Enhancement of Spectrum Utilization in Non-Contiguous DSA with Online Defragmentation

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***Abstract*—Rampant dynamic spectrum allocation over time leads to creation of narrow spectrum holes which can be aggregated to fulfill the bandwidth requirements of users. Even though this approach increases the throughput, it comes at the cost of degraded spectrum utilization due to a rise in the number of required guard bands. This paper proposes a framework for online defragmentation of non-contiguous channels as a way to mitigate the wastage of spectrum in channel aggregating DSA networks. The efficiency of this framework is studied through a testbed implementation and simulations.**

***Keywords*—Cognitive Radio, DSA, Spectrum Utilization, Non-Contiguous, OFDM, USRP, GNU Radio**

I. Introduction

With the exponential growth of demand for reliable wireless services in both military and civilian radios [1], scarcity of the available spectrum proves to be a major bottleneck in keeping pace with the increasing bandwidth requirements. Various studies on spectrum utilization show that large portions of the licensed bands are effectively unused for long periods of time [2], hence the idea of Cognitive Radios (CRs) was proposed to utilize the unused spaces in an effort to increase available spectrum. The enabling technology for Cognitive Radios is Dynamic Spectrum Access (DSA), in which unlicensed or Secondary Users (SUs) sense the wireless environment and opportunistically utilize idle portions of the spectrum known as holes, to establish their communication links.

As the number of users and their requirements vary over time, the process of dynamic allocation creates spectrum holes which are too narrow to satisfy bandwidth requirements of a SU. In such cases, multiple narrow holes can be aggregated to achieve the minimum requirements. Several ideas for dynamic channel aggregation in DSA have been proposed. One approach enables aggregation by using multiple radio interfaces in CRs, where each radio interface can access only one contiguous spectrum hole [3]. The obvious constraint of this approach is that it limits the maximum number of accessible holes to the number of available radio interfaces. A popular alternative is Non-Contiguous Frequency Division Multiplexing (NC-OFDM), in which non-contiguous subsets of OFDM subcarriers are assigned to a single radio to establish an aggregated channel. This approach has shown an improvement in spectrum utilization and the overall performance of DSA networks [4], [5], [6]. However, it comes with an inherent overhead: every fragment of an aggregated channel requires guard bands on both sides to suppress cross-channel interference. These guard bands cannot be utilized for data transmission and therefore degrade spectrum utilization.

The severity of this issue is illustrated in Figure 1, in which the spectrum allocation of different secondary and Primary Users (PUs) are shown over a period of time. At t0, 3 SUs

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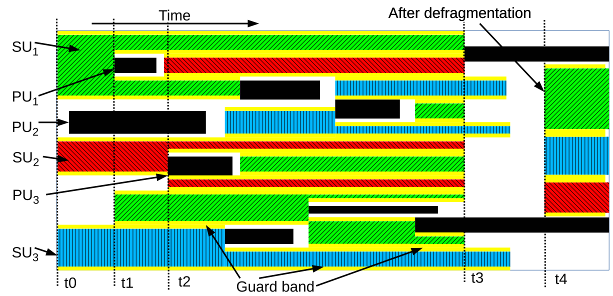


Fig. 1: An example of spectrum fragmentation problem

represented by colored blocks of red, green and blue are all utilizing contiguous blocks of spectrum, with yellow regions depicting guard bands on boundaries of these blocks. Then, beginning at t1, arrival of new PUs (black) forces the SUs to aggregate non-contiguous fragments and make up for the lost channels, hence more spectrum is dedicated to guard bands. At time t3, arrival of a PU leads to a situation where the total available spectrum is not sufficient for the SU depicted by red to utilize for its lost channels. Finally, time t4 shows that by rearranging non-contiguous fragments in bonded blocks, the bandwidth requirement of every user is met, as a smaller amount of spectrum is wasted on guard bands. It can be seen that increasing the number of fragments leads to a proportional increase in the number of guard bands, which are effectively wastage of spectrum as they cannot be utilized for data communications. Considering the purpose of DSA schemes is to achieve the highest spectrum utilization possible, mitigating techniques for the wastage issue must be investigated.

