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Availability-Aware Resource Allocation Strategy for Heterogeneous Cognitive Radio Networks

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Abstract: This paper addresses high availability for resource allocation, which might be found in cognitive radio networks so as to optimize network performance. Two resource allocation strategies, the High Available Spectrum Allocation (HASA) and the Optimized Heterogeneous Convergence (OHC), are developed by establishing and numerically solving two optimization multicast applications. The HASA is to minimize the required network-wide resource for scheduling and routing jointly via availability constraints, while the OHC strategy does not degrade response time for network convergence over heterogeneous wireless environment. The effectiveness of both strategies is demonstrated through theoretical analysis. These strategies are also evaluated through extensive experimental studies and the results show that when compared with traditional strategies, the proposed spectrum allocation schemes significantly improve the performance of spectrum scheduling in multicast applications, both in terms of the discovery time and the achieved ratio. *Copyright © 2013 IFSA.*

Keywords: Cognitive radio networks, High availability, Heterogeneity, Scheduling, Dynamic spectrum access.

1. Introduction

Since its inception, cognitive radio (CR) is a core technology that seeks to overcome the spectral shortage problem by enabling secondary wireless devices to communicate without interfering with the primary users [1, 2]. In a cognitive radio networks (CRN), each node is equipped with a CR, which employs cooperative relay technology for increasing transmission diversity gain in various types of wireless networks [3]. Such cooperative relay between secondary nodes can improve spectrum diversity and thus, a CRN dynamically provide high bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access (DSA) techniques [4]. In addition to DSA, CR's spectrum rich node is selected, as the relay node to improve the performance between the source and the destination. It is envisioned that CRN will be accepted as a general radio platform upon which numerous wireless applications can be implemented.

In parallel to the development of CRN for heterogeneous wireless architectures, high availability [5], has widely been implemented and deployed in commercial wireless products to increase throughput. To date, the research and development of high availability are largely independent and orthogonal to CRN [6]. In particular, many end-to-end performance require wireless platforms with high availability, since severe damage or fatal errors could occur when even only one computing node becomes unavailable [7]. Further, a scheduling strategy for heterogeneous systems has to factor in availability to deal with unexpected failures.

Currently, the advances of CRN (see, *e.g.*, [8-10]) and high availability (see, *e.g.*, [11-13]) are largely independent and parallel to each other. Recognizing the joint potential of CRN and high availability, the wireless service providers thus face unique challenges since spectrum availability of the leased channel is time-varying due to spectrum usage patterns of the legacy users [14]. In particular, researchers are interested in how such availability constraints will affect the throughput of each user communication session in a CRN, where a user communication session is defined as an information flow from a source node to its destination node. The main challenges to the efficient development of CRN include primary user detection and transmission opportunity exploitation.

In this paper, this trade-off problem is investigated. The answer to this question is important as it will show whether or not joint optimization of both technologies is necessary, given that a CR is capable of reconfiguring RF and switching to newly-selected frequency bands. This joint optimization problem is formulated into a mathematical program with the goal of maximizing the minimum throughput among user sessions.

2. Model Description and Problem Formulation

2.1. Heterogeneity Design for Multiple Overlays

In view of the complexity and range of control and management functions required, it is clear that the functionality of a CRN should be partitioned into three parts: 1) service overlay, 2) control overlay and 3) cognitive overlay. As Fig. 1 shows, in control overlay, the control streams are communicated in every layer protocol, where the heterogeneous networks include GSM, WCDMA, TD-SCDMA, WLAN, 802.22, WiMax. The control overlay protocol stack on each node contains the modules needed to support data communication between the wireless nodes and it exposes a set of controls for each module through an API. This API is used by a general and extensible control overlay to monitor, configure, and adapt the control overlay modules.

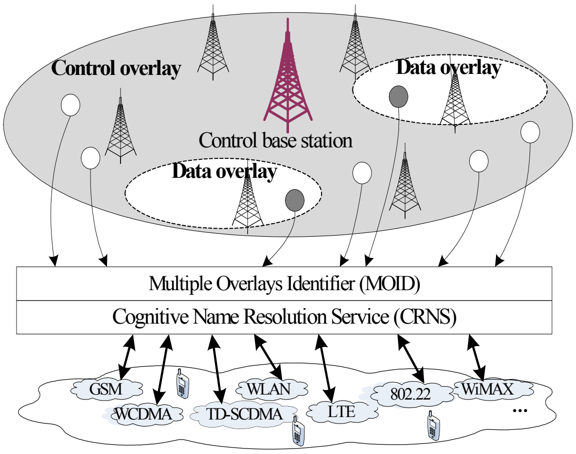

Fig. 1. Multiple plane overlays.

