CBRS Post Auction PAL Channel Assignment Technical Report

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Table of Contents

List of Figures

List of Tables

Contributors

SSC WG5 Chair

- Richard Bernhardt, WISPA

Primary Contributors

- Virgil Cimpu, Ericsson
- Sho Furuichi, Sony
- Abdulrauf Hafeez, Charter
- Ariful Hannan, Commscope
- Navin Hathiramani, Nokia
- Yi Hsuan, Google
- Masoud Olfat, Federated Wireless
- Luca Rose, Nokia Bell Labs
- Naotaka Sato, Sony
- Zaheer Syed, CableLabs

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1 Introduction

CFR 47 Part 96, section 96.25, establishes that each PAL licensee will be authorized to use a 10 MHz channel in the 3550-3650 MHz band, and that no more than seven PALs will be assigned in any given License Area at any given time [1]. Part 96 specifically requires that the SAS administrators consider the following in mapping PAL to a specific channel:

- *Contiguous geographic areas:* An SAS must assign geographically contiguous PALs held by the same Priority Access Licensee to the same channels in each geographic area, to the extent feasible.
- *Contiguous channels:* An SAS must assign multiple channels held by the same Priority Access Licensee to contiguous channels in the same License Area, to the extent feasible.

Priority Access Licenses (PAL) will be auctioned in Auction 105 [2]. Each license will give its owner rights for a generic 10 MHz spectrum block in the lower 100 MHz (3550-3650 MHz) of CBRS spectrum in a license area (US County), as established in the Part 96 rules. Up to 7 licenses will be awarded in each county. An entity can buy rights for up to 4 licenses per county. The exact frequency range of the license is not guaranteed and can be changed due to incumbent activity. The licenses will be mapped to specific 10 MHz channels by SAS after the auction, and in support of this The Wireless Innovation Forum CBRS Requirements Specification [3] established the following three requirements:

R1-SPU-04: PAL Steady State Channel Assignment: A SAS shall assign the "steady-state" channels designated per R2-SPU-10 to all CBSDs included in the user's PPA Cluster List as defined by the PPA and the governing PAL held by that licensee.

R1-SPU-05: Temporary PAL Channel Reassignment: According to 96.25(b)(1)(i) and 96.25(b)(2)(i), and to the extent necessary to protect Incumbent Users or if necessary to perform its required functions under Part 96 subpart F, SAS may temporarily reassign individual PALs (and their associated PPAs and CBSDs) held by the same licensee to channels different than the "steady-state" channels assigned per R2-SPU-10.

R2-SPU-10: PAL Channel Assignment Planning: At the conclusion of the auction and prior to PAL use commencing, and at the times requested by the Commission, SAS Administrators shall cooperate to apply appropriate protocols to allocate and to assign "steady-state" frequencies to PAL Licensees to meet FCC requirements 96.11 (a)(3), 96.13, 96.31, 96.25(b)(1)(i), and 96.25(b)(2)(i), as well as meeting incumbent protection requirements. The SAS Administrators may consider additional constraints and objectives provided by PAL Licensees. The proposed allocation methodology shall be presented to the PAL Licensees for review and comment.

Each SAS was tested, during certification, on use of the primary, steady state, channel assignment, as captured in the PAL Database [4][5]. The purpose of this technical report is to inform the SAS administrations on options they can consider in establishing the allocation methodology in creating this primary, steady state assignment that will be populated in the PAL Database. This database will be made public by the WInnForum. A previous report detailed the encumbrances that can be considered by the SAS Administrators in making this assignment [6].

The proposals presented in this report have been editorially reviewed, but have not been evaluated for technical merit, as it is understood that other factors not captured here will weigh into the SAS Administrators final selection of any channel mapping model. As such, the exact methodology chosen by the SAS administrators could differ significantly from the options mentioned in this report, or it might combine multiple options to best meet the bands requirements. The SAS Administrators will also decide the frequency in which the "steady state" assignments will be updated.

2 Proposal 1

This methodology proposes a channel assignment framework that addresses channel contiguity as well as geographic contiguity. It allows for operator's own channel priorities to be considered for each county and region. Furthermore, the solution attempts to provide fairness in channel assignment and allows licensees to collaborate with each other for a better solution.

2.1 Description

Adjacent license areas (counties) are grouped into an *Allocation Group*. The number of counties per Allocation Group (*N*) is greater than or equal to 1. The value of *N* for each region is the same for each SAS and licensee but it can be different for different regions. PAL channel assignment is done by SAS jointly for all counties in the *Allocation Group*, referred to as *Joint Channel Assignment*. Licensees provide a *Priority List* for Desired Channel Combinations in each *Allocation Group*. Each licensee is assigned a weight (*K*) which multiplies the priority values for that licensee. SAS finds Joint Channel Assignment for each Allocation Group that minimizes the *Sum Weighted Priority* for all licensees. Ties can be resolved in a random fashion.

2.2 Example

Suppose that 7 PAL licenses are auctioned in two geographically adjacent counties with a maximum of 10 channels available in each county. In this example the Allocation Group comprises 2 counties. Suppose also that the licenses were won by 4 operators.

- Licensee A wins 4 PAL licenses in both counties
- Licensee B wins 2 licenses in first county, 0 licenses in second county
- Licensee C wins 0 licenses in first county, 2 licenses in second county
- Licensee D wins 1 license in both counties

Licensee A won a total of 8 licenses in the allocation group, while Licensees B-D won a total of 2 licenses each. In this example the methodology assumes priority weights $Ka=Kb=Kc=Kd=1$
Suppose that Licensee A values avoidance of lower (left) edge channels followed by channel contiguity followed by geographical contiguity. Licensee A's priority list, represented as [County 1 desired channels marked a],[County 2 desired channels marked a] is given by:

- Priority 1: [0000aaaa00],[0000aaaa00]
- Priority 2: [00000aaaa0],[00000aaaa0]
- Priority 3: [000aaaa000],0000aaaa000]
- Priority 4: [000000aaaa],[000000aaaa]
- Priority 5: [0000aaaa00],[00000aaaa0]
- Priority 6: [00000aaaa0],[0000aaaa00]
- Priority 7: [000000aaaa],[00000aaaa0]

- Priority 8: [00000aaaa0],[000000aaaa]
- Priority 9: [000aaaa000],[0000aaaa00]
- Priority 10: [0000aaaa00],[000aaaa000]
- Priority 11: [000000aaaa],[0000aaaa00]
- Priority 12: [0000aaaa00],[000000aaaa]
- Priority 13: [00000aaa0a],[00000aaa0a]
- Priority 14: [0000aaa0a0],[0000aaa0a0]
- Priority 15: [000aaa0a00],[000aaa0a00]
- …

Licensees B and C value channel contiguity followed by avoidance of lower (left) edge channels. Licensee B's priority list (for first county marked b):

- Priority 1 [0000bb0000]
- Priority 2 [00000bb000]
- Priority 3 [000000bb00]
- Priority 4 [0000000bb0]
- Priority 5 [00000000bb]
- Priority 6 [000bb00000]
- Priority 7 [00bb000000]
- Priority 8 [0bb0000000]
- Priority 9 [0000b0b000]
- Priority 10 …

Licensee C's priority list same as Licensee B but for second county and marked c. Licensee D values geographical contiguity followed by avoidance of lower (left) edge channels. Licensee D's priority list (marked d):

- Priority 1 [00000d0000], [00000d0000]
- Priority 2 [000000d000], [000000d000]
- Priority 3 [0000000d00], [0000000d00]
- Priority 4 [00000000d0], [00000000d0]
- Priority 5 [000000000d], [000000000d]
- Priority 6 [0000d00000], [0000d00000]

- Priority 7 [000d000000], [000d000000]
- Priority 8 [00d0000000], [00d0000000]
- Priority 9 [0d00000000], [0d00000000]
- Priority 10 …

Channel assignment algorithm chooses channel assignment for the four licensees in the allocation group to minimize the weighted sum priority for all licensees. It runs for each channel combination and computes the weighted sum priority as follows. Weighted sum priority for licensees A+B+C+D:

- 1+5+5+7=18
- 2+6+6+5=19
- 3+4+4+5=16
- 4+1+1+7=13
- 4+6+6+1=17
- …

In this example, the algorithm chooses priority combination 4,1,1,7 for Licensees A-D, respectively. Channel allocation is: [000dbbaaaa],[000dccaaaa]. Physical and geographical channel contiguity is maintained and edge channels are avoided for all licensees.

2.3 Licensee Collaborations

Licensees can be allowed to coordinate their priority lists (prior to channel allocation) for better outcomes. Suppose that Licensees A and D got together before channel assignment and decided that Licensee D will change its list to accommodate Licensee A's priorities by switching its Priority 1 and 7 entries as follows. Licensee D's priority list:

- Priority 1 [00000d0000], [00000d0000]
- Priority 2 [000000d000], [000000d000]
- Priority 3 [0000000d00], [0000000d00]
- Priority 4 [00000000d0], [00000000d0]
- Priority 5 [000000000d], [000000000d]
- Priority 6 [0000d00000], [0000d00000]
- Priority 7 [000d000000], [000d000000]
- Priority 8 [00d0000000], [00d0000000]
- Priority 9 [0d00000000], [0d00000000]

- Priority 10 …

This changes the sum weighted priority for the first combination to: 1+5+5+1 = 12. Then the winner combination will be [000daaaabb],[000daaaacc] instead of [000dbbaaaa],[000dccaaaa]. A better outcome for Licensees A and D and less computation for SAS.

2.4 County Grouping Considerations

Grouping of adjacent counties in the Allocation Group is a WINNF decision that can be based on the following considerations. Counties isolated from each other can be put in separate allocation groups, e.g.

- Natural isolation, such as bodies of water
- Low population / demand along the border
- Based on an assumed PAL connected set
- Based on number of licensees in adjacent counties
- Channel impairments

Number of counties per group can be constrained to keep algorithm complexity low

2.5 Computational and fairness Considerations

The maximum possible number of channel combinations for a single county for 1, 2, 3 and 4 desired channels out of 10 is $\binom{10}{1}$=10, $\binom{10}{2}$=45, $\binom{10}{3}$=120, $\binom{10}{4}$=210, respectively. The number of combinations increases exponentially for each county in the allocation group. A large licensee with 4 licenses in each county will have a very large number of channel combinations possible (210^N) compared to a small licensee with only one license in a single county. To provide fairness for all licensees while ensuring convergence with low algorithm complexity, this methodology requires each licensee to provide at least *L* desired channel combinations for the allocation group, where *L = min(C, P)* , where *C* can be based on the computational complexity SASs can handle and *P* is the maximum number of channel combinations possible for the licensee. If no solution is found, then each licensee is asked to provide *L2* additional desired channel combinations, and so on, until a solution is found. A licensee can express abstract channel allocation priorities to its SAS which can be translated into channel combinations. Abstract channel allocation priorities can be expressed as, for example: avoid X lower edge channels, keep at least Y channels contiguous, keep at least Z counties contiguous, etc.