This paper proposes Online Spectrum Defragmentation as an effective solution to wastage of spectrum due to guard bands. In this method, changes in spectrum access - such as PUs vacating their channel or SUs changing their bandwidth requirements - trigger a defragmentation mechanism in the network that attempts to reduce the number of fragments by rearranging spectrum assignments, thereby reducing the number of guard bands required. Three techniques are presented for different network architectures: 1) Infrastructure Networks with a Central Controller that runs the spectrum reallocation algorithm; 2) ad hoc network running a completely distributed defragmentation algorithm; and 3) ad hoc networks with a temporarily elected "leader" overseeing the defragmentation process. All three algorithms are theoretically studied and their effectiveness and efficiency are compared based on simulation results. Also, to study the practical aspects of this approach, a prototype NC-OFDM DSA network is implemented with software defined radios, and the resultant hardware and network parameters are incorporated in the simulations.

The rest of this paper is organized as follows: Section II provides a survey of literature on efficient spectrum allocation and defragmentation in DSA networks. Section III formulates the problem and presents a detailed description and analysis of the defragmentation algorithms. Section IV describes the prototype implementation and measurements, while Section V presents the simulation results and comparisons of the algorithms. Finally, Section VI concludes the paper.

II. Related work

The problem of dynamic spectrum access has been the focus of research for many years [2]. However, investigating channel aggregation and fragmentation has only recently gained attraction. While traditional spectrum allocation algorithms assign contiguous channels to users, wireless techniques such as NC-OFDM [7] provide the possibility of spectrum aggregation, in which multiple spectrum holes can be joined together to satisfy the bandwidth requirements of a user [3].

Aggregation Aware Spectrum Assignment (AASA) [4] is one of the earlier spectrum aggregation algorithms presented in the literature. This greedy algorithm is developed based on the assumption that all users require the same amount of spectrum and uses a first-fit approach for channel assignments. In this method, a broker searches for spectrum opportunities and assigns the available channels to users starting from the lowest frequency and moving upwards. The simulation results presented in this paper demonstrate that AASA achieves a higher spectrum utilization than contiguous spectrum allocation schemes. In contrast to AASA, Maximum Satisfactory Algorithm (MSA) [5] is a best-fit algorithm developed for the case where users may have different spectrum requirements. In this approach, users with higher bandwidth requirements are prioritized as they are more difficult to fit in narrower spectrum holes. *Channel Characteristic Aware Spectrum Aggregation algorithm (CCASA)* [8] considers the heterogeneity of data carrying capacity in different parts of the spectrum. Once the channel state information of all users is known, a CCASA central controller allocates suitable spectrum fragments to the user by utilizing NC-OFDM. Using a sliding window method, CCASA calculates the maximum spectrum usage ratio for each user and allocates the spectrum to users in the decreasing order of their spectrum requirements. The work presented in [6] investigates fragmentation and aggregation in a software defined DSA prototype. They implemented a frequency agile testbed based on GNU Radio [9] and Ettus USRP [10] devices. Their framework includes a MAC overlay that senses the spectrum while receiving data, and once the requirements and access conditions change, the detected holes are dynamically allocated in a best fit manner. If a single hole is not wide enough to satisfy a user's requirements, the user then aggregates multiple narrower holes using NC-OFDM.

Even with the considerable amount of theoretical and some practical investigations on channel aggregation, the issue of guard bands and their adverse effect on spectrum utilization and the overall network performance has not been studied in the literature. The main contribution of this paper is presenting novel algorithms for solving this wastage for efficient practical implementations.

III. Theoretical Analysis

Dynamic bandwidth requirements of SUs, as well as the varying nature of spectrum allocation in DSA networks, necessitate agile mechanisms for efficient utilization of every available space in spectrum. Even though in theory orthogonal carrier frequencies do not require frequency separation for suppression of adjacent-channel interference, it was shown in [6] that non-contiguous subsets of OFDM carriers have to be sufficiently separated to prevent destructive leakage of energy from one subset to another. This separation is referred to as guard band. It is intuitive that as the number of non-contiguous channels increases, more guard bands will be required. Also, OFDM transceivers use pilot subcarriers to perform coherent detection and reliable channel estimation [7]. These two constitute inherent overheads of a NC-OFDM system that negatively affect spectral utilization in DSA radios, which are fundamentally used to achieve the opposite by exploiting as much of the available spectrum as possible. Therefore, there is a fundamental need for a method of decreasing the overhead due to guard band allocation.

In this section, the underlying theory of one such method is presented, which is based on reduction of the number of fragments through online reassignment and defragmentation of channels. Fundamental parameters considered by this method are not only the overhead caused by guard bands and pilot carriers, but also hardware limitations and the heterogeneity of the electromagnetic spectrum. Hence, this method takes into account the practical constraints of radio interfaces, and frequency selective fading of the environment to provide the most efficient solution. In the following, theoretical formulation of the spectrum assignment problem and the optimization goal are discussed. Then, the details of applying this framework in infrastructure and ad hoc DSA networks are presented.

