Coexistence-Aware Dynamic Channel Allocation for 3.5 GHz Shared Spectrum Systems

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***Abstract*—The paradigm of shared spectrum allows secondary devices to opportunistically access spectrum bands underutilized by primary owners. As the first step, the FCC targeted sharing the 3.5 GHz (3550-3700 MHz) federal spectrum with commercial systems. The proposed rules require a Spectrum Access System to implement a three-tiered spectrum management framework, and one of its key functions is dynamic channel allocation (CA) for secondary devices. In this paper, we introduce *coexistence-aware radio-channel-pair conflict graphs* to capture pairwise interference, spatial channel availability variations, channel contiguity, and coexistence opportunities. We develop a *super-radio formation algorithm* to identify valid *super-radios*, i.e., a set of radios that can coexist on the same channel(s) via WiFi-like carrier-sensing mechanisms. With the proposed generic graph representation, we formulate CA as *conflict-free max-demand CA with a min-demand constraint*, and develop algorithms based on maximum weighted independent set. Preliminary results demonstrate good performance of proposed algorithms and benefits of coexistence.**

I. Introduction

To meet the rapidly increasing demand in wireless network capacity, the FCC targeted release of the 3.5 GHz (3550-3700 MHz) band[1], termed *Citizens Broadband Radio Service* (CBRS), based on the paradigm of *shared spectrum*. It allows secondary devices to access the licensed spectrum that is underutilized by primary owners. Recent ruling [1] introduces a three-tiered framework to enable lower-powered network deployment (e.g., small cells), which includes: (1) *dynamic incumbents* in the top tier, (2) *Priority Access License (PAL)* users in the second tier, and (3) *Generalized Authorized Access (GAA)* users in the third tier. PAL and GAA users are also referred to as *Citizens Broadband Service Devices* (CBSDs). Incumbents have the highest priority and are protected from harmful interference caused by CBSDs. PAL users are allocated exclusive channels and protected from GAA users, while GAA users are expected to accept interference from all users.

The first end-to-end architecture proposed in [2] includes a Spectrum Access System (SAS) for channel allocation (CA). Dynamic CA has been studied in various contexts [3], [4], but new challenges arise in the CBRS band. In addition to *co-/adj-channel interference* and *spatial channel availability variation* due to incumbent exclusion zones, there is a practical need to enforce *channel contiguity*[2] (e.g., IEEE 802.11ac), i.e., assigning multiple contiguous channels to a radio, which has not been considered before. Another feature to be explored is *coexistence-awareness*, i.e., multiple interfering GAA radios sharing the same channel(s). Here, we assume that it is enabled by WiFi-like carrier-sensing mechanisms, such as CSMA/CA in WLAN, CSAT (Carrier Sensing Adaptive Transmission) and LBT (Listen-Before-Talk) in LTE-U/LAA.

In this paper, we study SAS-assisted centralized CA. We first introduce *coexistence-aware (super-)radio-channel-pair conflict graphs* to capture the above requirements. We develop a super-radio formation algorithm that identifies super-radios based on individual average traffic and carrier-sensing relationship. We further formulate it as a *max-demand CA with a min-demand constraint* and develop efficient algorithms based on *maximum weighted independent set* (MWIS) in graph theory. We conduct simulations to evaluate proposed CA algorithms and demonstrate the benefits of coexistence.

[1]The 150 MHz spectrum is divided into 15 10-MHz channels.

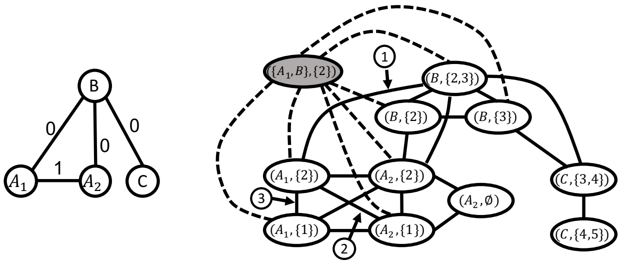
[2]But it may not be a must for all RATs.

