Greedy Channel Selection for Dynamic Spectrum Access Radios

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***Abstract*— Dynamic Spectrum Access (DSA) radios typically select their radio channels according to their data networking goals, a defined DSA spectrum operating policy, and the state of the RF spectrum. RF spectrum sensing can be used to collect information about the state of the RF spectrum and prioritize which channels should be assigned for DSA radio waveform transmission and reception. This paper describes a Greedy Channel Ranking Algorithm (GCRA) used to calculate and rank RF interference metrics for observed DSA radio channels. The channel rankings can then be used to select and/or avoid channels in order to attain a desired DSA radio performance level. Experimental measurements are collected using our custom software-defined radio (SDR) system to quantify the performance of using GCRA for a DSA radio application. Analysis of these results show that both *pre* and *post-detection average interference power* metrics are the most accurate metrics for selecting groups of radio channels to solve constrained channel assignment problems in occupied gray space spectrum.**

Keywords—spectrum sensing, spectrum sharing, gray space, opportunistic DSA, interference metrics

I. Introduction

Typically, the Radio Frequency (RF) spectrum sensing function of a Dynamic Spectrum Access (DSA) radio is concerned with detecting, characterizing, and classifying the emissions of other RF systems in a set of radio channels being evaluated for sharing [1]. Once the DSA radio has sensed and prioritized its channel access, it attempts to use the prioritized channels according to a defined DSA operating policy. For example, a DSA radio may possess a "do no harm" spectrum sharing policy that mandates that it cannot select radio channels that degrade the performance of band incumbents, such as military radars or radio links [2]. Conversely, a greedy spectrum usage policy is a reasonable DSA radio behavior when applied to military defense or emergency first-responders services, as recently addressed in DARPA's Spectrum Collaboration Challenge (SC2) [3]. A DSA radio could use spectrum sensing to decide whether it is able to effectively use a radio channel without considering the impact of its RF emissions to other RF systems using the same spectrum [4]. Prior research identified salient features of occupied "gray space" spectrum versus unoccupied "white space" spectrum but did not develop algorithms for prioritizing channel selection or analyze the accuracy of those algorithms [5]. In this paper, we describe an automatic radio channel ranking algorithm that optimizes greedy spectrum usage by DSA radios in gray space spectrum. We then quantify the accuracy of the DSA channel ranking algorithm with experimental measurements captured with our custom software-defined radio (SDR) system [6].

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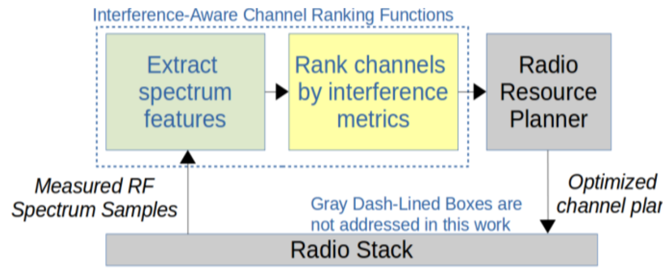

Fig. 1. Overview of Greedy Channel Ranking Algorithm (GCRA) integrated into DSA radio architecture

II. Operating Concept

The goal of the Greedy Channel Ranking Algorithm (GCRA) is to rank all observed radio communication channels in terms of their radio communication performance potential. This ranking can go from best to worst (In Best Order), or worst to best (In Worst Order). Notionally, a DSA radio's Radio Resource Planner (RRP) uses this information to decide which set of communications channels a radio should use on a link in order to maximize throughput, or some other related data networking performance goal.

As shown in Fig. 1, a DSA radio stack uses its RF receiver hardware to periodically sample RF spectrum that contains multiple radio channels. Collected In-phase and Quadrature (IQ) data samples are passed to the GRCA and interference metrics are extracted for each DSA radio channel and then passed into a sorting algorithm to identify which channels are expected to have the highest and lowest radio communications performance.

III. Detailed Description

The GCRA uses several steps to process a buffer of IQ samples prior to extracting interference metrics and ranking the predicted performance of the channels based on those metrics. The following text is a detailed description of the processing steps that describe the contents of all seven of the numbered boxes in Fig. 2.

