Dynamic Frequency Allocation Based On Graph Coloring and Local Bargaining for Multi-Cell WRAN System

Yuqin Chen, Ning Han, SungHwan Shon, and Jae Moung Kim
Graduate School of IT and Telecommunication
INHA University, Incheon, Korea

Abstract—WRAN system is a new standard under establishment to improve the efficiency of spectrum utilization and spectrum allocation scheme is one of its key techniques. In this paper, one spectrum allocation scheme called “pre-allocation and local bargaining” is proposed to avoid intra-cell and inter-cell co-channel interference among users. Based on color sensitive graph coloring problem and local bargaining, our scheme has the ability to guarantee the fairness among users and satisfy the user's minimum requirement of spectrum bandwidth.

Index terms—dynamic spectrum allocation, color sensitive graph coloring, local bargaining, WRAN system

A. INTRODUCTION

In conventional fixed spectrum allocation schemes, to eliminate interference between different wireless technologies, policies allocate a fixed spectrum splice to each wireless technology. The static spectrum assignment leads to underutilization of electromagnetic resource. Cognitive Radio (CR) [1], based on software-defined radio, has been proposed as the technology to improve the efficiency of the spectrum. In CR, spectrum utilization is significantly improved by making it possible for a secondary user to access a spectrum hole unoccupied by the primary user at the right location and time. Based on the proposed CR technique, the IEEE 802.22 WRAN standard is being established. WRAN system utilizes the spectrum holes of the DTV service, of which the operating spectrum band is between 54MHz and 862MHz. This standard is intended to enable deployment of interoperable 802 multivendor wireless regional area network products, to facilitate competition in broadband access by providing alternatives to wireline broadband access and extending the deployability of such systems into diverse geographic areas, including sparsely populated rural areas, while preventing harmful interference to incumbent licensed services in the TV broadcast bands [2]. Sensing and dynamic frequency selection are two key techniques of WRAN system. During sensing procedure, necessary information such as the available spectrum information is assembled and then dynamic frequency selection is processed. The objective of our dynamic frequency selection is not only maximizing the spectrum utilization and also guaranteeing the fairness among users, which means each user should be assigned at least the minimum required bandwidth.

To achieve our target, dynamic spectrum allocation scheme in Ad-hoc networks is used for reference, the channel assignment problem is reduced to a graph multi-coloring problem by mapping each channel into a color [3][4]. This topology-optimized allocation algorithm begins with no prior information, and assigns each user an optimal assignment. In our work, to avoid intra- and inter-cell co-channel interference among users, the graph coloring method via local bargaining is adopted and an allocation procedure is proposed to provide the fairness among users and reduce the complexity caused by new arrival and mobile users.

We propose an allocation procedure called “pre-allocation and local bargaining” in this paper. In the beginning, necessary information such as the users’ position information and the available channel information should be assembled by initialization. After initialization, all users are pre-allocated some channels according to the color sensitive coloring graph. Unfortunately, it is probable that some users cannot achieve enough channels to satisfy its minimum transmission data rate. To avoid the unfairness among users, local bargaining is processed then in order to meet the minimum required bandwidth for all users.

B. BACKGROUND OF SPECTRUM ALLOCATION

1st. Assumptions

We assume that the available spectrum is divided into a set of spectrum bands, and that bands differ from each other in bandwidth and transmission range. We also assume that spectrum bands are orthogonal, and that users can utilize a number of spectrum bands at one time. It is also assumed that the users (CPE in WRAN case) have assembled the available spectrum information through sensing procedure. The users in the same cell cannot transmit data between base station by the same band simultaneously due to the intra-cell co-channel interference. What’s more, users from adjacent cells locating within a constrained distance also suffer conflicts when they select the same channels at the same time. To solve this, a simplified interference metric is
applied to represent this co-channel interference problem, and then a proposed spectrum allocation procedure is operated.

The essence of spectrum allocation is to assign appropriate spectrum bands among users so that they can coexist. In this paper, our objective is to successfully allocate spectrum bands to users without conflicts in order to satisfy the minimum transmission data rate requirement in the WRAN system.