As for spectrum coordination, each node has a dedicated control interface along with data interface. The control interface provides an initial radio bootstrapping and service discovery function that can operate either on a frequency bands at the edge of the service band or a dedicated portion of a TDMA frame, and would have wider radio coverage than a typical service frequency band. The bootstrapping functions can utilize other nodes to rebroadcast control packets using a controlled flooding mechanism, thus, providing global awareness to all CRs within a subnet-work.

The multiple overlays framework is based on the idea of separating names of end-users or other network-connected objects, and their routable addresses or locators. Separation of names and addresses makes it possible for mobile devices to have a permanent, location independent name or Multiple Overlays Identifier (MOID) which can then be mapped to a set of routable network addresses corresponding to the CR nodes of attachment. This aims to integrate a Cognitive Name Resolution Service (CNRS) as a basic by end-user devices and CRN routers, base stations and CR nodes.

This concept is illustrated in Fig. 1 which shows the layering of functionality in the proposed architecture. The design consists of a set of application specific name assignment services which translate human readable names such as “cognitive node@xyz” or “ABC base station” to MOIDs. This framework also supports the concept of context-based descriptors such as band in New Brunswick which can be resolved by a context naming service to a particular MOID which serves as a dynamic multicast group for all bands currently in that area. The MOID is then assigned to the mobile device and entered into the network-level CNRS service shown in the figure. The CNRS is a distributed network service which is responsible for maintaining the current bindings.

2.2. The Global Convergence Process

Fig. 2 shows the architecture of the heterogeneous convergence system running on a typical node N_i, where i=1,2,…,n. In this system, each cognitive node keeps a row vector of trust matrix based on its outbound local convergence scores. In addition, each cognitive node also maintains a global convergence vector $V(t)$ at aggregation cycle t. Internally, this vector is represented by a collection of <*node_id*, *score*> pairs. At the first aggregation cycle, $V(0)$ is initialized with equal global convergence scores, *i.e.* $v_i(0)=1/n$, i=1,2, …, n.

This process continues until the allocated scores converge in g steps, where g is determined by a set error threshold ε . After the convergence of allocating steps, this system continues the next aggregation cycle until the global convergence vectors converge in d cycles, where d is determined by the aggregation error threshold δ. To reduce the memory on each node, a novel HASA scheme is designed for storage and retrieval of global priorities.

It considers a queuing architecture of a heterogeneous system in which *n* nodes are connected via a network to process independent *m* priorities of non-preemptive bands submitted by *m* users. Both *m* and *n* are finite integers that are greater than or equal to 1. Let $N = \{n_1, n_2, \ldots, n_j, \ldots, n_n\}$ denote the set of heterogeneous cognitive nodes. It is assumed that the nodes differ only in their speeds and availability levels. The system architecture model, depicted in Fig. 2, is composed of a band schedule queue, a High Available Spectrum Allocation (HASA) band scheduler, and *n* local band queues.

A schedule queue is used to accommodate incoming bands. The HASA scheduler then processes all arrival bands in a First Come First Served manner. The cognitive nodes, each of which maintains a local queue, can execute bands assignment in parallel. The centerpiece of the system architecture model is HASA, which is composed of three modules: 1) the Availability Provider Tracker (APT), 2) the Availability Cost Analyzer (ACA), and 3) the Load Imbalance Tracker (LIT). For bands assignment of each priority, the APT is utilized to find all nodes that can meet the band availability requirements and put these nodes in the set N_i.

3. Modeling Priority-based Bands with Availability Requirements

3.1. Modeling Priority-based Bands with Availability Requirements

Given that *m* priorities of bands are submitted to a heterogeneous CRN by users. Each priority of bands requires a common availability specified. Values of availability levels are normalized in the range 0~1.0. Without loss of generality, it is assumed that the bands of the *i*th($1 \le i \le m$) priority arrive concerning a Poisson process with rate ξ_i. All priorities of bands arrive at CRN at an aggregate rate of $\xi = \sum_{i=1}^{m} \xi_i$. Let P_{ij} be the probability that the bands of the *i*th priority are dispatched to node *j*, $1 \le j \le n$. Then, the aggregate band arrival rate of the *j*th node is $\zeta_j = \sum_{i=1}^{m} P_{ij}\xi_i$.