1. *Compute spectrogram*: A spectrogram (1024 point FFT) is computed for a buffer of IQ data samples collected by the radio receiver. Fig. 3 shows the results of the full-band (10 MHz) spectrogram used to efficiently estimate the time and frequency extents of RF interference that spans the entire set of observed radio channels. The minimum required duration of the spectrogram is a function of the interarrival time of the RF bursts from interference sources in each channel. For this paper we assume that interfering radio networks send one, or more, application data flows per channel (e.g., streaming video, file transfers, and/or web browsing) – creating a stream

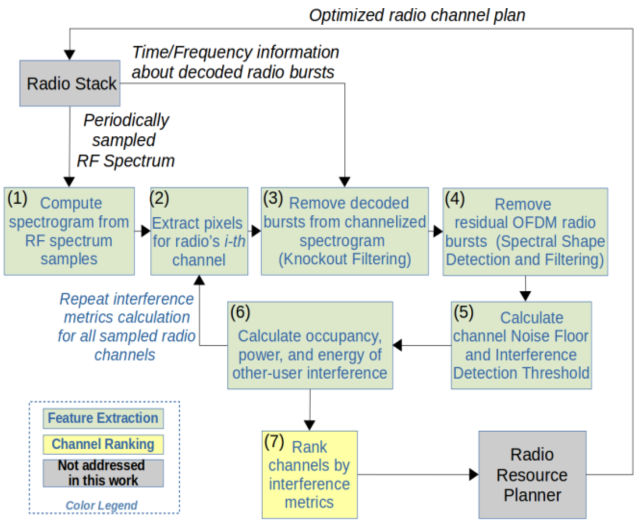

Fig. 2. Detailed block diagram of the Greedy Channel Ranking Algorithm (GCRA)

of sub-10 ms radio bursts with varying duty cycles. As shown in *Section V* of this paper, a 0.5 second duration spectrogram typically contains enough RF interference bursts to accurately characterize and rank the interference present within each radio channel.

2. *Extract channelized spectrogram pixels*: As shown in Fig. 4, spectrogram pixels associated with a single 1 MHz wide FDMA channel are extracted from the 10 MHz wide spectrogram prior to calculating interference metrics for each channel. This figure depicts 0.5 seconds of channelized spectrogram data for the 1 MHz wide FDMA channel offset -1.5 MHz from the DSA radio's center frequency. Extracting per-channel spectrogram pixel data requires mapping from the channel's time and frequency extents to the appropriate set of time-frequency indices in the spectrogram image.

3. *Apply Knockout Filter (KOF)*: Radio bursts sent by other radio nodes in the DSA radio network are demodulated using our SDR's highly parallelized receiver architecture. The start and stop sample numbers and the frequency extents of each successfully demodulated radio packet is stored by our SDR's demodulator module. This information is then provided to the Knockout Filter (KOF) and the spectrogram pixel data associated with every demodulated DSA radio burst are removed from the buffer of channelized pixels prior to calculating its interference metrics. Fig. 5 shows the channelized spectrogram after applying the KOF filtering process. This is a vital data filtering step because other radio nodes within the DSA radio network use one, or more, radio channels to send their data traffic and radio network control messages. If these DSA bursts remain in the channelized spectrogram pixel data, their RF power could bias the amount of *other-user* RF interference power in the channel.

4. *Apply Spectral Shape Detector and Filter (SSDF)*: The Spectral Shape Detector and Filter (SSDF) process is responsible for detecting and removing any residual spectrogram pixels associated with DSA radio packets that were not removed through the previous KOF processing step. This situation occurs when there is excessive RF interference on a DSA radio channel, and the receiving radio node is unable to successfully demodulate all DSA radio packets in the channel. If the receiver is unable to demodulate all transmitted DSA packets, then the time and frequency extents of the corrupted packets are unknown and the residual burst power biases the estimated interference metrics. The spectral shape detector operates by comparing the average power in the upper and lower subcarrier frequency bins to the power in the center frequency of the DSA channel [7]. This spectrum shape detection rule is convenient because it exploits the unique spectral shape of our radio's OFDM PHY. When the power in the center frequency is sufficiently below the power in the upper and lower subcarriers in a spectrogram time slice, the SSDF filter removed those pixels from the channelized spectrogram. This approach was experimentally demonstrated to remove a majority of the residual burst spectrogram time slices. Fig. 6 shows the result of using the SSDF to detect and remove the majority of the two residual OFDM radio bursts seen in the 1 MHz wide FDMA channel starting at 0.06 and 0.44 seconds.