A. Spectrum Assignment problem

Let $\mathbb{N}$ be the set of all SUs where $\mathbb{N} = \{u_i | i = 1, \ldots, N\}$. The whole spectrum range is divided into C subcarriers. we define $\mathbb{C} = \{c_j | j = 1, \ldots, C\}$. Let T_i^{req} be the throughput demand of u_i, $i \in \mathbb{N}$. Let the throughput requirement matrix be $\mathcal{T}^{req} = (T_1^{req}, T_2^{req}, \cdots, T_N^{req})$. Due to heterogeneity in the wireless spectrum, different subcarriers provide different data rate [8], [11]. Let's define the data-rate matrix $\mathcal{R}$ which contains maximum data rate that can be achieved by u_i over subcarrier c_j is known.

$$\mathcal{R} = \begin{pmatrix} R_{1,1} & R_{1,2} & \cdots & R_{1,C} \\ \vdots & \vdots & \ddots & \vdots \\ R_{N,1} & R_{N,2} & \cdots & R_{N,C} \end{pmatrix}_{N \times C} \quad (1)$$

At any given time, PU usage matrix can be defined as $\mathcal{A}_{PU} = (PU_1 \quad PU_2 \quad \cdots \quad PU_C), A_j \in \{0, 1\}$. Here $PU_j = 1$ if the subcarrier j is being used by its PU and 0 otherwise. Binary subcarrier assignment matrix is defined as:

$$\mathcal{A} = \begin{pmatrix} A_{1,1} & A_{1,2} & \cdots & A_{1,C} \\ \vdots & \vdots & \ddots & \vdots \\ A_{N,1} & A_{N,2} & \cdots & A_{N,C} \end{pmatrix}_{N \times C}, A_{i,j} \in \{0, 1\} \quad (2)$$

Where $A_{i,j} = 1$ if C_j is assigned to u_i, and 0 otherwise. We consider all SUs are within communication distance of each other. If multiple SUs transmit on the same subcarrier then the transmissions collide and data is lost. So, a subcarrier should not be assigned to an SU if another SU is using it or PU is occupying it. $\sum_{i \in \mathbb{N}} A_{i,j} + PU_j \leq 1, \forall j \in \mathbb{C}$.

In NC-OFDM transmission, the total allocated subcarriers consists of data, guard and pilot subcarriers. As the required guard band and pilot insertion are system and hardware dependent, we consider these two factors in the theoretical analysis. Let's define three $N \times C$ matrices: data-subcarrier assignment matrix $(\mathcal{D})$, pilot-subcarrier assignment matrix $(\mathcal{P})$ and guard-subcarrier assignment matrix $(\mathcal{G})$. Where $D_{i,j}, P_{i,j}, G_{i,j} \in$

$\{0,1\}$. $D_{i,j} = 1$ if channel j is allocated to u_i as data subcarrier at this point, and 0 otherwise. $P_{i,j}$ and $G_{i,j}$ follow same definition for pilot and guard subcarriers respectively. Essentially, $\mathcal{D} + \mathcal{P} + \mathcal{G} = \mathcal{A}$.

For u_i, the expected throughput is expressed as:

$$T_i = \begin{pmatrix} D_{i,1} & D_{i,2} & \cdots & D_{i,C} \end{pmatrix} . \begin{pmatrix} R_{i,1} & R_{i,2} & \cdots & R_{i,C} \end{pmatrix}^T \quad (3)$$

Let's define cross interference matrix for subcarriers as:

$$\mathcal{I} = \begin{pmatrix} I_{1,1} & I_{1,2} & \cdots & I_{1,C} \\ \vdots & \vdots & \ddots & \vdots \\ I_{C,1} & I_{C,2} & \cdots & I_{C,C} \end{pmatrix}_{C \times C} \quad (4)$$

Where $I_{j,k}$ denotes the interference created by the transmission of j^{th} subcarrier on k^{th} subcarrier. To investigate a worst case scenario, nodes are assumed to be in close proximity of each other, and therefore, the effect of path loss on cross channel interference can be ignored. $I_{j,k} \in (0,1)$ and $I_{j,j} = 1$. Value of $I_{j,k}$ for $j \neq k$ depends on the hardware. Subsequent guard bands must be placed to keep the interference under a threshold I_{th}. When an SU uses a set of subcarriers, it must ensure the transmission does not cause interference to other subcarriers. So, the constraint becomes,

$$\sum_{i \in \mathbb{N}} \sum_{k \in \mathbb{C} \wedge k \notin A_i} (D_{i,j} + P_{i,j}) I_{j,k} \le I_{th}; \forall j \in \mathbb{C} \quad (5)$$