2nd. Problem Model and Definitions

We consider the case where the collection of available spectrum ranges forms a spectrum pooling, divided into non-overlapping orthogonal channels. We assume in one cell N users indexed from 0 to N-1 competing for M spectrum channels indexed 0 to M-1. Each user, according to its particular geometric position and environment, has its own spectrum pooling. We modeled the system as mentioned in the WRAN standard requirement, the total spectrum bands are between 54MHz and 862MHz, divided into 6MHz sub-bands by DTV users. Other primary users also include wireless microphone users and medical telemetry users, etc. The secondary users obtain their environment information through sensing technique, consisting of global geometric position and available spectrum pooling information. Each user selects appropriate communication channels and adjusts transmit power accordingly to avoid interfering with primaries. The spectrum access problem becomes a channel allocation problem such as obtaining a conflict free channel assignment for each user which satisfies the minimum transmission data rate requirement.

1. Channel availability \( L(n) \).

\[
\Gamma = \{ l_{m,n} : l_{m,n} \in \{0,1\} \}_{M \times N}
\]

is a \( M \) by \( N \) binary matrix representing the channel availability: \( l_{m,n} = 1 \) if and only if channel \( m \) is available at user \( n \). In general, \( l_{m,n} = 0 \) when channel \( m \) is occupied by a primary user who conflicts with user \( n \), so that the transmissions of \( n \) on this channel will interfere with the primary’s activity if they use channel \( m \) concurrently. Let \( L(n) = \{ 0 \leq m \leq M - 1 | l_{m,n} = 1 \} \) be the set of channels available at \( n \)[3].

2. Interference constraints \( C \).

Let \( C = \{ c_{n,k} : c_{n,k} \in \{0,1\} \}_{N \times N} \) a \( N \) by \( N \) matrix, represents the interference constraints among users. If \( c_{n,k} = 1 \), users \( n \) and \( k \) would interfere with each other if they use the same channel. The interference constraint depends on the signal strength of transmission and the distance between users. A simple mode of interference constraints is the binary geometry metric, i.e. two users coming from different cells conflict if they are within \( \pi \) distance from each other.

3. Conflict free assignment \( A \).

\[
A = \{ a_{m,n} : a_{m,n} \in \{0,1\} \}_{M \times N}
\]

where \( a_{m,n} = 1 \) denotes that spectrum band \( m \) is assigned to user \( n \), otherwise 0. \( A \) satisfies all the constraints defined by \( C \), that is ,

\[
a_{m,n} + a_{m,k} \leq 1, \text{if } c_{n,k} = 1, \forall n,k < N, m < M.
\]

Let \( \Lambda_{N,M} \) denotes the set of conflict free spectrum assignments for given set of \( N \) users and \( M \) spectrum bands.

4. Maximum and minimum required bandwidth. Most of previous spectrum assignment methods considered providing optimum spectrum utilization, while, in our case, the fairness among users is more important. So our model’s objective is to satisfy each user’s minimum required bandwidth.

3rd. Color-Sensitive Graph Coloring

In [4], it is shown that by mapping each channel into a color, the channel assignment problem can be reduced to a graph multi-coloring problem. We define a bidirectional graph \( G = (U, E_C, L_B) \) where \( U \) is a set of vertices denoting the users that share the spectrum, \( L_B \) represents the available spectrum bandwidth, or the color list at each vertex, and \( E_C \) is a set of undirected edges between vertices representing interference constraints between two vertices. For any two distinct vertices \( u, v \in U \), a \( m \)-color edge between \( u \) and \( v \), is in \( E_C \) if and only if \( c_{u,v,m} = 1 \). Hence, any two distinct vertices can have multiple colored edges between them. We define the color \( m \) specific degree of a vertex \( u \), i.e., \( D_{u,m} \) to represent the number of neighbors that are color \( m \) mutually constrained with \( u \) (those who can not use \( m \) if \( u \) uses color \( m \)). It is also a relatively good measure of the impact (to neighbors) when assigning a color to a
vertex. The equivalent graph coloring problem is to color each vertex using a number of colors from its color list, such that if a color \( m \) edge exists between any two distinct vertices, they can’t be colored with \( m \) simultaneously. We name this the color-sensitive graph coloring (CSGC) problem \([4]\).