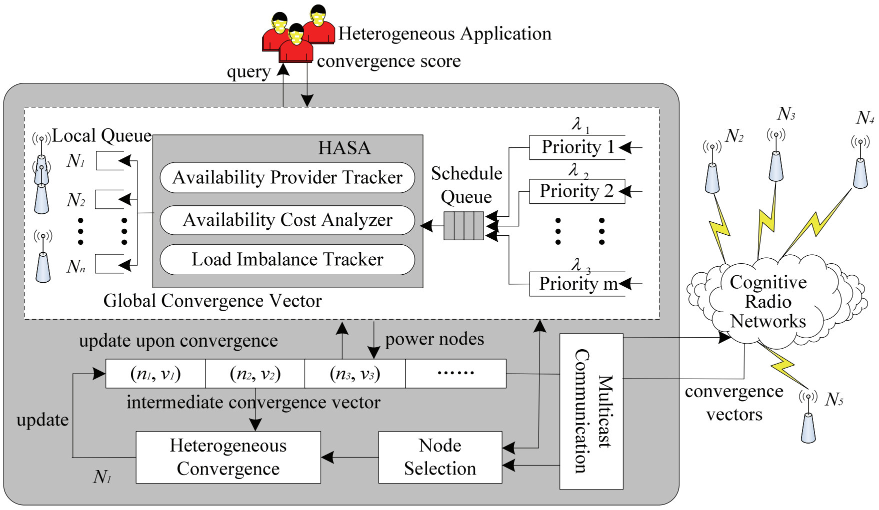

Fig. 2. Heterogeneous Convergence and global convergence process.

Let a_{ij} be the service rate of bands in priority *i* assigned on node *j* and the corresponding expected service time is computed by $1/a_{ij}$. Consequently, the allocating utilization of priority *i* and the spectrum utilization for all bands allocated to node *j* can be obtained as follows can be written as

$$\theta_i = \sum_{j=1}^{n} \left(P_{ij}\xi_i / a_{ij} \right), \tag{1}$$

$$\sigma_j = \sum_{i=1}^{m} \left(P_{ij}\xi_i / a_{ij} \right), \tag{2}$$

Each node in CRN can be modeled as a single M/G/1 queue [15]. Let $E(\rho_j)$ and $E(\rho_j^2)$ be the mean and mean-square allocating times. Thus, the average response time of node *j* can be computed as

$$ATN_j = E(\rho_j) + \frac{\zeta_j E(\rho_j^2)}{2(1-\sigma_j)}, \tag{3}$$

The expected response time ETP_i of the *i*th priority bands can be readily derived from the average response times of the nodes. Hence, ETP_i is given as follows:

$$ETP_i = \sum\nolimits_{j=1}^{n} \left(P_{ij} \cdot ATN_j \right), \tag{4}$$

To minimize the average response time without taking availability constraints into account, it has to balance the load of the nodes by evenly distributing the spectrum resource. That is, the process for making all the node equal-spectrum utilization results in a perfect load balance. It has

$$\sigma_j = \sum\nolimits_{i=1}^{m} \left(P_{ij} \xi_i / a_{ij} \right) = \sigma_0, \tag{5}$$

Let ar_i be the availability requirement of band priority i. The availability shortage factor ASF_{ij} of band priority i on node j is estimated as a step function. Thus, it has

$$ASF_{ij} = \begin{cases} 0, & \text{if } ar_i \le \lambda_j \\ ar_i - \lambda_j, & \text{otherwise} \end{cases} (0 \le ar_i \le \lambda_j \le 1), \tag{6}$$

The availability shortage of node j is calculated based on the availability factor as

$$AS_j = \sum\nolimits_{i=1}^{m} \frac{P_{ij}\xi}{\zeta_j ASF_{ij}} = \frac{1}{\zeta_j} \sum\nolimits_{i=1}^{m} P_{ij} \xi_i ASF_{ij}, \tag{7}$$

where $\zeta_j = \sum\nolimits_{i=1}^{m} P_{ij} \xi_i$.

Specifically the availability of the CRN is modeled for all of the priorities as below. Let $\tilde{A}_j$ be the unavailable rate of node j. Since the availability model relies on the concept of availability cost, the availability cost of priority i on node j can be introduced using

$$ASP_{ij} = P_{ij} \frac{\tilde{A}_j}{a_{ij}}, \tag{8}$$

Thus, the availability cost A_i of priority i is derived from above as follows:

$$C_i = \sum\nolimits_{j=1}^{n} C_{ij} = \sum\nolimits_{j=1}^{n} P_{ij} \frac{\tilde{A}_j}{a_{ij}}, \tag{9}$$

3.2. Optimized Heterogeneous Convergence with Load Imbalance Detection

Also, each node in the Optimized Heterogeneous Convergence (OHC) model is inherently heterogeneous in both allocation method and availability level. The allocation heterogeneity of the ith priority AHP_i can be measured. Thus,

$$AHP_i = \sqrt{\frac{1}{n} \sum\nolimits_{j=1}^{n} (\tilde{\omega}_i - \omega_{ij})^2}, \tag{10}$$

where $\bar{\omega}_i$ is the average allocation weight.