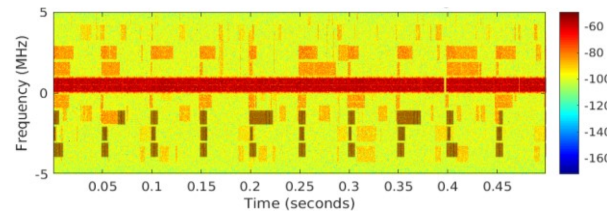

Fig. 3. Spectrogram of 10 MHz of RF spectrum showing activity of multiple radios and other-user interference

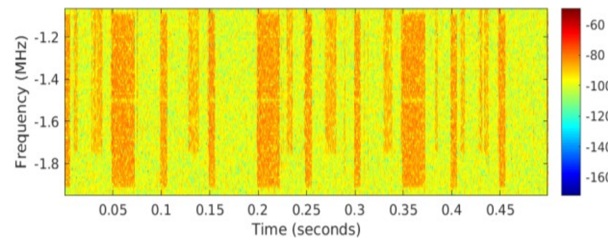

Fig. 4. Spectrogram of 1 MHz wide FDMA channel extracted from Fig. 3 spectrogram data, centered at -1.5 MHz from center frequency

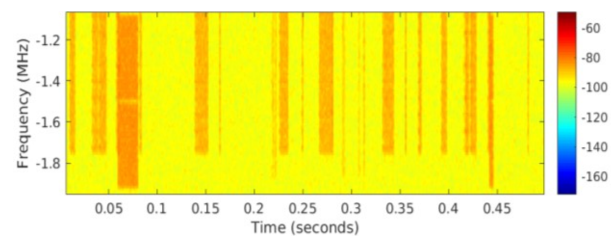

Fig. 5. Spectrogram of 1 MHz wide FDMA radio channel after applying Knockout Filtering (KOF)

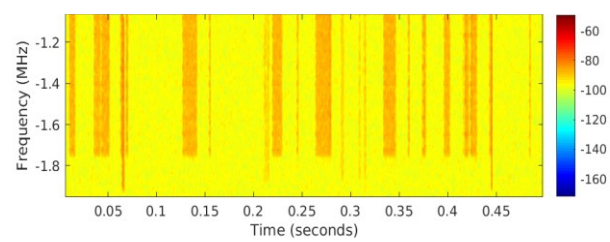

Fig. 6. Spectrogram of 1 MHz wide FDMA radio channel after applying OFDM Spectral Shape Detection and Filtering (SSDF)

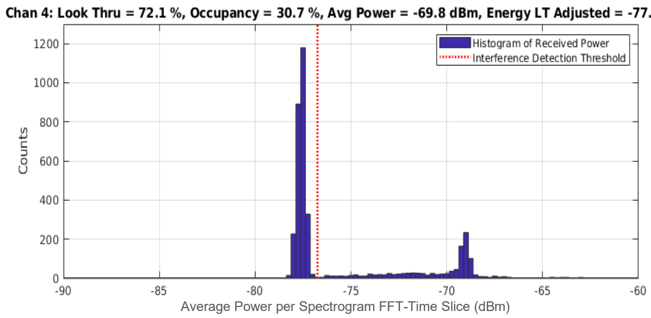

Fig. 7. Histogram of the residual RF interference power in the 1 MHz wide FDMA channel after removing DSA radio bursts

5. *Calculate noise floor and detect interference*: The mode of the thermal noise floor power within the channel is estimated from the spectrogram data and this information is used to select an appropriate RF interference detection threshold. Unlike most DSA radio sharing policies that are mandated to follow a *polite* spectrum etiquette of "do no harm" to Primary Users, GCRA's *greedy* goal function of avoiding strong interference implies that there is no penalty for missing the detection of weak interference waveforms. Our approach to identifying the appropriate interference detection threshold is the apply a peak detector to a histogram of the spectrogram pixels and select a threshold midway between the lowest peak (the mode of the thermal noise) and the next highest peak (the mode of the weakest RF interference waveform). Fig. 7 is the histogram of the residual RF interference power in the channelized spectrogram pixels for the 1 MHz wide FDMA radio channel shown in Fig. 6.