II. Coexistence-Aware Radio-Channel-Pair Conflict Graph

Denote the set of available channels and the set of requested channel numbers of radio i as $\Gamma(i)$ and $D(i)$, which jointly determine the set of available and contiguous channel assignments $\mathcal{C}(i)$. A *radio-channel (RC) pair* is a tuple (i, C_i) where $C_i \in \mathcal{C}(i)$. We further introduce *super-RC pairs* (S, C) where $C \in \mathcal{C}(i)$ for each $i \in S$. We call S a *super-radio* on C, and require that radios in S be within each other's carrier-sensing range so as to "politely" share the same channel(s) (primarily for downlink traffic). The *coexistence-aware RC-pair conflict graph*[3] $G = (V, E)$ is an undirected graph, where each vertex $v \in V$ is a RC or super-RC pair and each edge $e(v, u) \in E$ indicates a conflict due to one-channel-assignment-per-radio or interference constraints. Pairwise interference relationship can be determined based on the interference model.

Fig. 1 is an example of a RC-pair conflict graph, derived from the following requests: (1) $\Gamma(A_1) = \{1, 2\}$, $D(A_1) = \{1\}$; (2) $\Gamma(A_2) = \{1, 2\}$, $D(A_2) = \{0, 1\}$; (3) $\Gamma(B) = \{2, 3\}$, $D(B) = \{1, 2\}$; and (4) $\Gamma(C) = \{3, 4, 5\}$, $D(C) = \{2, 4\}$. When a super-RC pair (e.g., $(\{A_1, B\}, \{2\})$) is identified, it is first added to the graph and naturally inherits the adjacency relationship of its children RC pairs, that is, $(A_1, \{2\})$ and $(B, \{2\})$ in this example. Then edges among its children RC pairs are removed to include all coexistence possibilities.

[3]Note that our conflict graph also supports non-contiguous channel assignments. For example, if radio i requests 2 or 3 non-contiguous channels, we can create 3 copies of that radio (i_1, i_2 and i_3) with $D(i_1) = \{1\}$, $D(i_2) = \{1\}$ and $D(i_3) = \{0, 1\}$, and they cannot be assigned the same channel.



(a) (b)

Fig. 1: (a) Interference graph of 3 CBSDs and 4 radios (A has two radios). The value on each edge indicates the min. channel distance. (b) Coexistence-aware conflict graph. ① and ② indicate co-channel and adj-channel interference, respectively. ③ represents the one-channel-assignment-per-radio constraint.

III. Proposed Algorithms

Super-Radio Formation: For each possible C, we consider the graph, where each vertex is a radio with C available and each edge means that connected radios are within each other's carrier-sensing range. Since coexisting radios need to be able to sense each other's transmission, our first task is to find all *cliques* (i.e., complete subgraphs) in the graph[4].

Radios in each clique are qualified to coexist, but we want to divide them into smaller groups to balance loads. Each radio has an *activity index* $\alpha_i(C) \in (0, 1]$, which is the percentage usage of C. Given the total activity index limit $\bar{\alpha}$ (e.g., 1) of a super-radio, the task is to group radios (i.e., items with weights) into fewer super-radios (i.e., bins with capacity $\bar{\alpha}$), which is the well-known *bin packing* problem.

CA Algorithms: Given a conflict graph $G = (V, E)$ for n radios and a *weighting function*[5] $W : V \mapsto \mathbb{R}^+$, SAS wants to find a CA scheme $I \subseteq V$ so as to

$$\max_{I \subseteq V} W(I) \text{ s.t. } |\bigcup_{v \in I} S(v)| = n, \text{ and } e(u, v) \notin E, \forall u, v \in I$$

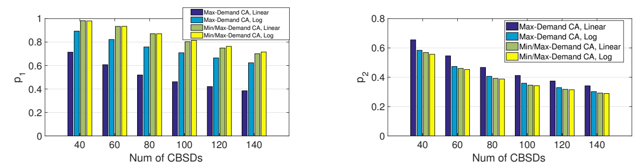
where $S(v)$ is the set of radios at vertex v. We call the above *conflict-free max-demand CA with a min-demand constraint*.