Note that the availability level offered by a node is orthogonal to its allocation method. LIT uses load index LIT_j, defined as follows to measure relative band frequency of node:

$$LIT_j = \frac{\sigma_j}{\sigma / n}, \tag{11}$$

where σ_j is the spectrum utilization of node j, and ϕ / n is the average node spectrum utilization of the whole CRN.

4. The Availability-Aware Scheduling Algorithm

Now the HASA scheduling strategy is presented, which is intended to determine the probability in a heterogeneous way to improve the availability while maintaining good performance in response time.

A-HASA: Available Scheduling Strategy for HASA with Availability Constraints

Initiation:

Preprocessing, set up the trade-off problem, and label spectrum priorities.

Iteration:

```
1. For each class i, Initialize the availability cost and response time in priority i with a set $N_i$ of nodes, node $j \in N_i$ .
2. If ( $N_i = \sigma$ ) {for each node j in CRN, calculate the availability cost of priority i on node j, $ASP_{ij}$.
3.     If ($ASP_{ij} < ASP$) or ($ASP_{ij}=ASP$ and $C_i < C$ ) update $ASP_{ij}=ASP$, update $C_i \leftarrow C$, $v \leftarrow j$, and go to step 1.}
4. Otherwise {for each node j in $N_i$, evaluate expected response time of priority i, $C_i$.
5.     If $C_i < C$ update $C_i \leftarrow C$, $v \leftarrow j$, and go to step 1.}
6. Find a feasible solution with multicast communication.
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The HASA algorithm is divided into A-HASA and L-HASA. In A-HASA, it firstly determines if there exists at least one node whose availability shortage factor for priority i. Given a possibility that node set N_i is empty, no node in the heterogeneous CRN is capable of guaranteeing the availability constraint of priority i. In this phrase, it can make an effort to improve CRN availability derived from.

L-HASA: Load Imbalance Detection Scheduling Strategy for HASA with Availability Constraints

Initiation:

Assume node 1 is the lightest load node and its node index is ∞.

Main loop:

```
1. For each node $n_j \in N$ calculate its load index $L_j$.
2. Load imbalance tracker distributes the schedule queue to different local queues according to global convergence vector.
3. If $L_j < L_{\min}$ , $L_{min}=L_j$, $N_{min}=j$.
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4. If node v is not overloaded, determine that priority i to node v, allocate priority i to node v, else allocate priority i to node n_{min}.
5. Export the estimation results into heterogeneous applications.

L-HASA determines the load index value L_j for each node j in the CRN and finds a node n_{min} with the lightest load L_{min}. The mean response time of all of the priorities is further reduced through load imbalancing tracker. In practical, in case node v is overloaded, it allocates priority i to a node with the lightest load.

5. Simulated Performance Results

For the ease of exposition, all units for priority, average response time, expected response time, availability shortage factor are normalized with appropriate convergence. This experiment is repeated for 5, 10 and 20 MHz frequency band widths by HASA, with varying the traffic intensity [16]. All the reported numbers are over 10 runs.

Now the performance of the A-HASA and L-HASA algorithms is evaluated in convergence process of cognitive nodes. Two CR devices are set up, with configured one as a cognitive node and the other as a client. These cognitive node started to beacon on a randomly chosen frequency band and width. It then measures the time for the client to schedule nodes using A-HASA and L-HASA.

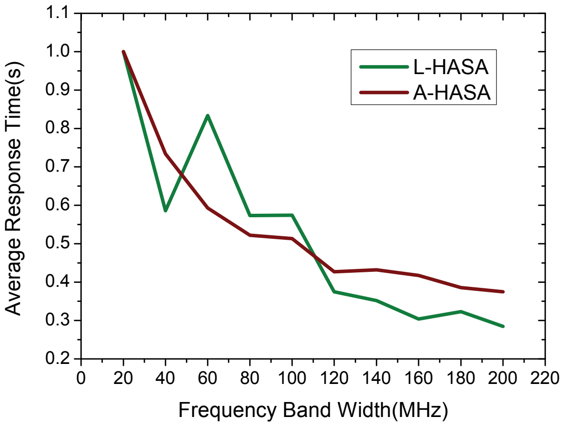

Fig. 3. Reduction in average response times using A-HASA and L-HASA.