Fig. 1 illustrates an example of CSGC graph. There are five colors available. The numbers outside the brackets attached to each node denote the colors assigned to that node, while the numbers inside the brackets denote the available color list of each node.

![Fig. 1. An example of GMC graph](image)

A CSGC problem is to color each vertex using a number of colors from its color list, and find the color assignment that maximizes system utility. The coloring is constrained by that if an edge exists between any two distinct vertices, they can’t be colored with the same color. Most importantly, the objective of coloring is to maximize system utility. This is different from traditional graph color solutions that assign one color per vertex. Notice that the solution to this graph coloring problem is to maximize system utility for a given graph, i.e. a given topology and channel availability. This characterizes the optimal solution for a static environment.

The optimal coloring problem is known to be NP-hard. Efficient algorithms to optimize spectrum allocation for a given network topology exist. In \([4]\), the authors presented a set of sequential heuristic based approaches that produce good coloring solutions. The algorithm starts from the empty color assignment and iteratively assigns colors to vertices to approximate the optimal assignment. In each stage, the algorithm labels all the vertices with a non-empty color list according to some policy-defined labeling. The algorithm picks the vertex with the highest valued label and assigns the color associated with the label to the vertex. The algorithm then deletes the color from the vertex’s color list, and from the color lists of the constrained neighbors. The color list and the interference constraint of a vertex keep on changing as other vertices are processed, and the labels of the colored vertex and its neighbor vertices are modified according to the new graph. The algorithm can be implemented using a centralized controller who observes global topology and makes decisions or through a distributed algorithm where each vertex performs a distributed voting process. Results in \([4]\) show that the heuristic based algorithms perform similarly to the global optimum (derived off-line for simple topologies), and the centralized and distributed algorithms perform similarly.

C. SPECTRUM ALLOCATION ALGORITHM FOR MULTI-CELL WRAN SYSTEM

1st. Spectrum Allocation for Multi-cell WRAN System

In WRAN system case, the users in the same cell cannot select the same spectrum bandwidth at the same time. In addition, the users coming from adjacent cells also suffer co-channel interference if they locate within the constrained distance from each other. Therefore, we consider the users as the vertices in the coloring graph. The users from adjacent cells which locate within the \( \pi \) distance are connected by the constraints with the edge. Fig. 2 illustrates the CSGC example of multi-cell WRAN system. At the boundaries of the cells, users coming from different cells conflict each other while selecting the same spectrum at the same time.

![Fig. 2. CSGC example of multi-cell WRAN system](image)

The spectrum allocation for multi-cell WRAN system begins from the central cell and then to the outer cells. And an allocation approach called “pre-allocation and local bargaining” is applied. In the pre-allocation stage, all users try to select the maximum required number of spectrum bandwidth. Actually, probably many users cannot be assigned enough bandwidth. To satisfy the minimum required bandwidth of all users, the users allocated with less than minimum required bandwidth have the right to borrow some bandwidth from its neighbors locating within the constraint distance. Detailed description of the spectrum allocation is following:
1. Initialization.
   In the beginning of spectrum allocation, necessary information, including the users’ global position information and the available channel information, etc, needs to be assembled by the base station through any kind of detection technique, or sensing technique. Based on the global position information, the color-sensitive coloring graph can be drawn by the base station and the users constrained by co-channel interference are connected by edges described by Fig. 1. And then we calculate the value:
   $$\text{ratio} = \frac{\text{the number of connected user}}{\text{the number of total available bands}}$$
   of each user. The numerator denotes the number of competing users and the denominator shows the available spectrum source it has. Therefore, larger value means worse situation for allocation and this is our policy-defined labeling mentioned in part B.