With the first min-demand constraint, the *conflict-free max-demand CA* becomes the classic MWIS problem, and heuristic-based solutions are in place with certain performance guarantee. To meet the min-demand constraint (with best efforts), we propose a two-phase algorithm called *min-/max-demand CA*: meeting minimum demands in Phase I and then maximizing the total demand in Phase II. Specifically, we solve the MWIS problem in Phase I for the reduced subgraph that only consists of min-demand RC pairs, and apply heuristics to keep as many extensions as possible in the process. In Phase II, we solve MWIS again for the subgraph derived from Phase I selections.

IV. Preliminary Results

We use 100 outdoor WiFi AP locations from a real dataset as CBSD locations, which are densely distributed in a 2.3km-by-1.0km region. We assume a total of 15 channels and $U[1, 2]$ radios per CBSD. All radios are able and willing to coexist. The number of requested channels for each radio ranges from $U[1, 2]$ to 4. We set α_i to $U[0, 2]$, and $\alpha_i(C) = \min(\frac{\alpha_i}{|C|}, 1)$. Transmit power is 30 dBm/10 MHz, and the signal threshold at service boundaries is -80 dBm/10 MHz. We assume circular service areas and use the Stanford University Interim model to compute the radius (approx. 170 meters). Two radios interfere if their service areas overlap. For simplicity, we assume that the carrier-sensing range is the same with the radius of service area. We vary n (number of CBSDs) by sub-sampling the current set or randomly generate more CBSD locations.

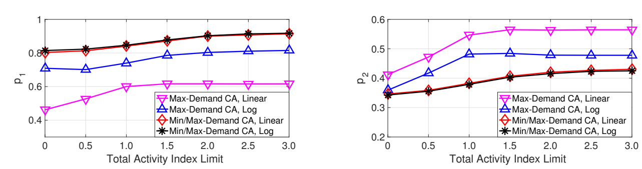
We consider max-demand and min-/max-demand CA algorithms with linear ($W(S, C) = |S||C|$) and log ($W(S, C) = |S|(1 + \log(|C|))$) weighting functions. We use two metrics: (1) *min-demand service ratio* (p_1), the percentage of radios with minimum demand serviced, and (2) *max-demand service ratio* (p_2), the percentage of total demand serviced.



(a) (b)

Fig. 2: Impact of n ($\bar{\alpha} = 0$, coexistence disabled).

As shown in Fig. 2, both p_1 and p_2 decrease as n increases for all schemes. We observe that max-demand CA with linear weights has the highest p_2 but the lowest p_1, consistent with the goal of MWIS. But max-demand CA with log weights has a significant increase in p_1, which suggests that the choice of a weighting function can reflect our preferences and affect max-demand CA behaviors. Min-/max-demand CA, on the other hand, produce higher p_1 values but lower p_2, as expected.



(a) (b)

Fig. 3: Impact of coexistence with varying $\bar{\alpha}$ ($n = 100$).

As shown in Fig. 3, increasing $\bar{\alpha}$ effectively increases both p_1 and p_2 for all schemes, but such increase stops when radios in a clique are grouped into fewer super-radios and eventually a single one (which means each super-radio is more crowded).

References

[1] FCC, "In the matter of amendment of the commission's rules with regard to commercial operations in the 3550-3650 mhz band,," pp. FCC Document 12–148, Dec 2012.

[2] C. W. Kim *et al.*, "Design and implementation of an end-to-end architecture for 3.5 GHz shared spectrum," in *IEEE DySPAN'15*.

[3] C. Peng, H. Zheng, and B. Y. Zhao, "Utilization and fairness in spectrum assignment for opportunistic spectrum access," *Mobile Networks and Applications*, vol. 11, no. 4, pp. 555–576, 2006.

[4] F. Hessar and S. Roy, "Resource allocation techniques for cellular networks in tv white space spectrum," in *IEEE DySPAN'14*.

[4] Each radio can only belong to one clique.

[5] An example is $W(S, C) = |S||C|$ - the total number of channels assigned.