In Fig. 3, the number of UHF frequency bands is varied in the fragment from 1 to 40, since 40 are the total number UHF frequency bands that are available to portable cognitive nodes. The average response time taken by A-HASA and L-HASA is plotted to schedule cognitive nodes as a fraction of the total time. According to availability constraints, A-HASA outperforms L-HASA initially since it does not require the convergence of trying to find the proper placing of the cognitive node frequency band. As exactly predicted by load imbalance detection, L-HASA becomes more efficient for white spaces spanning more than 10 UHF frequency bands.

Apart from detecting frequency band width, HASA is also utilized to measure the expected response time utilization for spectrum assignment algorithm. It is clear that HASA performs as expected in Fig. 4. The total time occupied by the packets doubles on halving the frequency band width. It stems from the observation that halving the frequency band width also halves the effective transmission rate. Given that the same number of packets is sent at a given width, the expected response time is constant, even when it changes the rate of injected packets.

Figs. 5 and 6 show the achieved opportunity ratios of convergence and non-convergence schemes. Note that the same frequency band can be used by multiple priorities with availability constraints. In both figures, the achieved opportunity ratio demonstrates the superiority of the proposed HASA algorithm. The convergence scheduling is found to have more opportunities than the previous sensing schemes without sensing-period convergence. This increase could be greater as the initial sensing period grows.

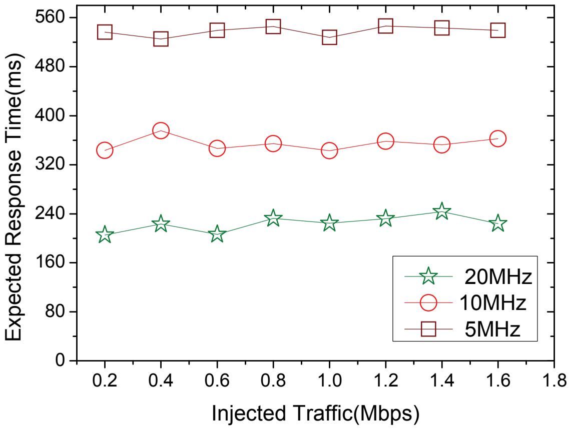

Fig. 4. Accuracy of air time utilization measurement.

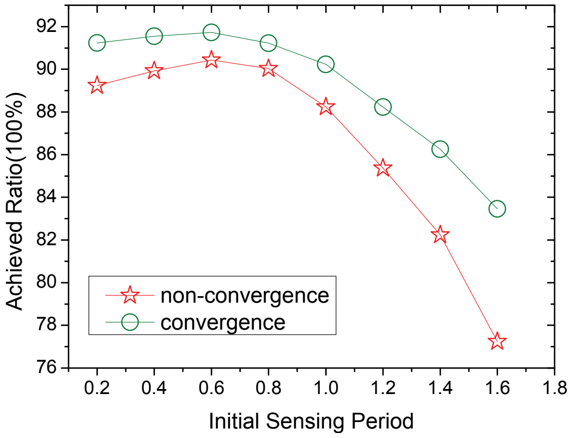

Fig. 5. Homogeneous case: achieved opportunity ratio.

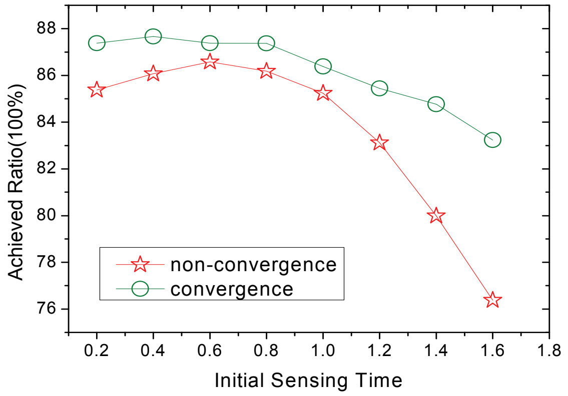

Fig. 6. Heterogeneous case: achieved opportunity ratio.

6. Conclusion

In sum, this paper addresses the resource allocation for CRN with high availability constraints. Multicast sessions are characterized by the allocation time and availability requirements by taking priorities into account. The High Available Spectrum Allocation (HASA) is proposed. To meet the convergence vectors in a CRN, the optimized heterogeneous convergence to gain the global convergence process is obtained. Finally, a priority-based spectrum allocation schemes is proposed, and an efficient dynamic distributed design with for the discovery time and the achieved ratio is given that achieves more flexible, efficient, and fair spectrum usage. Simulation and experimental results prove that the use of scheduling and routing jointly is a good design method.

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