2.6 Extensions

A satisfaction metric can be used to favor channel assignment for licensees not satisfied with their assignments. Such a metric can be derived from the priority values picked for each licensee in assignments for previously run allocation groups. The metric can be applied to the multiplicative factor *K* for each licensee to weigh favorable outcomes for unsatisfied licensees. Licensees can exchange their channel assignments after SAS allocation

2.7 Example 2

Suppose that Licensee A's priority weight is *Ka*=3, while all other licensee's priority weights are 1. Priority values for Licensee A (Section 2.2) are multiplied by *Ka*=3:

- Priority 3: [0000aaaa00],[0000aaaa00]
- Priority 6: [00000aaaa0],[00000aaaa0]
- Priority 9: [000aaaa000],[000aaaa000]
- Priority 12: [000000aaaa],[000000aaaa]
- Priority 15: [0000aaaa00],[00000aaaa0]
- Priority 18: [00000aaaa0],[0000aaaa00]
- Priority 21: [000000aaaa],[00000aaaa0]
- Priority 24: [00000aaaa0],[000000aaaa]
- Priority 27: [000aaaa000],[0000aaaa00]
- Priority 30: [0000aaaa00],[000aaaa000]
- Priority 33: [000000aaaa],[0000aaaa00]
- Priority 36: [0000aaaa00],[000000aaaa]
- Priority 39: [00000aaa0a],[00000aaa0a]
- Priority 42: [0000aaa0a0],[0000aaa0a0]
- Priority 45: [000aaa0a00],[000aaa0a00]
- …

Using Licensee B-D's priority lists on Slides 10 and 11, the methodology gets a weighted sum priority for licensees A+B+C+D:

- 3+5+5+7=20
- 6+6+6+5=23
- 9+4+4+5=22
- 12+1+1+7=21
- 12+6+6+1=25
- …

In Example 2, the algorithm chooses priority combination 3,5,5,7 for Licensees A-D, respectively. Channel allocation is: [000daaaabb],[000daaaacc]

2.8 Summary

The solution proposes a simple framework for PAL channel assignment with a few knobs which can be adopted by all SAS. The framework has several advantages. It allows licensees to provide quantitative values for their desired channel priorities. It allows for county contiguity as much as possible. It attempts to provide fairness in allocation for each county and region. The following items are FFS: County grouping and size *N*.

3 Proposal 2

This PAL channel assignment method takes inputs from PAL licensees regarding their preferred physical PAL channel assignment and tries to find a solution. If no solution is available, PAL licensees pick their PAL channels in a random order per license area. PAL licensees are encouraged to collaborate in creating mutually agreeable channel assignments before and after the process. SAS administrators will adopt the mutually agreed channel assignment on a county-by-county basis when creating the final PAL channel assignment. A *PAL channel assignment system* (a.k.a. "the system" hereafter) is devised to collect relevant information and perform PAL channel assignment according to the following process.

3.1 Step 1: Auction Data Input

After PAL auction is completed, the system takes the PAL auction results, potentially from an FCC database, as its inputs. In particular, the auction results required by the system include the following information for each PAL licensee in each county.

1. County ID
2. PAL licensee ID (possibly FRN)
3. Number of PAL channels the PAL licensee wins in the county

3.2 Step 2: PAL Licensee Input

The system provides a proper interface to allow PAL licensees to indicate their preferred physical PAL channels. The interface ought to have an authentication procedure in order to verify the identities of PAL licensees. Once a PAL licensee is authenticated, it can enter one or multiple sets of *preferred PAL channel assignment* for each county where it wins one or more PAL channels. Each set of preferred PAL channel assignment represents a possible PAL channel assignment that the PAL licensee desires for its PAL license(s) in a county. Each set of preferred PAL channel assignments ought to be verified by the system against the following restrictions:

1. Each selected physical PAL channel is one of the 10 MHz channels between 3550-3650 MHz. This restriction can be automatically enforced by the interface with the PAL licensees.
2. The number of selected physical PAL channels is the same as the number of PAL channels the licensee wins for the county in the auction.

A set of preferred PAL channel assignment is accepted by the system only if it meets the above restrictions. A fixed time frame ought to be allocated for PAL licensees to enter this information. After the time frame, the system no longer takes the preferred PAL channel assignments from PAL licensees and moves to the next stage.

3.3 Step 3: Creation of Common PAL Channel Assignment

The system performs operations in this step county by county. The system tries to find a common PAL channel assignment for a county, composed of preferred PAL channel assignments of all PAL licensees in the county, without assigning a physical channel to more than one PAL licensee. If more than one common PAL channel assignment is possible, the system randomly chooses one as the PAL channel assignment for the county.

For example,

- User 1 has 2 PAL channels
- User 2 has 3 PAL channels
- User 1 desires channel (2,3) or (3,4)
- User 2 desires channel (4, 5, 6) or (5, 6, 7)

There are three common PAL channel assignments for this county, i.e.,

- User 1 (2,3), User 2 (4,5,6)
- User 1(2,3), User 2 (5,6,7)
- User 1(3,4), User 2 (5,6,7).

One of the three assignments will be randomly picked as the final assignment in this step. If a PAL licensee does not indicate any preferred PAL channel assignment, the system will attempt to find its PAL channel assignments that are contiguous in frequency after a common PAL channel assignment is found for licensees who have indicated their preferred PAL channel assignments.
If the system successfully finds a common PAL channel assignment for a county, it moves to Step 5 below. Otherwise the system moves to Step 4.

3.4 Step 4: Sequential PAL Channel Selection

Operation of this step is performed county by county. First, the system creates an ordered list of PAL licensees based on their FRN numbers. An algorithm like the Knuth Shuffle is then used to permute the list of PAL licensees and create a new ordered list.

PAL licensees in the new ordered list are then asked to pick their physical PAL channels according to the order of the list. PAL licensees are subject to the following restriction in PAL channel selection:

1. A PAL licensee needs to pick the exact same number of PAL channels for a county as the number of PAL channels it wins in the auction.
2. A PAL licensee can only choose its physical PAL channels in a way that later PAL licensees can still choose their PAL channels contiguous in frequency.

An example of the second restriction is given in the following:

- User 1 gets 1 PAL channel.
- User 2 gets 1 PAL channel.
- User 3 gets 4 PAL channels.
- User 1 selects its PAL channel first and is offered 10 channels to pick. It picks C4.
- User 2 cannot pick C7 and C8 because selecting C7 or C8 prohibits User 3 from having 4 contiguous PAL channels (refer to Figure). User 2 picks C5 and C6 instead.
- User 3 is guaranteed with one option of 4 contiguous PAL channels. In this case, User 3 can pick C7, C8, C9, C10, but can choose not to have contiguous channels.

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10

3.5 Step 5: PAL Channel Swapping

After finishing Step 4, the system informs all PAL licensees their PAL channel assignments. PAL licensees are allowed to swap or trade their PAL channels within a certain time frame. Once PAL licensees mutually agree a new common PAL channel assignment in a county, the PAL licensees enter the new common PAL channel assignment into the system. The system verifies if there is any conflict in the new common PAL channel assignment and if the new assignment is consistent with the auction results. If the new common PAL channel assignment passes the verification, the system accepts it as the final PAL channel assignment.

3.6 Step 6: Finalization

The system updates the WInnForum PAL database [5] with the final PAL channel assignment results. The final PAL channel assignments ought to stay unchanged for a certain period of time. The industry and PAL licensees ought to have further discussion on when and how to allow changes of PAL channel assignments if there is such a need.

3.7 Possible Simplification

Implementation of the PAL channel assignment system requires serious engineering resource. Simplification of the system can be deemed necessary due to limitation of engineering resource and timeline to complete the system. A possible simplification can eliminate Step 2 and 3 above. Such simplification not only saves engineering resource but also speeds up the process to complete the PAL channel assignment work.

4 Proposal 3

This methodology acknowledges that the preference of PAL licensees in each county could be different due to factors tied to technology, use cases and general services. The algorithm provides a way to meet the FCC Part 96.25 for providing contiguous channels within the county and across required county borders for a PAL licensee.

The methodology proposes a data driven approach of finding a solution by defining a common impairment definition across all counties and opportunity for finding a solution that is fair to all winners of PAL licenses in a county. This approach does not favor a PAL licensee which can have a larger share of PAL licenses in a county compared to another licensee with a smaller number of PAL channels.

In this analysis, a solution of finding licensee preferred channels is possible for a large number of counties. However, the analysis also finds that in a smaller number of counties, there are cases where the number of assignable channels are less than seven or the channels are expected to be impaired to a level, where CBSD operational parameters could be extensively impacted. In such cases, this methodology proposes that a tiered and guided random approach be used so that the goal of maximizing the licensee's interest is well aligned with the overall fairness metric. The methodology does not define a fairness metric as it can not be possible to achieve fairness in heavily constrained channel assignment scenarios.

The algorithm begins with compiling the licensee's preferences for each county that can be expressed through a set of parameters for the primary section of the algorithm and a set of parameters for the secondary section of the algorithm. The primary section along with its parameters convey the preference and allowed tolerance choice within the county. The secondary set of parameters are a method for the PAL licensee to convey assignment of same resources across a subset of neighboring counties.

4.1 Summary of Methodology

1. Step 1: A common standard is applied to the definition of impairments due to "Known Factors" (KF) across all counties. This common definition facilitates and minimizes conflicts arising out of differences in interpretations of impairments across customers of SASs.
2. Step 2: Using the common set of impairments from Step 1, a licensee expresses preference of parameters that contain extent of channel contiguity, a frequency channel range, EIRP tolerance and options for a SAS to apply in order of priority to find a solution. This ensures all PAL licensees, small or large, with respect to a county, provide an input for conflict resolution, when faced with conflicting preferences from different licensees. It is possible that the PAL licensees are customer of multiple SASs.
3. Step 3: The SASs utilize information from Step 1 and Step 2 to build a comprehensive list of PAL licensee preferences and their conflict resolution choices that is influenced by both the Known Factors and if available Unknown Factors.
4. Step 4: The SASs combine the information provided by "All" PAL licensees to begin solution development. In counties, where the solution is easy, the SASs are able to find a common solution with ease within the bounds of primary and secondary set of parameters.

