Fast handover support in a WLAN environment: Challenges and perspectives," *IEEE Netw.*, vol. 19, no. 3, pp. 14–20, May/Jun. 2005.

[12] M.-C. Chuang, J.-F. Lee, and M.-C. Chen, “SPAM: A secure password authentication mechanism for seamless handover in proxy mobile IPv6 networks,” *IEEE Syst. J.*, vol. 7, no. 1, pp. 102–113, Mar. 2013.

[13] S. Cespedes, L. Ning, and S. Xuemin, “VIP-WAVE: On the feasibility of IP Communications in 802.11p vehicular networks,” *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 1, pp. 82–97, Mar. 2013.

[14] H. Ali-Ahmad, X. Lagrange, M. Ouzzif, and P. Bertin, “Comparative cost analysis on global mobility management schemes in IPv6 mobile networks,” in *Proc. IEEE 77th VTC Spring*, Jun. 2–5, 2013, pp. 1–6.

[15] C.-M. Huang, C.-H. Lee, and J.-R. Zheng, “A novel SIP-based route optimization for network mobility,” *IEEE J. Sel. Areas Commun.*, vol. 24, no. 9, pp. 1682–1691, Sep. 2006.

[16] J.-T. Park, S.-M. Chun, J.-H. Choi, and S.-M. Lee, “Simple mobility management protocol for global seamless handover,” in *Proc. IEEE CCNC*, Jan. 14–17, 2012, pp. 677–681.

[17] K. I. Pedersen, P. H. Michaelsen, C. Rosa, and S. Barbera, “Mobility enhancements for LTE-advanced multilayer networks with inter-site carrier aggregation,” *IEEE Commun. Mag.*, vol. 51, no. 5, pp. 64–71, May 2013.

[18] T. Kim and J. Lee, “Mobility and QoS support in 4G wireless networks,” *J. Commun. Netw.*, vol. 7, no. 2, pp. 178–191, Jun. 2005.

[19] T. Taleb, A. Jamalipour, Y. Nemoto, and N. Kato, “DEMAPS: A load-transition-based mobility management scheme for an efficient selection of MAP in mobile IPv6 networks,” *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 954–965, Feb. 2009.

[20] A. Al-Dulaimi, S. Al-Rubaye, and J. Cosmas, “Adaptive coexistence between cognitive and fibre networks,” in *Proc. Wireless Multi-Access Environ. Quality Service Provisioning: Solutions Appl.*, G. M. Muntean and R. Trestian, Eds., 2011, pp. 311–336, PA, USA: IGI Global.

[21] O. Jo and D.-H. Cho, “Seamless spectrum handover considering differential path-loss in cognitive radio systems,” *IEEE Commun. Lett.*, vol. 13, no. 3, pp. 190–192, Mar. 2009.

[22] A. Motamedi and A. Bahai, “MAC protocol design for spectrum-agile wireless networks: Stochastic control approach,” in *Proc. 2nd IEEE Int. Symp. DySPAN*, Apr. 17–20, 2007, pp. 448–451.

[23] A. Al-Dulaimi, H. S. Al-Raweshidy, J. Cosmas, and J. Loo, “Cognitive mesh networks,” *IEEE Veh. Technol. Mag.*, vol. 5, no. 3, pp. 54–60, Sep. 2010.

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