NC-OFDM transmission is limited by several hardware factors such as maximum aggregation limit (B_i), maximum usable subcarriers (C_i^{max}), maximum fragments per SU (F_i^{max}), maximum transmission power, etc [6], [8], [12]. If Cu_i and Cl_i are indices of highest and lowest allocated subcarrier for u_i then we can write, $B_i \le Cu_i - Cl_i$. If u_i can only use C_i^{max} number of subcarriers as pilot or data subcarriers then, $\sum_{j \in \mathbb{C}} D_{i,j} + P_{i,j} \le C_i^{max}$.

B. Optimization Goal

For any spectrum allocation problem, the ultimate goal is to maximize the total achievable throughput $\sum_{i \in \mathbb{N}} T_i$ in the network. Equivalently, our goal translates into maximizing the throughput while minimizing the number of allocated subcarriers to achieve that throughput. This can be written as:

$$\begin{aligned} \max \quad & \frac{\sum_{i \in \mathbb{N}} T_i}{\sum_{i \in \mathbb{N}} \sum_{j \in \mathbb{C}} A_{i,j}} \qquad (6) \\ s.t. \quad & \sum_{i \in \mathbb{N}} \sum_{k \in \mathbb{C} \wedge k \notin A_i} (D_{i,j} + P_{i,j}) I_{j,k} \le I_{th}; \forall j \in \mathbb{C} \\ & T_i \ge T_i^{req}, \forall i \in \mathbb{N} \\ & PU_j + \sum_{i \in \mathbb{N}} A_{i,j} \le 1, \forall j \in \mathbb{C} \\ & A_{i,j} \in \{0,1\}, \forall i \in \mathbb{N}, \forall j \in \mathbb{C} \\ & Cu_i - Cl_i \le B_i; \forall i \in \mathbb{N} \\ & \sum_{j \in \mathbb{C}} D_{i,j} + P_{i,j} < C_i^{max}; \forall i \in \mathbb{N} \\ & \sum_{j \in \mathbb{C}} D_{i,j} + P_{i,j} \le C_i^{max} \\ & \text{no. of fragments} \le F_i^{max} \end{aligned}$$

Theorem 1: The throughput maximization problem in eq. (6) is NP-hard even if there is no PU present.

Proof: The proof follows the reduction of the *0-1 knapsack* problem [13] to our problem. In absence of PUs, the problem is to simply say how many SU's requirement can be accommodated given the total available spectrum. Let's look at a very simplified version of the problem where all the subcarriers provide same data rate for all the SUs, i.e. in eq. (1), $R_{i,j} = r; \forall i, j$. Let's also assume that there is no cross channel interference i.e. $I_{i,j} = 0, \forall i \in \mathbb{C}, j \in \mathbb{C}; i \neq j$. All SUs have different data rate demand, $T_i^{req}, \forall i \in \mathbb{N}$. Each SU requires T_i^{req}/r subcarriers. Assume an SU can be allocated with spectrum if and only if its demand is met. Now, the goal is to maximize total throughput of the system, $\sum_{i \in \mathbb{N}} x_i T_i^{req}$ where $x_i \in \{0,1\}$ and $\sum_{i \in \mathbb{N}} T_i^{req}/r \le C$. This problem is exactly same as the 0-1 knapsack problem. Since the simplified problem resemblance the 0-1 knapsack problem, we can say that the knapsack problem can be solved in polynomial time if spectrum assignment problem can be solved in polynomial time. Since 0-1 knapsack problem is NP-hard and it can be mapped to our problem, we can conclude that the spectrum assignment problem is at least NP-hard. ■

C. Spectrum allocation methods

The proposed allocation methods are developed based on the optimization problem in eq. (6). In this paper the spectrum allocation problem is addressed for three cases: 1) centralized spectrum allocation, 2) decentralized spectrum allocation where all SUs individually optimize spectrum utilization and 3) distributed SUs periodically perform coordinated spectrum defragmentation. Even though the current work assumes pilotless OFDM system, the same mechanisms can be applied to transceivers which do require pilot carriers by considering pilots' spectrum requirement along with the similar requirement of guard bands.

1) Centralized Method: In this case one central controller or base station supervises the spectrum allocation. All SUs periodically sense the spectrum and send the spectrum usage map to the controller. Each SU also notifies the controller of changes in its throughput requirements (T_i^{req}). The network is assumed to use a dedicated out-of-band common control channel (CCC) [14] for transmitting control messages.