5. Step 5: In counties where SASs encounter conflicts, conflict resolution choices provided by licensees, expressed in Priority 2 and above of primary and secondary parameters can be utilized. This order of priority is applied in order of decreasing operator preference as indicated by Primary P1, P2 and P3 parameters. This process continues till one of partners in the conflict resolution consideration runs out of priority choices.
6. Step 6: In certain counties, the SASs cannot find a solution if the number of licenses or the quality of licenses that are available are outside the realm of choice expressed through primary and secondary parameters. In such cases, a joint licensee guided random solution set is offered to the PAL licensees to make the final choice.
7. Step 7: A solution among licensee participants of Step 6 can be facilitated by the SAS. The licensees can come to an agreement through various means including geographic partitions, secondary market PAL leasing transactional arrangements, etc. This arrangement, once agreed upon, will be provided to the SAS for application.
8. Step 8: The SASs at this stage have a mapping that maps the PAL licensee's logical channels to the physical channels, that can be utilized for PAL channel assignment to licensees claiming PAL Protection through PPAs.

4.2 Schema of Primary and Secondary parameters

The below schema explains a possible structure for a PAL licensee to express their PAL channel assignment preferences. These preferences are expected to guide the SAS in channel assignment and incremental conflict resolution. The algorithm considers the set of primary and secondary set of parameters of each licensee for each county and iteratively attempts to find a solution.

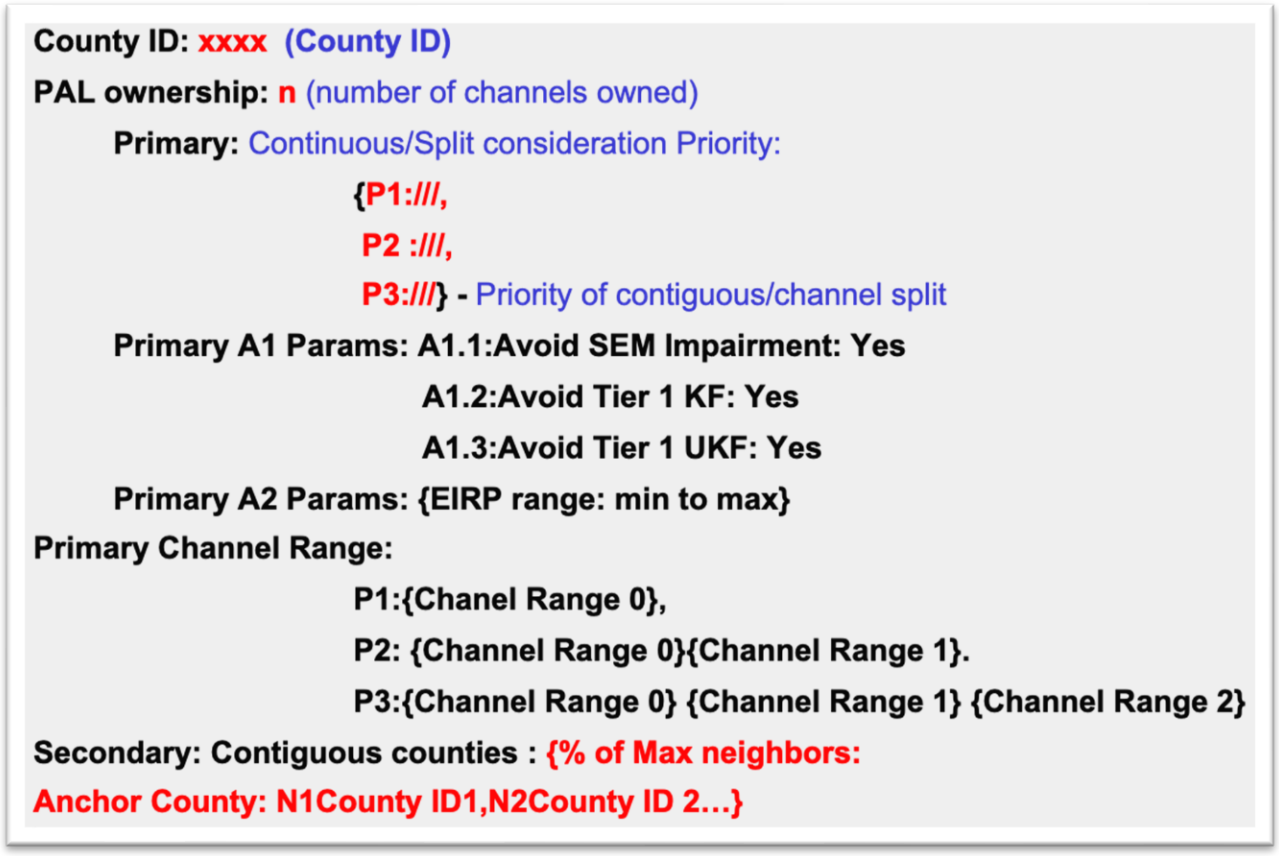


Figure 1: Schema explaining possible structure for a PAL licensee to express their PAL channel assignment preferences

4.3 Explanation of Schema

County ID:

Description: County Identifier as referenced in United States Census Bureau's 2017 counties

PAL Ownership:

Description: This field describes the number of licenses won by the bidder in competitive bidding. Example: If the bidder won 3 licenses for the county, this number will be 3 to indicate the number of PAL licenses owned.

Primary Parameters: The Primary set of parameters contain the preference of PAL licensees. The parameters include:

1. Extent of channel contiguity within a county expressed in terms of priority referenced as P1, P2 and P3.
2. Application of impairment avoidance and their nature
3. Tolerance of power reduction that a SAS can use in its incremental solution finding.

Example: In this example, a PAL licensee owns 4 channels and can express the preference in the following way.

County ID: 2348
PAL Ownership: 4
Primary County Contiguity:
P1: 4/0/0
P2: 3/1/0
P3: NA

Description: The PAL licensee as priority P1 prefers that all 4 channels be contiguous and as priority P2 is willing to compromise and split their channel contiguity requirement to at least 3 channels to be contiguous and one channel which can or can not be contiguous to the 3 channels. Priority P2 is applied if the SAS is unable to find a solution with P1. The licensee chose not to compromise any further and leaves priority P3 empty.

Primary A1 parameters:
A1.1: Avoid SEM impairment: Yes
A1.2: Avoid "Known Factor" impairments: No
A1.3: Avoid "Unknown Factor impairments: Yes

Description: Primary A1 parameters. In this case, the PAL licensee chooses two out of three A1 parameters. The licensee is willing to accommodate impairments due to "Known Factors" possibly due to limited perceived impact or possible removal of an Incumbent in future. Here the licensee prefers to avoid impairments due to SEM as referenced in [7] and avoid impairments that can only be known to SASs.

Primary A2 parameters:
EiRP reduction tolerance(min-max): 0 to 2 dBm

Description: Primary A2 parameters. In this case, the operator is willing to tolerate up to 2 dBm of EiRP reduction if the SAS is able to find a solution within the realm of P1 and P2 preferences. Primary A2 parameters can be applied in conjunction with Primary A1 parameters.

Primary Channel Range:
P1:{4-10},
P2: {3-10}{1-10}.

Description: In addition to expressing the extent of channel contiguity within the county, the operator provides a range where the physical channels can be located. As shown above for P1, the range {4-10} relays the meaning that the 4 channels ought to be contiguously assigned anywhere within the 3590 to 3650 MHz range. In the case of P2:{3-10} {1-10}, the set of ranges relay that 3 contiguous channels ought to be assigned in the range of 3580 to 3650 MHz and the single channel can be placed anywhere in the 3550 to 3650 MHz range.

Secondary: Contiguous counties :{20%:
2348: N1:2347, N2:2345…}

Description: The secondary parameters serve to provide a guidance to SAS to allocate physical channels across a subset of neighboring counties. Assigning same resources across all counties may not be feasible for the SAS, however meeting licensee preferences can be possible across isolated set of neighboring counties. In this illustration, a licensee for County 2348, expresses the set of neighboring counties that ought to be considered for assigning same physical channels across county boundaries.

4.4 Closing

A PAL channel assignment mapping approach that considers a multi-step algorithm to find a licensee preferred solution is proposed. This approach recommends a data driven approach that characterizes the nature of impairments and combines with a tiered solution finding to achieve mapping of PAL logical to PAL physical channels. PAL licensee consideration is very much needed to meet expanding 5G use cases and implementation of new verticals.

5 Proposal 4

According to WInnForum Release 1 specification that was used for SAS certification, the PAL Channel Mapping results are captured in a PAL database that will be accessible by all SASs. As such, all SASs will consistently assign PAL grants based on the content of the PAL database.

The following are required for a PAL licensee, to be able to request a PAL grant:

1. FCC publishes the results of the PAL Auction
2. PAL licenses from the auction are mapped to physical PAL Channels and the PAL Channel mapping results are recorded in the WInnForum PAL database
3. The PAL licensee registers CBSDs with a Serving SAS and obtains CBSD IDs
4. The PAL licensee registers a PPA with a Serving SAS and includes the CBSD IDs that are part of the PPA
5. A CBSD that is part of the PPA, does a Spectrum Inquiry to find out which channels are eligible for PAL, and then requests grants in those channels

Note that item 3 above can happen at any time, even before item 1, and that the CBSDs can always operate prior to PAL Auction using GAA grants.

One approach to address the discrepancies between the opinions of different PAL Licensees is to directly involve the PAL Licensees into the process of determining the PAL Channel mapping. This can be done by the SAS administrators in the following order:

1. Auction results are published by FCC
2. SAS Administrators organize the First Channel Selection Event:
    a. PAL Licensing Areas (i.e. the counties) are ordered based on the number of Licensees in each area. The PAL Licensing Areas with the fewer numbers of PAL Licensees are on top of the list
    b. For each PAL Licensing Area in the list (that was ordered in step 2.a):
        i. The Licensees within the PAL Licensing Area are ordered based on the number of PAL channels awarded per Licensee
            - Licensees with equal number of PAL channels, will be ordered in a fair fashion consistent with the PAL auction results
            - The Licensee with the greatest number of PAL channels will be at the top of the list
        ii. The Licensee at the top of the list gets the first chance to pick the PAL physical channels that are **mandatory to be contiguous**
        iii. Then, the next Licensee in the list will pick the physical channels, which again are mandatory to be contiguous
        iv. Repeat step 2.b.iii until all the Licensees have selected the physical channels
    c. SAS Administrators publish the first daft version of the PAL database
3. SAS Administrators will organize a Channel Trading Event
    a. Licensees are allowed to trade physical channels **within** a PAL Licensing Area
    b. There is a *TBD* time limit for the Channel Trading Event
    c. Traded channels are recoded by the SAS Administrators in the second PAL Database draft
4. PAL database is officially published

Advantages of the proposed approach:

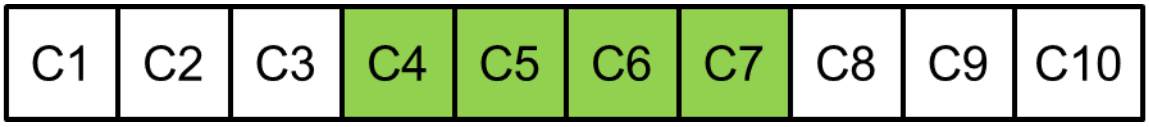
- At the end of the First Channel Selection Event, it is guaranteed that the PAL Licensees will have a block of contiguous physical PAL channels in each PAL Licensing Area, and hence enabling the deployment of wider 5G carriers in the CBRS band
- PAL Licensees are in charge of selecting their physical PAL channels based on their individual needs
- Channel Trading Event can be used to further optimize the PAL channel mapping