2. Pre-allocation.
The allocation operation is applied cell by cell, and starts from the central cell. During this operation, each user tries to achieve the maximum spectrum bandwidth as it requires. According to the heuristic approach, the user with highest labeling is picked up first to allocate channels from the available spectrum pooling. The algorithm then deletes the allocated spectrum bands from the spectrum pooling of itself and of its constrained neighbors. In the following allocation loops, the user with the largest labeling among the left users is subsequently selected to allocate as before. This spectrum allocation procedure goes on until all users coming from all cells have been assigned appropriate spectrum channels.

3. Local bargaining among users.
   When the pre-allocation operation is finished, it is probable that some users are assigned as many channels as enough to satisfy the maximum bandwidth requirement and meanwhile the others are not able to satisfy the minimum desired bandwidth. To improve the fairness, local bargaining operation among users is proposed. The users without enough channels have the opportunity and right to borrow channels from their constrained neighbors. The base station will check the situation and judge who should lend channel source to them. This procedure improves the efficiency of fairness.

When selecting channels from the available spectrum pooling, the algorithm should better select spectrum sub-bands from different 6MHz DTV bands. The reason is to avoid shutting down all the transmission between one user and the base station when primary DTV user appears in one 6MHz band.

D. SIMULATION RESULTS
   We conduct computational simulation to evaluate our spectrum allocation approach for multi-cell WRAN system. We simulate a 19 multi-cell system, and in each cell, hundreds of users are transmitting data with base station. Co-channel interference from neighboring cells has a significant effect on the performance of the sample cell. Because the boundary cells suffer co-channel interference from fewer adjacent cells, it would show better performance than inner-located cells. Due to the performance difference between the inner-located cells and boundary cells, only the inner 7 cells are considered to evaluate the system performance. Each user has its own condition, including geometric position and information of available spectrum pooling. We further abstract the network into a conflict graph where each vertex represents a working user. The parameters in simulation are given as Tab. 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>User number per cell</td>
<td>700 ~ 1600</td>
</tr>
<tr>
<td>Maximum required channel number</td>
<td>10</td>
</tr>
<tr>
<td>Minimum required channel number</td>
<td>5</td>
</tr>
<tr>
<td>Available channel number for each user</td>
<td>21~70</td>
</tr>
<tr>
<td>Cell coverage</td>
<td>30Km</td>
</tr>
<tr>
<td>Constrained distance</td>
<td>0.5*30Km</td>
</tr>
</tbody>
</table>

Fig.3 Block Probability vs. user number in each cell
In our work, we consider only the spectrum allocation model and procedure without channel quality. So the simulation is only related to the allocation result, including the block probability versus the user number per cell, the maximum required channel number and the minimum required channel number. Fig. 3 shows the trend of block probability as user number per cell changing. Fig. 4 and Fig. 5 illustrate that the block probability is related to minimum required channel instead of maximum required channel because the algorithm guarantees the minimum required channel of users.

E. CONCLUSION AND FURTHER WORK

In this paper, we propose a spectrum allocation scheme called “pre-allocation and local bargaining” for multi-cell WRAN system. This scheme adopts the color sensitive graph coloring problem, regarding the users from different cells which will conflict with each other when they locate within constrained distance as the vertices in the graph. And each vertex should select appropriate colors without interfering with other users connected with it by constrained edge.

In our scheme, the first stage is named “pre-allocation”, during which it is tried to allocate all users spectrum bands as many as maximum requirement. Actually, some users would fail to get enough spectrum bands, therefore, the second stage called “local bargaining” is processed to reduce the block probability or guarantee the minimum bandwidth requirement. The “local bargaining” has other advantages that it is capable to reduce the complexity for new arrival and mobile users.

To evaluate our proposed scheme, computer simulation has been done. However, due to the lack of consideration about channel environment effects, our simulation results only give us an impression about the efficiency on block probability. To evaluate this model more precisely, other parameters should be considered during simulation such as the frequency domain channel response [5]. Therefore, adding and considering the practical channel effects is our further work.

REFERENCES