The controller has two states: $Steady$ state and $Arrangement$ state. It stays in the $Steady$ state until a PU activity or change in an SU's requirement is detected, at which time it transits to the $Arrangement$ state, where it invokes Algorithm 1 to calculate subcarrier allocation vectors: $\mathcal{A}, \mathcal{D}, \mathcal{G}$ for all SUs. The input to Algorithm 1 is the current PU usage vector and the throughput requirements of all SUs. The controller broadcasts the resulting $\mathcal{A}, \mathcal{D}, \mathcal{G}$ to all SUs and returns to $Steady$ state afterwards. The idea behind the Algorithm 1 is straightforward. Spectrum is allocated for the SUs with higher throughput demand with more priority, intending to reduce the number of fragments used by a single SU. An SU is allocated with spectrum if its requirement can be fully satisfied. First the SUs are sorted in the descending order of their throughput demand. Then for each SU, Algorithm 2 is used to allocate subcarriers. This is a recursive algorithm that explores all the possible combinations of allocating spectrum fragments to an SU and fix the combination that occupies minimum number of subcarriers. First it finds out the spectrum holes with the function *find holes*, which takes the channel usage vector and the subcarrier boundaries that an SU can use. This function returns list of usable holes considering guard bands, within the spectrum allocation boundaries of u_i. For each spectrum fragment, the required number of guard carriers is provided. If the demand is satisfied, it returns the number of allocated subcarrier considering guard bands, and also the number of fragments used. If the throughput demand

Algorithm 1: $Centralized\_allocation(\mathcal{A}_{PU}, \mathcal{T}^{req})$

input : A_{PU}, T^{req}
output: $\mathcal{A}, \mathcal{D}, \mathcal{G}$

$sorted\_list \leftarrow$ list of SUs in descending order of $\mathcal{T}^{req}$
for $i \in sorted\_list$ **do**
  $S, A, D, G \leftarrow channel\_assignment(\mathcal{A}_{PU}, low, high, T_i^{req}, i)$
  if $S \neq \infty$ **then** $A_i \leftarrow A$; $D_i \leftarrow D$; $G_i \leftarrow G$;
  else $A_i \leftarrow (0,.,0)$; $D_i \leftarrow (0,.,0)$; $G_i \leftarrow (0,.,0)$;
  $A_{PU} \leftarrow A_{PU} + A_i$
end
return $\mathcal{A}, \mathcal{D}, \mathcal{G}$

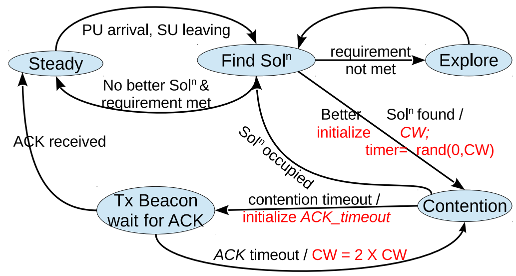


Fig. 2: State diagram of an SU in complete distributed method

is not satisfied, the spectrum usage boundary is updated and the function is recursively called. If for a combination one hole is left such that no other SU can use it due to guard bands, the remaining subcarriers are considered as wasted. This process is repeated considering all holes in descending order and then takes the combination that provides the lowest number of wasted subcarriers. If an SU cannot be allocated with spectrum, the function returns ∞. Algorithm 1 checks the returned value and if spectrum can be allocated for an SU, it updates $\mathcal{A}, \mathcal{D}, \mathcal{G}$ and moves on to allocate the next SU.

2) Distributed method: In this method the SUs are completely distributed. Hence central coordination is not possible. The receiver senses the entire spectrum in its aggregation range while receiving data. It then piggybacks the sensing information to the transmitter with acknowledgments (ACK) or other data packets. Figure 2 illustrates the state diagram of an SU following this procedure. While in the $Steady$ state, the SU transmits data over the subcarriers acquired earlier. If interrupted by a PU, it jumps to the $Find\ Sol^n$ state to find another possible opportunity for its transmission. During the $Steady$ state, if a new spectrum hole is observed, then it transits to $Find\ Sol^n$ to trigger defragmentation. In $Find\ Sol^n$ state, the SU calls Algorithm 2 to compute better subcarrier assignment opportunities. If the computed subcarrier assignment cannot facilitate the required throughput, the SU goes to the $Explore$ state where it scans the spectrum outside of its current scanning range. If a better solution is found then the SU initializes the contention window (CW) and goes to the $Contention$ state, where it begins counting down for contention timeout while monitoring the spectrum. If the SU senses another transmission on the targeted subcarrier before the timeout, it returns to $Find\ Sol^n$. If the desired subcarriers are idle throughout the contention period, the transmitter sends identifying beacons and waits for the ACK from the receiver. If the ACK is not received due to collision, the SU increases its contention window and goes to the $Contention$ state. If the ACK is received successfully, it starts transmitting on the desired subcarriers and transits to the $Steady$ state.