Disadvantages of the proposed approach:

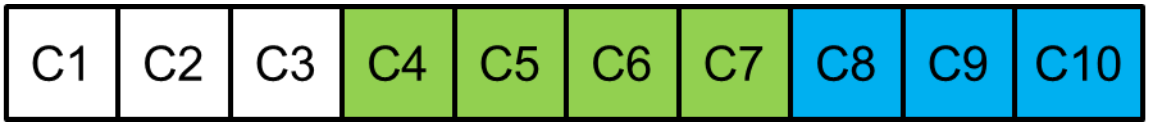
- Depending on the PAL Licensee position in the list, only a subset of physical PAL channels will be available for selection
- Requirement §96.25(b)(1)(i) for contiguous geographic areas (to assign geographically contiguous PALs held by the same Priority Access Licensee to the same channels in each geographic area, to the extent feasible) might not be met unless the Licensees agree to solve it in the Channel Trading Event

Examples of the proposed PAL Channel mapping:

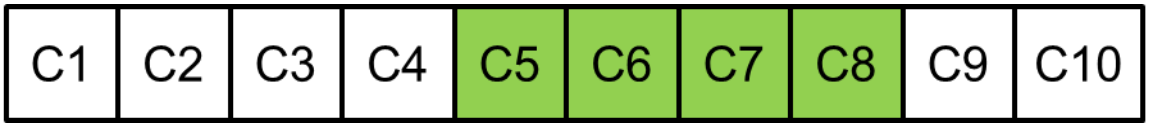
1. Use case 1
   - In a PAL Licensing Area (county), the "Green" PAL licensee is awarded 4 PAL licenses and the "Blue" PAL licensee is awarded 3 PAL licenses
   - First Channel Selection Event,
     - The licensees are ordered: "Green", "Blue"
     - "Green" selects its PAL channels:



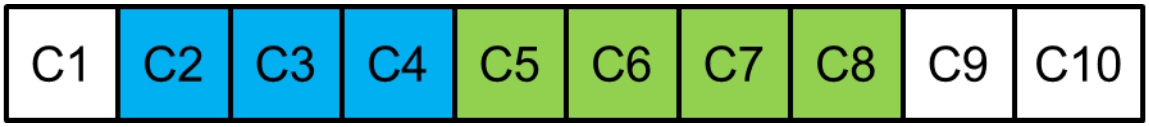
     - "Blue" selects its PAL channels from the remaining channels



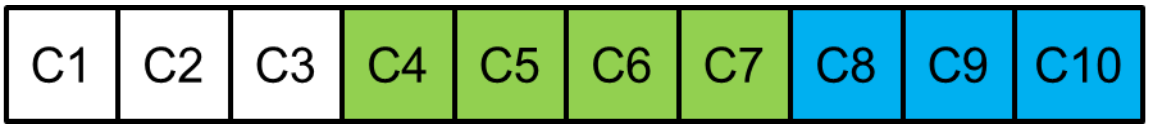
   - Channel Trading Event:
     - No changes are made
2. Use case 2
   - In a PAL Licensing Area (county), the "Green" PAL licensee is awarded 4 PAL licenses and the "Blue" PAL licensee is awarded 3 PAL licenses
   - First Channel Selection Event,
     - The licensees are ordered: "Green", "Blue"
     - "Green" selects its PAL channels:



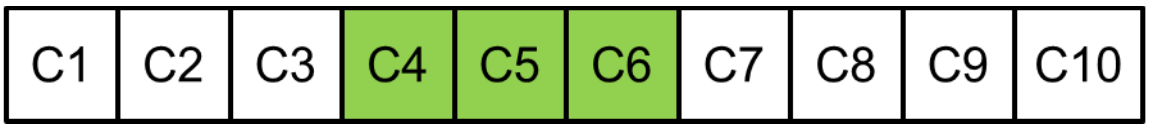
- "Blue" selects its PAL channels from the remaining channels



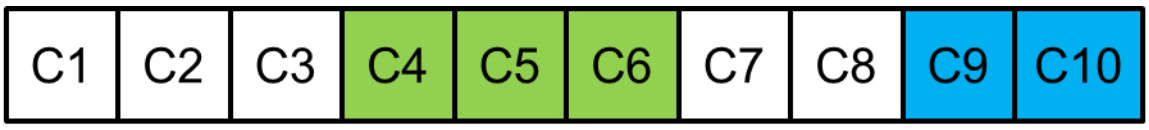
- Channel Trading Event:
  - The following changes are made:



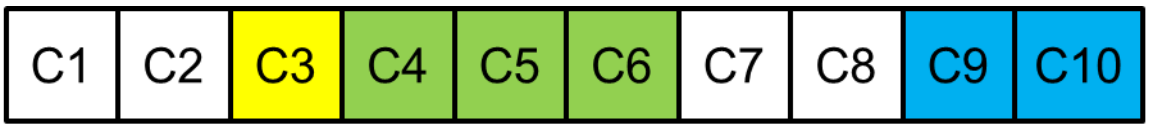
3. Use case 3
   - In a PAL Licensing Area (county), the "Green" PAL licensee is awarded 3 PAL licenses, the "Blue" PAL licensee is awarded 2 PAL licenses, the "Red" PAL licensee is awarded 1 PAL license and the "Yellow" PAL licensee is awarded 1 PAL license
   - First Channel Selection Event,
     - The licensees are ordered: "Green", "Blue", "Yellow", "Red"
     - "Green" selects its PAL channels:



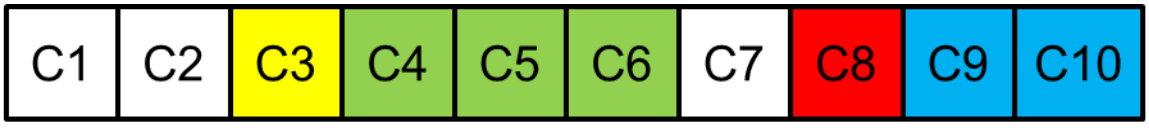
     - "Blue" selects its PAL channels from the remaining channels



     - "Yellow" selects its PAL channels from the remaining channels



     - "Red" selects its PAL channels from the remaining channels



- Channel Trading Event:
  - No changes are made

A variant of the proposed channel mapping process could include restricting the selection of at most 2 continuous channels at a time in steps 2.b.ii and 2.b.iii above. This will allow more options to be available for each licensee for counties where some channels are perceived to be impacted by Part 96 rules. However, this approach is most likely to result in some licensees not being able to get contiguous PAL channels in the same county.

6 Proposal 5

6.1 Prerequisite Consideration for PAL Channel Mapping

There are always at least three unassigned Channels for PAL within the 3,550 – 3,650 MHz band and those Channels can be used for temporary (i.e. evacuation) purposes in case of DPA activation.

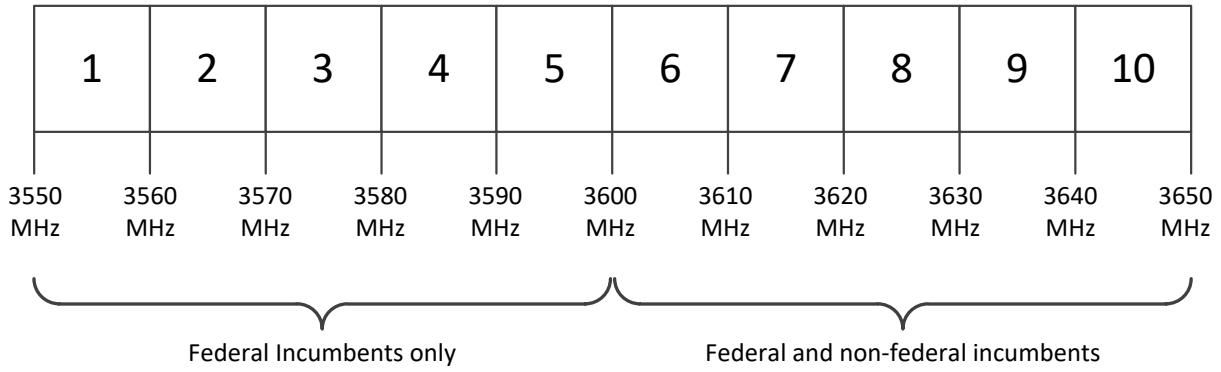


Figure 2: Incumbents in 3,550 – 3,650 MHz band

In general, as illustrated in Figure 2, lower side of 3,550 – 3,650 MHz band is allocated to federal incumbents only and the upper side is allocated to both the federal and non-federal incumbents. In other words, a PAL Grant can be in *Authorized* State subject to federal incumbent protection in the lower side, and a PAL Grant can be in *Authorized* State subject to federal and non-federal incumbent protection in the upper side.

When a CBSD is located in only the neighborhood area of federal incumbent, as long as the associated DPA is deactivated, a PAL Grant can immediately be transitioned to *Authorized* State by including the PAL Grant in the associated DPA Move List.

On the other hand, when a CBSD is located in the neighborhood area of a non-federal incumbent or an ESC Sensor, a PAL Grant can be transitioned to *Authorized* State in only the following situations:

- Headroom interference margin is remained for the PAL Grant just after approval of Grant request from the Managing SAS; or
- The PAL Grant successfully passed IAP during the CPAS.

Considering these conditions, it can be found that, even if a CBSD wants to switch a Channel for a PAL Grant (from the Primary to the Secondary Channel) in response to the DPA activation, a new Grant in the Secondary Channel needs to;

- be verified that a new Grant satisfies the headroom interference margin which is available during the daytime;
- wait completion of CPAS in order to be in *Authorized* State;

That is, a CBSD cannot immediately commence its radio transmission using the PAL Grant in the Secondary Channel in most cases.

Consideration of licensees' own priorities for channels is also important. The licensees can have different priorities with respect to geographical or channel contiguity or desired channel quality. For example, operators planning to use CBRS for mobility, traffic offload and backhaul use cases can have different priorities. An operator's priorities can also be different in different license areas.

6.2 Consideration on PAL Channel Mapping for Secondary Channel

6.2.1 Discussion

This section describes consideration on PAL Channel Mapping for Secondary Channel, especially how to allocate Secondary Channel. To simplify the discussion, the following Primary Channel allocation is considered.