Algorithm 2: channel_assignment(ch_usage, low, $high$, req, i)

input : Channel usage vector : ch_usage, Frequency lower limit : low, Frequency higher limit : $high$, Required throughput : req, SU: i
output: Number of fragments ∞ means unsuccessful allocation; channel allocation vectors: A, D, G

$hole \leftarrow find\_holes(ch\_usage, low, high, req, i)$
$H \leftarrow no\_of\_holes$
Sort $hole$ in descending order
$S \leftarrow (0, 0, \ldots, 0)$
Initialize A, D and G with $H \times C$ null matrices.
if H=0 **then** Return $\infty, (0,..,0), (0,..,0), (0,..,0)$;
if $req < 0$ **then** Return $0, (0,..,0), (0,..,0), (0,..,0)$;
for k := 1 to H **do**
  for $c := hole_l^k$ to $hole_l^k + guard - 1$ **do**
    $A_{k,c} \leftarrow 1$; $G_{k,c} \leftarrow 1$
  end
  for $c := hole_l^k + guard$ to $hole_u^k - guard$ **do**
    if $req > 0$ **then**
      $A_{k,c} \leftarrow 1$; $D_{k,c} \leftarrow 1$
      $S_k \leftarrow c$; $req \leftarrow req - R_{i,c}$
    end
  end
  for $c := S_k + 1$ to $S_k + guard$ **do**
    $A_{k,c} \leftarrow 1$; $G_{k,c} \leftarrow 1$
  end
  $S_k \leftarrow S_k + guard$
  if $hole_h^k - S_k \leq 2 \times guard$ **then** $S_k \leftarrow hole_h^k$;
  if $req > 0$ **then**
    update low, $high$
    $S_c, A_c, D_c, G_c \leftarrow channel\_assignment(ch\_usage + A_k, low, high, req, i)$
    $S_k \leftarrow S_k + S_c$; $A_k \leftarrow A_k + A_c$
    $D_k \leftarrow D_k + D_c$; $G_k \leftarrow G_k + G_c$
    if $\neg constraints\_satisfied$ **then** $S_c \leftarrow \infty$;
  end
end
$m = \text{argmin}\, S$
return S_m, A_m, D_m, G_m

3) Semi-centralized method: The efficiency of the completely distributed method is not optimal since in such cases coordinated defragmentation or reassignment cannot be performed. On the other hand, the completely centralized method requires a dedicated controller. One idea is to combine both of these approaches to achieve a more efficient performance. But, in a distributed ad hoc network, committing individual resources to coordination is not desired by any user, since the central controller needs more computational power and spare time to coordinate the network. To overcome this issue, we propose a semi-centralized method. In this approach, all the SUs periodically defragment the spectrum through reassignment by a temporarily elected leader.

In this method, an SU follows the state transition of completely distributed method as discussed in Section III-C2 with an extra interruption. For periodic defragmentation, all SUs use a timer for the defragmentation cycle. The timer is initiated at the end of the defragment process. Upon timeout, an SU goes to $Leader\ election$ where the network elects a leader in a cooperative manner. A leader can be elected with many different criteria such as the SU with the minimum amount of load, computational power, battery life, etc. or simply in round robin fashion. Leader election, integrity and the successful delivery of the control messages through CCC are well studied areas [15], [16], [17]. When an SU becomes the leader, it collects spectrum usage information as well as throughput requirements from all SUs. If the whole spectrum is not sensed, the leader initiates a cooperating sensing to scan the uncovered spectrum. The leader follows the centralized method described in section III-C1 to compute $\mathcal{A}, \mathcal{G}, \mathcal{P}$ and broadcasts them. After the broadcast the leader becomes a normal SU. If an SU is not acting as a leader it waits for beacons from the leader and sends its information to the leader. After receiving $\mathcal{A}, \mathcal{G}, \mathcal{P}$, if an SU finds that it has not been assigned spectrum, it goes to $Find\ Sol^n$ state otherwise it goes to $Steady$ state and starts transmitting over the assigned subcarriers.