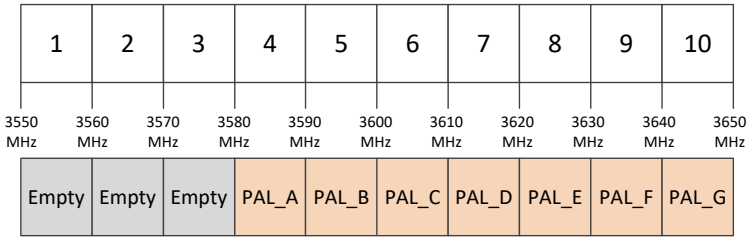
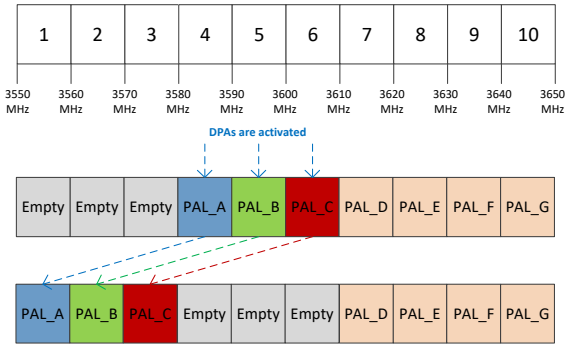
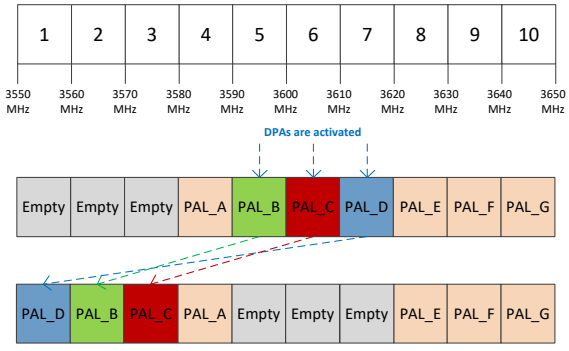


Figure 2 shows examples of how PAL Channels are switched while considering the possible DPA activation where three continuous Channels are activated at the same time.

Case 1) Channels #4-#6 are activated

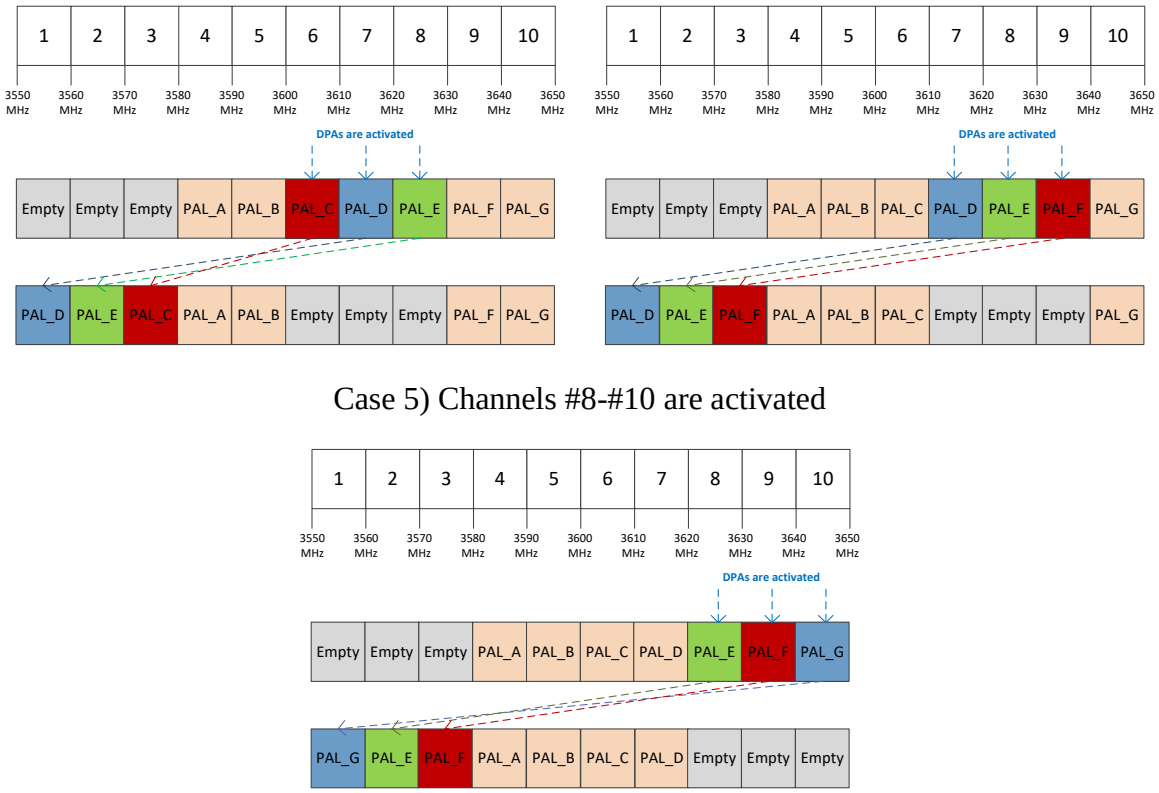


Case 2) Channels #5-#7 are activated



Case 3) Channels #6-#8 are activated

Case 4) Channels #7-#9 are activated



Case 5) Channels #8-#10 are activated

Figure 3: Examples of PAL Channel Evacuation in response to DPA Activation

For example, comparing cases 1-2 and 5, PALs A, D and G are moved to the same Channel (#1), but there is no case where they are moved at the same time. That is, the same Secondary Channel can be allocated for those PALs. Same thing can be said for a pair of PALs B and E and a pair of PALs C and F. This theorem can be established unless non-contiguous three Channels are activated. According to this theorem, it can be found that Secondary Channels can easily be allocated without establishing and using the complicated algorithm once Primary Channels are allocated.

In addition, CBSD Users' preferences can be considered in the Secondary Channel allocation. For example, a CBSD User holding PALs A (Primary Channel #4) and B (Primary Channel #5) might prefer a Secondary Channel for the PAL B to be #3 so that it can continuously use contiguous PAL Channels after DPA activation on Channel #5. In other words, especially CBSD Users that are allocated Primary Channels adjacent to empty Channels might have the preference for Secondary Channel allocation.

6.2.2 Observations

The following observations are shown according to the above discussion.

- The complicated algorithm will not be needed for Secondary Channel Allocation. Secondary Channels can easily be allocated once Primary Channels are allocated.

- Upon the result of Primary Channel allocation, there might be CBSD Users' preference for which Secondary Channels to be allocated. Especially CBSD Users that are allocated Primary Channels adjacent to empty Channels might have the preference for Secondary Channel allocation.

6.3 Consideration on PAL Channel Mapping for Primary Channel

6.3.1 Discussion

This section describes consideration on PAL Channel Mapping for Primary Channel, especially what factors can potentially be considered.

6.3.1.1 Geographical Contiguity

For each CBSD User holding multiple PALs across multiple License Areas, *PAL-Holding Connected Set* can be established for consideration in Primary Channel allocation, where *PAL Holding Connected Set* is a connected set which represents contiguous License Areas where a CBSD User holds at least one PAL as shown in the following figure.

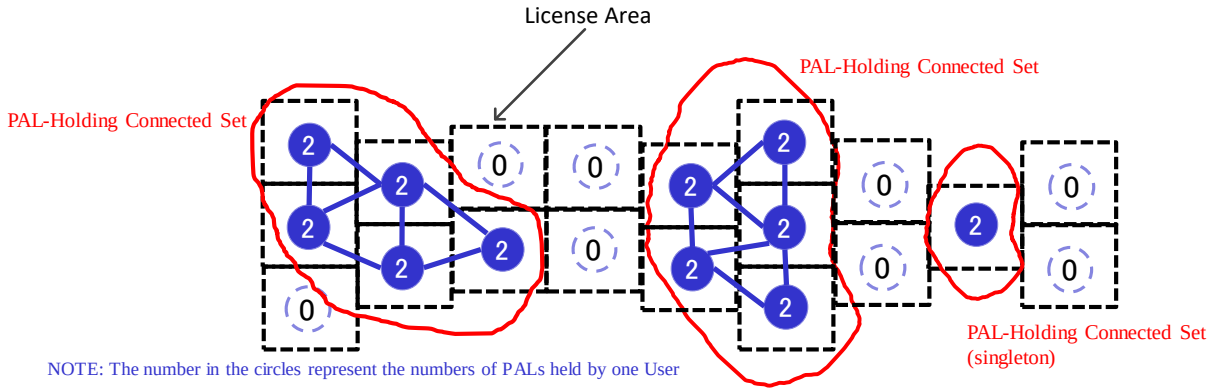


Figure 4: PAL-Holding Connected Set

As the CFR Part 96 requires the geographical contiguity of channel assignment to the extent feasible, PAL-Holding Connected Set can be considered as the basis of Primary Channel allocation "to the extent feasible". For each PAL Holder, to meet geographical contiguity within its PAL-Holding Connected Set to the extent possible could be the first priority in the Primary Channel allocation. On the other hand, one CBSD User can have multiple PAL-Holding Connected Sets. Each of CBSD Users might have different preferences on whether same Channel needs to be allocated among its multiple PAL-Holding Connected Sets (including singleton).

6.3.1.2 Frequency Domain Contiguity

Within a PAL-Holding Connected Set, the number of PALs could be different among the License Areas as shown in the following figure.

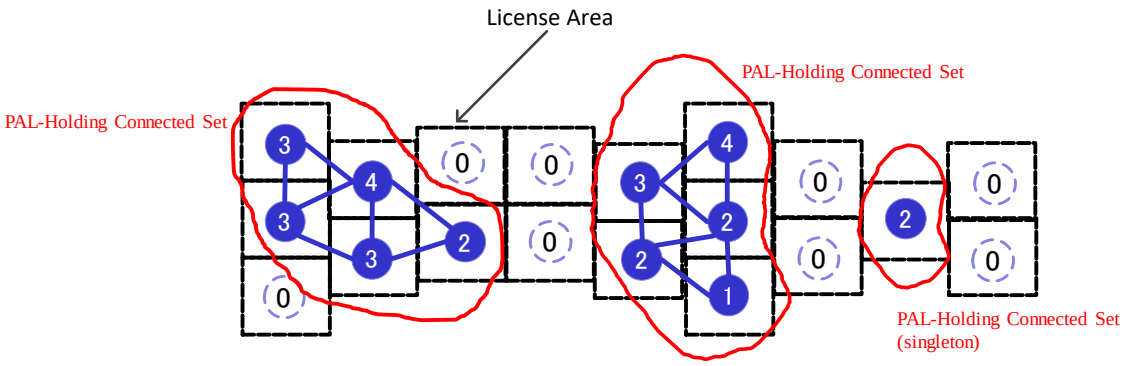


Figure 5: Different number of PALs in a PAL-Holding Connected Set

In this case, the minimum number of contiguous Primary Channels in the frequency domain can be considered for each CBSD User so that geographical contiguity of Primary Channel allocation can be ensured "to the extent feasible". Different CBSD Users might have different preferences on how to determine the minimum number. The examples are as follows:

- Fixed value (e.g. 1)
- The minimum number of PALs within one PAL-Holding Connected Set

If the minimum number of contiguous Primary Channels in the frequency domain is considered, *PAL-Holding Sub-Connected Set* can be established as shown in the figure 5, where the minimum number of contiguous Primary Channels is assumed to be the minimum number of PALs within one PAL-Holding Connected Set.