IV. System Development

To investigate the feasibility of the proposed methods and relevant parameters of their practical implementation, a prototype based on a network of GNURadio [9] controlled Ettus-USRP B210 [10] Software Defined Radios has been developed. This network is formed of two pairs of transceivers as secondary users. Each node is an OFDM transceiver, capable of both contiguous and non-contiguous transmissions.

The radios were configured to operate over a 200 KHz band centered at 5.25GHz. OFDM transmitters and receivers divide this band to 256 subcarriers of 781.25 Hz each, which can be dynamically allocated to any user. For correct detection of OFDM preamble in each channel, a minimum of 28 subcarriers must be assigned to each transmission, which can be both contiguous and non-contiguous. Also, each radio has a spectrum sensing block, capable of sensing the entire aggregation range.

It was observed that, even after accounting for the frequency offset at the OFDM receiver, filtering alone is not sufficient for effective elimination of cross-channel interference, and some degree of frequency separation is required between adjacent transmitters. Figure 3 depicts power spectral densities of two radios, and their concurrent Non-Contiguous OFDM transmission. From figure 3(a), it can be seen that when the two transmitters operate simultaneously, there is a considerable amount of interference in the frequency space between the two non-contiguous. Therefore, implementing guard bands between two adjacent transmitters is evidently necessary. To find the minimum number of required guard bands, the frequency separation between two transmitters using contiguous blocks was increased until the level of cross-channel interference fell below a threshold determined by the error rate in received data. Measurements indicate that the number of required guard bands varies with the level of received power. To achieve a practical number for necessary guard bands, multiple measurements with varying distances between antennas and minute changes in transmit power and receive chain gain were performed. It was then concluded that for the majority of the cases, given the fragile stability of USRP interfaces, a minimum of 2 guard bands is a practical choice, which is one of the considerations in simulations discussed in following sections.

V. Simulation Results

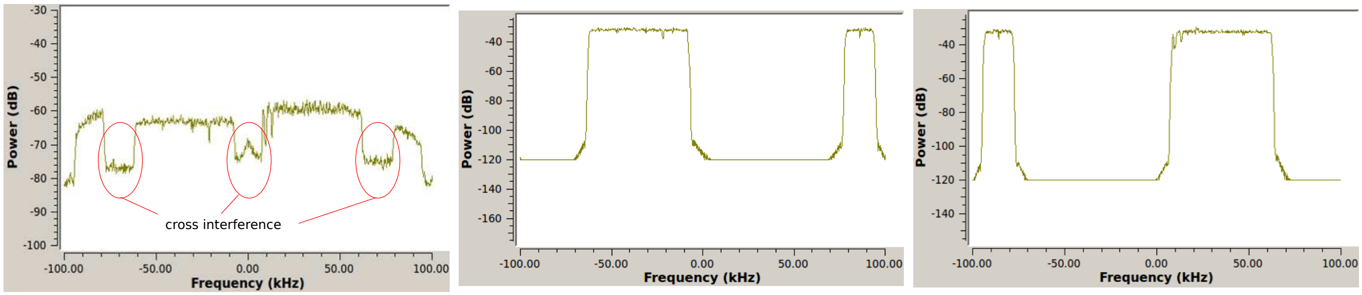
The proof of concept testbed described in section IV has limited capacity in terms of number of SUs, subcarrier aggregation range, etc. We developed a discrete event simulator in order to analyze the performance of the proposed method with broader spectrum range and more SUs. Necessary system parameters are obtained from the testbed in order to correctly evaluate the methods through the simulation. Table I provides the list of parameters used. Every simulation is run for *simulation time* and the simulator begins recording results after *Warm-up-time* to eradicate the fluctuations that occur in the early stage. The PU occupancy list and SU requirements list for the whole simulation time is generated at the beginning and identical copies are used for comparing multiple method. This whole process is replicated several times and the values are averaged in order to obtain reliable results. In this simulation each PU has a different spectrum width and hence occupies a different number of subcarriers.