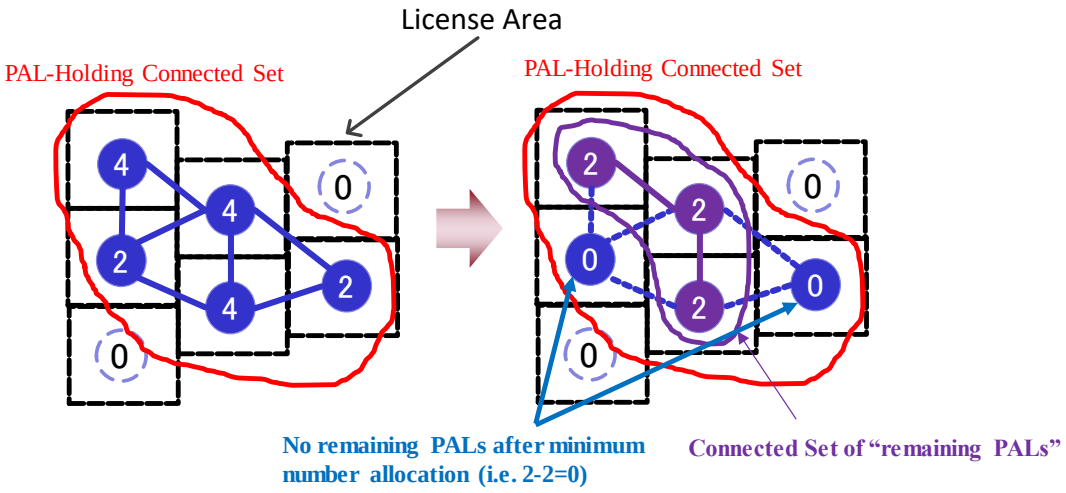


Figure 6: PAL-Holding Sub-Connected Set (see purple boundary in the right side)

Likewise, the minimum number of PALs within one Sub-Connected Set could be considered as the minimum number of contiguous Primary Channels in the frequency domain so that geographical contiguity of Primary Channel allocation for this Sub-Connected Set can be ensured "to the extent feasible".

6.3.2 Observations

The following observations are shown according to the above discussion.

- *Geographical Contiguity*
  - For each CBSD User holding multiple PALs across multiple License Areas, to meet geographical contiguity within its PAL-Holding Connected Set to the extent possible could be the first priority in the Primary Channel allocation.
  - Each of CBSD Users might have different preferences on whether same Channel needs to be allocated among its multiple PAL-Holding Connected Sets (including singleton). This preference might need to be considered in the Primary Channel allocation.
- *Frequency Domain Contiguity*
  - In case where different number of PALs is assigned to one CBSD User in a PAL-Holding Connected Set, the minimum number of contiguous Primary Channels in the frequency domain can be considered for each CBSD User so that geographical contiguity of Primary Channel allocation can be ensured “to the extent feasible”.
  - PAL-Holding Sub-Connected Set can also be established and considered in the Primary Channel allocation.

7 Proposal 6

7.1 Summary

The Multi-Algorithmic approach targets to maximize the fairness of PAL channel allocation between PAL licensees via a set of four algorithms which are executed in a sequential manner until one of them provides a successful output. A weight-based function, deemed the Happiness Factor is employed to ensure the fairness of the PAL channel mapping within PAL licensees and across all the counties. This Multi-Algorithmic approach is envisioned to provide a baseline mapping of PAL channels which later can be used by licensees for bi-lateral trading agreements.

The proposed method ensures intra-county contiguous channel allocation and maximizes the chances of providing inter-county contiguous channel allocation if desired by PAL licensees with licenses in several adjacent counties. The flexibility of the algorithm can be exploited to relax the constrains of the intra-contiguous channel allocation by establishing a threshold for the maximum number of contiguous PAL channels the algorithms will attempt per PAL licensee.

This approach requires each PAL licensee to provide on a per county basis the below information:

- Preferred Channel Allocation: Ordered list of PAL Channels which the PAL licensee desires to be allocated
- Undesired Channels: Ordered List of undesired PAL channels

Additionally, to the above inputs, the PAL licensee will indicate if it desires to prioritize inter-county contiguity, i.e., attempt to maximize the same frequency allocation across neighboring counties.

Prior to PAL channel mapping procedures on a county basis, the approach recommends creating a Prioritized County List which is an ordered list of counties arranged from most challenging for PAL channel allocation to least.

Once the Prioritized County List is created, for each county in the list, the algorithm will:

1. Attempt to meet all PAL licensees' requests in terms of Preferred Channel Allocation (PCA) input for the county. This step first attempts to find a solution which satisfies the PCA of all the PAL licensees within the county. If successful the algorithm proceeds to step 6, else proceed to next step.
2. Search for an allocation where each PAL licensees Undesired Channels can be avoided for their assignments. If successful the algorithm proceeds to step 6, else proceed to next step.
3. Upon failure of meeting PAL licensees requests in steps 1 & 2, this algorithm will attempt to find a solution employing the SASs knowledge of least favorable channels e.g., encumbrances within the county. If successful the algorithm proceeds to step 6, else proceed to next step.
4. Prior to executing the last algorithm (step 5), the method ensures that there are no other counties where the algorithms in step 1-3 would yield a successful solution. This is done by placing the current county at the bottom of the County Prioritization List if steps 1-3 were attempted in this county previously. This ensures the methodology keeps 'pseudo-random' based allocations as a last step and employ this to better equalize fairness based on the output

of other counties where solutions were found in the previous steps. If steps 1-3 were not attempted in this county previously, select the next county and return to step 1, else proceed to the next step.

5. The last algorithm in set is based on 'pseudo-random' ordering of the PAL licensees in the county where the first PAL licensee in the list will have priority in the selection of its channel. This algorithm will always yield a solution. The ordering of the list is performed in a 'pseudo-random' manner based on the Happiness Factor values of each PAL licensee in the county.
6. Update the Happiness Factor per PAL licensee based on the result of the PAL Channel Mapping process. The Happiness Factor is updated based on a weight-based function which evaluates channels allocated vs desired/undesired, the number of impaired channels assigned and a factor which considers the number of counties remaining for assignment vs the number of counties in which the PAL licensee has licenses.
7. Select next county in the Prioritized County List.

Note: The inter-county contiguity is attempted for PAL licensees which selected this option by adding the PAL channel allocations from all adjacent counties to the beginning of the Preferred Channel Allocation list in step 1. Since the Preferred Channel Allocation list is an ordered list the adjacent counties with highest number of PAL licenses can be employed to determine the order of addition to the list.

7.2 Detailed Description

As described in section 7.1, the proposed method requires the following inputs for each PAL licensee on a per county basis:

- Preferred Channel Allocation (PCA): Ordered list of PAL Channels which the PAL licensee desires to be allocated. The maximum dimension for this ordered list (M) provided by the PAL licensees can be limited by SAS admin.
- Undesired Channels (UC): List of undesired PAL channels. The maximum dimension for this ordered list (N) provided by the PAL licensees can be limited by SAS admin

Additionally, to the above inputs, the PAL licensee will indicate if it desires to prioritize inter-county contiguity, i.e., attempt to maximize the same frequency allocation across neighboring counties.

Prior to performing the PAL channel mapping procedures on a county basis, the approach recommends creating a Prioritized County List which is an ordered list of counties arranged from most challenging for PAL channel allocation to least. The complexity of PAL channel allocation within a county can be evaluated based on several criteria's, e.g., a weighted function considering:

- Number of PAL licensees in the county.
- Sum of the PAL Undesired Channels provided by PAL licensees in the County.
- Number of impaired channels, as per SAS information, in the county
- Number of neighbor counties where Step 1, could not find a successful solution based on the input of PAL Preferred Channels from PAL licensees.

The fairness in channel allocation is measured via a Happiness Factor. The Happiness Factor is a weight based function which is updated on per county basis and represents the cumulative level of satisfaction for each PAL licensee. The Happiness Factor is initialized to 0 for all PAL licensees. Once the Prioritized County List is created, for each county in the list the algorithm will:

1. Attempt to meet all PAL licensees requests in terms of Preferred Channel Allocation(PCA) input for the county. This step first attempts to find a solution which satisfies the PCA of all the PAL licensees within the county. If successful the algorithm proceeds to step 6, else proceed to next step.

Note 1: The inter-county contiguity is attempted for PAL licensees which selected this option by adding the PAL channel allocations from all adjacent counties to the beginning of the Preferred Channel Allocation list in this step. Since the Preferred Channel Allocation list is an ordered list the adjacent counties with highest number of PAL licenses can be employed to determine the order of addition to the list.

Note 2: If this algorithm was already run previously for the selected county, i.e., it was put back in the list due to requiring 'pseudo-random' allocation, proceed to Step 5.

Pseudo Code:
Assumption: K PAL licensees in the county. Each licensee provides an ordered list of T PCAs, each element of the list is composed of N_chan consecutive channels.
Step 1.1

- Set n =1, and for all the K PAL licensee, select the first n elements of the PCA. For all of them, select one element, starting with the first, and check if the combination of PCAs has no overlap and hence it is a possible channel assignment.

Step 1.2

- If there is no overlap of PCAs in the combination selected, add the solution to a Possible_solution vector (Everyone is assigned as per their request since they were all orthogonal)
- If there is no possible combination without overlap, and if n<T, increase n (i.e., include one extra element from the PCAs list from each PAL licensee) and repeat from Step 1.1. Once all combinations are tested proceed to Step 1.3

Step 1.3

- If Possible_ solution vector is not empty, select a solution where the solution employs the highest priority PCA of each licensee or the overall Happiness Factor of the K licensees can be maximized ; proceed to Step 6;
- If the Possible_solution vector is empty proceed to Step 2

2. Search for an allocation where each PAL licensees Undesired Channels can be avoided for their assignments. If successful the algorithm proceeds to step 6, else the algorithm could proceed in two possible ways:
    a) Repeat step 2 and reduce the UC list provided by each PAL licensee by 1, i.e., trim the length of UC list to N-1.
    b) Proceed to next step.

Pseudo Code:
Step 2.1

- Order the PAL licensees from the one requesting the largest set of contiguous channel to the least, indicate such list by the vector V. If there are several licensees with the same number of PAL channels, they will be ordered randomly or based on the happiness factor metrics.
- Set n = 1.

Step 2.2

- User selected = V(n).
- Remove from the assignable channel set the channel disliked from the user. Allocate the channels from the first available channel. If no set of contiguous set of channels is available, then:
- If n =1, go to Step 3. Algorithm is unsuccessful in finding an allocation.
- If n>0, set n=n-1. Add V(n). first_channel to the list of disliked channel and repeat Step 2.2 .
- Otherwise:
    - Set V(n). first_channel = the first channel allocated to the user.
    - Remove the channels allocated to user n from the list of assignable channels.
    - If n= N, algorithm ends successfully, proceed to step 6.
    - If n<N, set n=n+1, repeat 2.

Note: From a fairness point of view, it is indifferent which PAL licensee the algorithm starts with first. All users needs to be satisfied for a successful outcome. Setting PAL licensees with the highest number of licenses first, increases the probability of finding allocations of PAL licensees with fewer iterations.

3. Upon failure of meeting PAL licensees requests in steps 1 & 2, this algorithm will attempt to find a solution employing the SASs knowledge of least favorable channels e.g., encumbrances within the county. If successful the algorithm proceeds to step 6, else proceed to next step.

Pseudo Code:
Step 3.1

- Remove from the set of assignable channels, the ones known from the SAS to be impaired.

Step 3.2

- List the users(PAL licensees) from the one requesting largest set of contiguous to the least, denote this set as the vector V. Note if there are several users with the same number of PAL channels, they will be ordered randomly.
- Set n =1

Step 3.3

- For V(n) allocate a set of contiguous channel using the lowest possible V(n). first_channel .
- If an allocation is not possible, this algorithm is unsuccessful, proceed to step 4.
- If an allocation is found, then

- If n = N , algorithm is successful, proceed to step 6
- If n< N, then set n=n+1, and repeat step 3.3.

Note: From a fairness point of view, it is indifferent which PAL licensee the algorithm starts with first. All users needs to be satisfied for a successful outcome. Setting PAL licensees with the highest number of licenses first, increases the probability of finding allocations of PAL licensees with fewer iterations.

4. Prior to executing the last algorithm (step 5), the method ensures that there are no other counties where the algorithms in step 1-3 would yield a successful solution. This is done by placing the current county at the bottom of the County Prioritization List, if steps 1-3 failed to provide a solution for this county. This ensures that the 'pseudo-random' based allocations is adopted only as a last resort and employ this as an additional method to improve fairness. If steps 1-3 were not attempted in this county previously, select the next county and return to step 1, else proceed to the next step.

5. The last algorithm in set is based on 'pseudo-random' ordering of the PAL licensees in the county where the first PAL licensee in the list will have priority in the selection of its channel. This algorithm will always yield a solution. The ordering of the list is performed in a 'pseudo-random' manner based on the Happiness Factor values of each PAL licensee in the county.

Pseudo Code:
Step 5.1

- Order the PAL licensees randomly, and report the order in a vector V. The pseudo-random order can be defined based on uniform distribution considering the Happiness Factor of each PAL licensee.
- Set n= 1.

Step 5.2

- Assign V(n).first_channel = the first available channel.
- Remove the channels assigned from the list of the available channels.
- If n=N, algorithm is successful, proceed to step 6
- If n<N then set n=n+1, repeat Step 5.2.

6. Update the Happiness Factor per PAL licensee based on the result of the PAL Channel Mapping process. The Happiness Factor is updated based on a weight-based function which evaluates channels allocated vs desired/undesired, the number of impaired channels assigned and a factor which considers the number of counties remaining for assignment vs the number of counties in which the PAL licensee has licenses. An example function which can be used for the calculation of the Happiness Factor is:

Happiness_factor(n)= $w_1(CA \neq PCA) + w_2(CA == UC) + w3(CA == SAS.impaired) + w4(RC)$

Where:

- n: Identifies the PAL licensee
- CA is the set of channel allocated.

- (CA≠PCA) represents the amount of allocated channels present in the PCA set.
- (CA==UC)) represents the amount of allocated channels present in the UC set.
- (CA==SAS.Impaired) represents the amount of allocated channels present in the SAS impaired channel set.
- RC = Remaining counties in which channel allocation needs to be done) / (Number of counties in which licensee has licenses and PAL channel allocation has not been performed)
- w1, w2, w3 and w4 are weights to be determined by the SAS admin. Example values for the weights could be w1 = 1, w2 = -1, w3 = -1.5, w4=0.1

7. Remove current county from the Prioritized County List and select the next county in the list.

7.2.1 Example Scenarios

The following section provides some example scenarios to better illustrate the proposed PAL channel mapping method described in section 7.2.

For all the examples below, it is assumed that the following weights are employed in the evaluation of the Happiness Factor: w1 = 1, w2 = -1, w3 = -1.5, w4=0.1.

7.2.1.1 Example 1: Single County – Preferred Channel Allocation Possible

The following example provides the PAL channel mapping outcome for a single county in which the algorithm converges to a solution based on the PAL licensees inputs of Preferred Channel Allocations, thus the relative Happiness Factor for all licensees is 100% for this county.

Table 1 Example 1: Single County – Preferred Channel Allocation Possible

County Id	PAL Licensee ID	Number of PAL Channels	Preferred Channel allocation (PCA)	Undesired Channels (UC)	Inter County Contiguity preferences	PAL Primary Channel Allocation	Happiness Factor	Relative Happiness Factor
1	1	1	{6,7,8,9}	{1,10}	No	{9}	1	100%
1	2	4	{(3,4,5,6),(4,5,6,7),(5,6,7,8)}	{1,10}	No	{5,6,7,8}	4	100%
1	3	2	{(3,4),(4,5),(5,6)}	{1,10}	No	{3,4}	2	100%

7.2.1.2 Example 2: Single County – Preferred Channel Allocation Not Possible

The following example provides the PAL channel mapping outcome for a single county in which the algorithm cannot converge to a solution based on the PAL licensees inputs of Preferred Channel Allocations. The algorithm does find a solution in step 2 where every PAL licensees Undesired Channel requests can be met. In this case the relative Happiness Factor for *PAL licensee Id* =1 is 25%, since 1 out of the 4 allocated channels is included as part of its PCA, where as for *PAL licensee Id* =2 is 100% and *PAL licensee Id* =3 its 0%.

Table 2 Example 2: Single County – Preferred Channel Allocation Not Possible

County Id	PAL Licensee ID	Number of PAL Channels	Preferred Channel allocation	Undesired Channels	Inter County Contiguity preferences	PAL Primary Channel Allocation	Happiness Factor	Relative Happiness Factor
1	1	4	{(5,6,7,8),(6,7,8,9)}	{1,10}	Yes	{2,3,4,5}	1	25%
1	2	2	{(4,5),(5,6),(6,7),(7,8)}	{1,3,10}	No	{6,7}	2	100%
1	3	1	{4,5,6}	{1,2,10}	No	{9}	0	0%

7.2.2 Example 3: Multi-County Scenario with requirements for inter-county contiguity

The following example provides the outcome of running the proposed multi-algorithmic approach for a multi-county scenario depicted in **Error! Reference source not found.**.

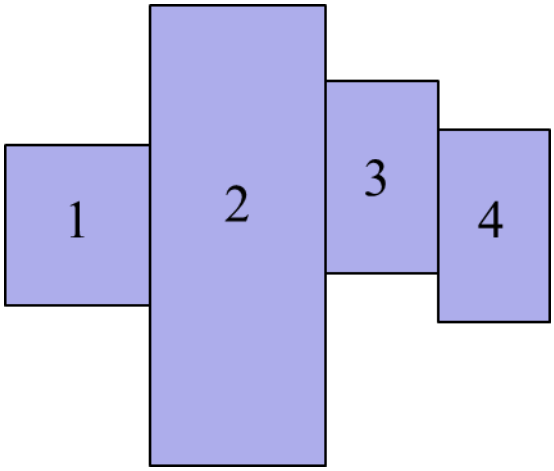


Figure 7: County Layout

In this example all PAL licensees prioritize inter county contiguity as shown in **Error! Reference source not found.**. The outcome of the county prioritization list, in this scenario happens to be *County Id*={1,2,3,4}, hence *County Id*=1 is the first selected for PAL channel mapping process. The algorithm in Step 1 cannot find a solution for *County Id*=1 and hence proceeds to the algorithm in step 2 which does find a suitable solution based on avoiding every PAL licensees Undesired Channels(UC). The Happiness factor are updated based on the outcome of the assignments.

For *County Id*={2,3,4} a solution is found within Step 1 algorithm. For these counties, since inter-county contiguity was chosen by the PAL licensees, the PCA input provided by the PAL licensees is modified to include the PAL channel allocation of adjacent counties as the highest priority. These modifications are highlighted in red font, where applicable, within the '*Modified PCA for inter-county contiguity*' column.

The outcome of processing the four counties shows that all PAL licensees have a positive Happiness Factor and although their cumulative values are different, their relative values are more equalized.

Table 3 Example 3: Multi-county

County Id	PAL Licensee ID	Number of PAL Channels	Preferred Channel allocation (PCA)	Undesired Channels (UC)	Inter County Contiguity preferences	Modified PCA for inter-county contiguity	PAL Primary Channel Allocation	Cummulative Happiness Factor	Relative Happiness Factor
1	1	4	{(5,6,7,8),(6,7,8,9)}	{1,10}	Yes	N/A	{2,3,4,5}	1	25%
1	2	2	{(4,5),(5,6),(6,7),(7,8)}	{1,10}	Yes	N/A	{6,7}	2	100%
1	3	1	{4,5,6}	{1,2,10}	Yes	N/A	{9}	0	0%
2	1	4	{(3,4,5,6),(4,5,6,7),(5,6,7,8),(6,7,8,9)}	{1,10}	Yes	{(2,3,4,5),(3,4,5,6),(4,5,6,7),(5,6,7,8),(6,7,8,9)}	{2,3,4,5}	5	62.5%
2	2	2	{(4,5),(5,6),(6,7),(7,8)}	{1,10}	Yes	{(6,7),(4,5),(5,6),(7,8)}	{6,7}	4	100%
2	3	1	{4,5,6}	{1,2,10}	Yes	{9,4,5,6}	{9}	1	50%
3	1	4	{(2,3,4,5),(3,4,5,6),(4,5,6,7),(5,6,7,8)}	{1,10}	Yes	{(2,3,4,5),(3,4,5,6),(4,5,6,7),(5,6,7,8)}	{2,3,4,5}	9	75%
3	2	2	{(4,5),(5,6),(6,7),(7,8)}	{1,10}	Yes	{(6,7),(4,5),(5,6),(7,8)}	{6,7}	6	100%
3	3	1	{2,3,4,5,6}	{1,10}	Yes	{9,2,3,4,5,6}	{9}	2	66.7%
4	1	4	{(2,3,4,5),(3,4,5,6),(4,5,6,7),(5,6,7,8)}	{1,10}	Yes	{(2,3,4,5),(3,4,5,6),(4,5,6,7),(5,6,7,8)}	{2,3,4,5}	13	81.3%
4	2	3	{(4,5,6),(5,6,7),(6,7,8)}	{1,10}	Yes	{(5,6,7),(6,7,8),(4,5,6),}	{6,7,8}	9	100%

8 Proposal 7

Once PAL auction is complete, the PAL channel assignment method takes the PAL auction results, from an FCC database, as its inputs. In addition to these inputs the method also seeks input from PAL licensee on their preferred physical PAL channels.