TABLE I: Simulation Parameters

Parameter	Symbol	Value
Simulation Time		$1,00,000\ sec$
Warm-up-time		$10,000\ sec$
replication		25
PU's width		$\sim U(10-20)$
PU active time		$\sim U(20,40)\ sec$
PU sleep time		$\sim U(60,120)\ sec$
Total subcarrier	$\mathbb{C}$	2048
Aggregation range	B_i	256
Data Rate per subcarrier	$R_{i,j}$	$\sim U(293,586)$ bps
Maximum fragmentation	F_i^{max}	10
no. of guard carrier		2
SU's requirement	T_i^{req}	$\sim U(10,30)$
SU's demand change interval		$\sim U(2,4)\ sec$
Initial Contention Window	CW	8
ACK timeout		$10\ msec$
central timeout		4 sec

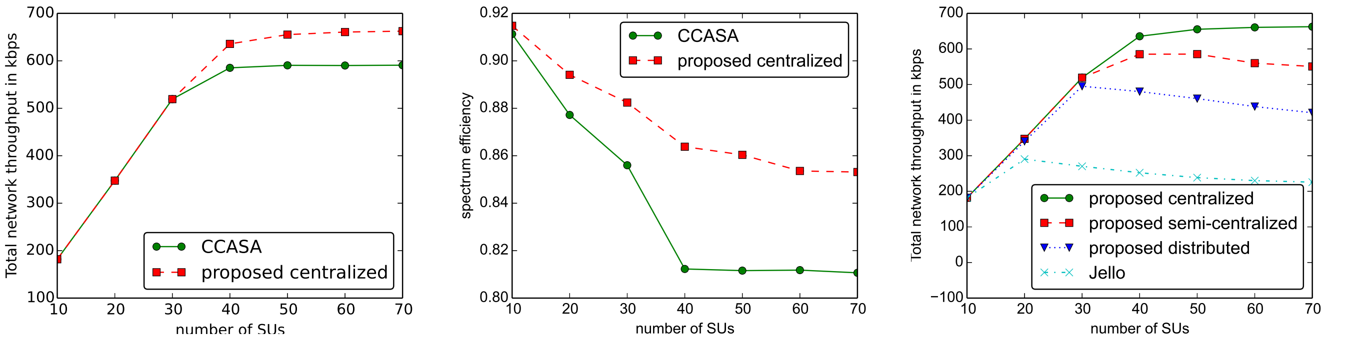
In the first stage, the performance of the centralized method is evaluated. We compare our centralized spectrum allocation method with CCASA [8]. While CCSA does not consider the waste of spectrum as a constraining parameter, our centralized algorithm takes the guard bands and pilot carriers into account in the calculation of the minimum spectrum requirement and allocation. **Figure 4a** plots the total throughput obtained for the network which is the sum of throughput for all SUs in the network. It can be seen that, for both approaches, the average throughput increases linearly with increase in number of SUs present in the system. But it is also observed that in our centralized algorithm, the maximum capacity is significantly improved in comparison with CCASA. **Figure 4b** plots the spectral efficiency of the system. Spectral efficiency is defined as $\frac{\text{no. of allocated data carriers}}{\text{no. of allocated carriers}}$. The plot reveals that when there are more SUs contending in the system, the spectral efficiency is lower, which reveals the spectrum is heavily fragmented. It is also evident that, regardless of the number of SUs, the centralized algorithm performs better than CCASA in terms of spectral efficiency.

To assess the performance of our proposed methods, we compare them with the approach introduced in the Jello testbed [6], since it provides the most relevant results to ours, as it is developed based on similar fundamental systems assumptions, and also considers the problem of fragmentation. **Figure 4c** provides the total throughput achieved for the entire network. The results obtained from all of our methods indicate a significantly better performance in comparison with Jello. As the number of contending SUs increase, the probability of collision increases during the contention period, which results in the fall of the average throughput of the network. When the spectrum aggregation range is much smaller compared to the total spectrum width, the proposed semi-centralized method performs significantly better than Jello. One reason for this enhancement



(a) Received signal (b) NC spectrum allocation for node A (c) NC spectrum allocation for node B

Fig. 3: Power Spectral Density plots at receiver



(a) Throughput for centralized method (b) Spectral efficiency for centralized method (c) Throughput comparison

Fig. 4: Simulation Results

is that Jello looks for spectrum in a fixed frequency range, while our methods are capable of looking for holes anywhere in the frequency range supported by the transceivers using a sliding frequency window approach. The proposed distributed method obtains 42.43% higher throughput compared to Jello. It is also noteworthy that the semi-centralized approach does not perform as well as the completely centralized algorithm, but the semi-centralized method achieves a 27.14% improvements over the proposed distributed method.

VI. Conclusion

In this paper, Online Defragmentation was proposed as a method of increasing spectrum utilization in channel-aggregating DSA radio networks. Efficiency of this method was investigated in three different network scenarios:Infrastructure, distributed and semi-centralized. By including parameters retrieved from a proof-of-concept prototype into simulations, realistic comparisons of the three scenarios with regards to effectiveness of the presented algorithm have been presented. It was concluded that regardless of scenario, defragmentation provides better performance in terms of spectral efficiency and throughput.

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