The choice of preferred physical license in each county is evaluated to identify if there are other mutually interchangeable channels available which has similar incumbent protection criteria.

8.1 Equivalent Channel identification

For a given county, there is a contiguity in spectral dimension in terms of impairment. PAL channel assignment problem can be simplified by recognizing this contiguity in the PAL impairment. In most cases, contiguity in impacted PAL channel can be observed from the point of view of incumbent or other protection entities.

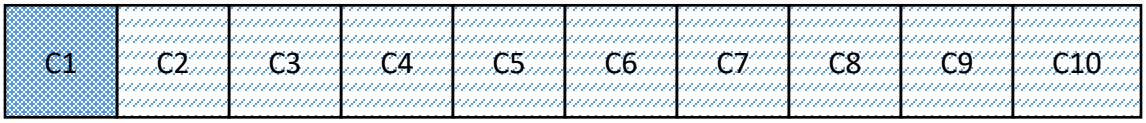
1. All ten channels are free
2. All ten channels are equally impacted
3. A block of channels in lower portion is impacted and impacted channels are encumbered similarly
4. A block of channels in upper portion is impacted and impacted channels are encumbered similarly

The choice of preferred physical license in each county is evaluated against the above scenarios to identify if there are other mutually interchangeable channels available which is similar in terms of incumbent protection criteria. Depending on the CBSD transmission bandwidth, the first two PAL channels can be subject to A-MPR and hence ought to be accounted when identifying equivalent channels.

8.2 Expansion of channel choices provided by Licensee

Once the equivalent channels are identified, the choices provided by licensee ought to be augmented to add other equivalent alternate channels. The channel preference from the licensee can be maintained in terms of rank when trying to find the best fit or solution.

Example: Case1



PAL owner **A** has two licensee and provides (2,3) and (4,5) as their channel choices for the county. Since all PAL channels (2-10) are equally encumbered from the incumbent's point of view then the choice could be extended to (3,4), (5,6), (6,7), (7,8), (8,9) and (9,10).

Example: Case2

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10

PAL owner **B** has two licensee and provides (2,3) and (4,5) as their channel choices for the county. Since all PAL channels (2-5) are unencumbered from the incumbent's point of view then the choice could be extended to only (3,4).

8.3 Applicability

The criteria of expanding equivalent channel choices for a licensee can be extended to any method for PAL channel assignment.

9 References

[1] https://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=0076fe7586178336d9db4c5146da8797&mc=true&n=pt47.5.96&r=PART&ty=HTML
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[5] Wireless Innovation Forum, "Operations for Citizens Broadband Radio Service (CBRS): Priority Access License (PAL) Database Technical Specification", https://winnf.memberclicks.net/assets/CBRS/WINNF-TS-0245.pdf
[6] Wireless Innovation Forum, "CBRS Incumbent Protections and Encumbrances Overview", https://winnf.memberclicks.net/assets/CBRS/WINNF-TR-5003.pdf
[7] RTG-19-002, Nokia N48 A-MPR Study, 2019.01.08

10 Appendix: PAL Channel Mapping Policies and Decision Points

According to WinnForum requirements (R2-SPU-10 in [3]), after the PAL auction is completed, and prior to any use of the PAL licenses, the collection of SAS Admins must cooperate to determine the Steady State Primary PAL Channel Assignment for each licensee within each PAL service area.

It is generally agreed that in most practical scenarios, finding a solution that meets all regulatory and performance requirements for all Licensees is impossible. Therefore, the solution must involve the proposals from PAL licensees in each PAL service area

Even though this Technical Report is providing multiple proposals to achieve this goal, it is understood that there must be one single algorithm applied by SAS Admins. To that end, SAS Admins must make decisions at several decision points.

Moreover, it is proposed to categorize the algorithm in two stages, Stage 1 and Stage 2. This Appendix provides high level PAL channel mapping policies in both Stage 1 and Stage 2 and outlines the decision points at each stage to determine the final algorithms for the consideration of SAS Admins.

Note 1: This Appendix does not attempt to propose a new algorithm, in addition to what have been proposed in this Technical Report. Moreover, this Appendix does not try to draw a one to one mapping between the approaches discussed in this Appendix and the proposals discussed in the main body of this Technical Report. Rather, this Appendix attempts to provide a high-level framework and decision points for the PAL Channel Mapping Algorithm, which can contain all methodologies proposed in the main body of this Technical Report.

Note 2: Upon the completion of PAL Channel Mapping, PAL licensees might engage in channel swapping with a second PAL licensee within a PAL service area, assuming that there is no impact on the operation and performance of channels allocated to a third PAL licensee.

10.1 PAL Channel Mapping Stage 1

The PAL Channel Mapping Algorithm would run in an “Allocation Area” consisted of N neighboring counties. Default value of N is N=1.

- Decision Point 1: Decide whether algorithm is run in every county independently (N=1), or the algorithm is run over an area consisting of N neighboring counties (N > 1).

The process starts with each licensee providing its proposal(s) for the Allocation Area, based upon its own priority criteria. The criteria could be channel adjacency within a county, same channel on adjacent counties, individual channel performances, encumbrances at each channel and/or geographical area, etc. If a licensee does not propose any combination, SAS Admins might assume a default proposal for that licensee in the Allocation Area.

If there is no conflict (channel overlap) among the proposed mappings for an Allocation Area, SAS Admins will accept the proposal, and consider the process completed for that particular Allocation Area.

Note 3: In any case, whether there is overlap among the channels or not, PAL licensees might revise their proposals based upon the guidance provided by the SAS Admin(s).

10.2 PAL Channel Mapping Stage 2

If there is channel overlap among proposals from multiple licensees within an Allocation Area, then SAS Admins must resolve the contentions using an algorithm that could be one of the methodologies in this Technical Report, or a combination of those methodologies or modified versions of those methodologies. In the following, a framework containing four (4) main Approaches are classified. Note that some of these approaches might be combined within a certain Allocation Area. For example, if in Approach 2, some licensees have the same priority, or in Approach 4, the proposed lists are the same, we will end up with Approach 3.

- Decision Point 2: Decide which approach (Approach 1 to 4) or combination of approaches are used by SAS Admins.

10.2.1 PAL Channel Mapping Approach 1

In Approach 1, SAS Admins decide the PAL channels based on some channel priorities. If the proposed channel combinations by licensees overlap, the algorithm would develop the fairness criteria and allocation mechanisms among the channels for PAL Licensees to determine the final channel allocations

- Decision Point 2_1_1: Define the fairness criteria and priorities for Approach 1

10.2.2 PAL Channel Mapping Approach 2

In Approach 2, the Algorithm apply some criteria and ranking among licensees to decide the priority among PAL licensees for selecting the channels. Note that in this approach, the algorithm will not compare or decide PAL channels based on some performance criteria. Rather, the order of selection is defined among multiple PAL licensees.

- Decision Point 2_2_1: Define the priority mechanism to define order/ranking among PAL licensees to select channels within an Allocation Area, for Approach 2.

In Approach 2, the licensee who is selected to pick the channels first, could pick all its channels in one shot, or channel selection might be iterative and/or in a round robin fashion.

- Decision Point 2_2_2: In Approach 2, decide whether the channel selection for the selected PAL Licensee occurs in one shot, or is performed in an iterative/round robin fashion.

If iterative/round robin fashion is selected, then the algorithm must decide about the number of channels selected by the PAL licensee at each iteration.

- Decision Point 2_2_3: For iterative/round robin fashion Approach 2, decide maximum number of channels selected at each iteration by the PAL Licensee

10.2.3 PAL Channel Mapping Approach 3

In Approach 3, the algorithm selects order/rank among the PAL licensees to pick their desired channel(s) in a random fashion. The random criteria might be a simple uniform random mechanism or some weighted random mechanisms.

- Decision Point 2_3_1: For Approach 3, decide the random mechanism to select the order/rank of PAL licensees to pick their desired channels.

Similar to Approach 2, the licensee who is selected to pick the channel(s) first, could pick all its channels in one shot, or channel selection might be iterative and/or in a round robin fashion.

- Decision Point 2_3_2: In Approach 3, decide whether the channel selection for the selected PAL Licensee occurs in one shot, or is performed in an iterative/round robin fashion.

Moreover, the random algorithm might run independently among multiple Allocation Areas, or consider dependence among Allocation Areas to avoid a Licensee randomly given a high order in many or all Allocation Areas

- Decision Point 2_3_3: In Approach 3, decide whether there is a dependence among the random criteria in different Allocation Areas.

10.2.4 PAL Channel Mapping Approach 4

In Approach 4, the PAL licensees are expected to provide multiple proposals for their desired channel allocations within the Allocation Area, with associated priority for each of those proposals. The algorithm would resolve the conflict by optimizing an objective function according to the priority lists and some assigned weight factors among multiple PAL Licensees.

- Decision Point 2_4_1: In Approach 4, define the objective function to select the most optimum channel allocations
- Decision Point 2_4_2: In Approach 4, decide the weight factors among multiple PAL licensees to be used in defining he objective function

The proposed lists by PAL licensees may be provided in one shot or in different steps/iterations

- Decision Point 2_4_3: In Approach 4, decide whether the proposals are provided in one shot or in different steps/iterations

Whether the optimization converges or not greatly depends on the number of proposals provided by each licensee. In other words, if for example only one desired combination is proposed by all licensees, and there is conflict among those proposals (beyond Stage 1), the algorithm is blocked and no convergence is achieved, The algorithm might require the number of desired channel combinations proposed by each licensee to be more than a given value, so that the algorithm may converge

- Decision Point 2_4_4: For Approach 4, decide the minimum number of desired channel combinations provided by each PAL licensee.

10.3 PAL Channel Mapping Repetition

The PAL license term is defined by FCC to be 10 years. The PAL channel allocation algorithm determined by SAS Admins might be applied only once for the duration of PAL license term (10 years) or be repeated within some given time duration (e.g., every 2 years). In other words, whether we need to refresh the PAL static channels for each licensee during the 10 years PAL license term or not.

- Decision Point 3: Decide how often the selected algorithm is repeated with one PAL license term (10 years)

10.4 Summary