6. *Calculate interference metrics*: Once the RF interference is detected, the following interference metrics are calculated for each DSA radio channel: percent occupancy, average interference power (pre-detection), average interference power (post-detection), interference energy, average interference length, and predicted Error Vector Magnitude (EVM).
   - *Percent occupancy* is calculated by taking the ratio of the number of spectrogram FFT time slices that are above the interference detection threshold to the total number of spectrogram time slices extracted from the buffer of IQ data samples.
   - *Average interference power (pre-detection)* is the arithmetic mean of the power across all of the spectrogram time slices after applying KOF and SSDF. This average power metric includes the biasing effect of including spectrogram time slices when no interference is present in the average interference power. Units are dBm per channel.
   - *Average interference power (post-detection)* is the arithmetic mean of the power in the filtered spectrogram time slices after applying the interference detection threshold.
   - *Interference energy* is the time integration of the detected RF interference power. Units are in dB milli-Joules (dBmJ) per channel. A related metric is the *interference energy, Look Thru adjusted*. This metric divides the measured channel interference energy by the channel's measured "look through" factor - removing the biasing effect of reducing the interference observation window due to the KOF and SSDF filters. The "look through" factor is calculated by taking the ratio of the number of spectrogram time slices post-KOF and post-SSDF to the original number of extracted FFT time slices.
   - *Predicted EVM* is the average mean square error between the ideal and measured Quadrature Amplitude Modulation (QAM) symbol constellation points over all of the symbols per OFDM subcarrier and all of the DSA radio packets in the channel. We created a regression model for EVM using a Support Vector Machine (SVM) with a cubic distance metric to predict the average EVM based on a DSA packet's received signal power and average interference level.

7. *Rank channels by their interference metrics*: The final step in the GCRA is to use the measured interference metrics to rank the channels in both their "best" and "worst" order. We assume that the RRP requires knowledge of which channels should be prioritized for usage versus avoidance. Knowledge of both conditions is useful for finding feasible, or even optimal, channel assignment plans under congested RF spectrum conditions.

IV. Experimental Approach

Experiment data is collected under repeatable test conditions where the throughput per FDMA channel is measured for all 10 FDMA channels. The goal is to evaluate which interference metric provides the best channel ranking *accuracy* for the ensemble of FDMA radio channels and interference waveforms.

Two identical SDR nodes are positioned two feet apart in our lab and a third SDR node is positioned near the traffic source as a programmable RF interference source. Our DSA SDR system consists of an Ettus Research USRP x310 radio hardware connected over 10Gb Ethernet to a 12-core host computer running Ubuntu 16.04 LTS. The SDR's OFDM PHY layer is based on the *liquid-dsp* C++ signal processing library [8] and a highly parallelized SDR signal processing architecture and hybrid TDMA/FDMA MAC protocol [6]. For these experiments, the DSA SDR is configured to transmit on a single 1 MHz FDMA channel that is sequentially tuned to 10 uniformly spaced center frequencies that spans -4.5 to 4.5 MHz around a center frequency of 2.2 GHz.

A traffic dataflow is generated using the iPerf2 network benchmarking application [9] to send UDP packets uni-directionally at an average offered load of 4 Mbps in 1024-byte sized packets. The average throughput is measured over a 10 second measurement window at the destination node. Average throughput for each of the 10 FDMA channels is measured sequentially from low to high channels, starting at Channel 1's -4.5 MHz frequency offset.

Fig. 8 depicts a random realization of a 10 MHz wide composite waveform synthesized to resemble eight independent bursty RF interference sources. These interference waveforms create a wide range of interference conditions across our DSA SDR's 10 FDMA channels. The number of test cases is increased by a factor of three by varying the transmit RF gain over 20 dB in steps of 10 dB (e.g., 0, 10, and 20 dB transmit gain). A third set of interference test cases are created by synthesizing another version of the randomized interference waveforms where all eight interference sources have the same transmit power. As expected, Fig. 9 shows that the realized throughput for each FDMA channel is anti-correlated with the RF interference transmit gain and occupancy in the channel.

V. Analysis of Results

A primary performance metric for quantifying the prediction accuracy of GCRA is to compare the agreement between sets of channels that were ranked based on GCRA's interference metrics and sets of channels based on the measured average throughput per channel. Fig. 10 shows the average percent error (GCRA vs. measured throughput) for selecting sets of channels ranked for a variety of interference metrics for being *In Best Order* (IBO). The number of channels compared in each set is incremented from left to right on the x-axis. IBO refers to sorting the channels from highest to lowest predicted performance, grouping the N best channels into sets of *{1, 2, …, 10}* channels. In contrast, *In Worst Order* (IWO) sorts the channels from lowest to highest predicted performance.

We present GCRA's average channel selection percent error across the nine interference test cases assuming that the RRP's channel assignment algorithm benefits from knowledge of which set of N channels are to be prioritized or avoided during the channel assignment process. Selecting the appropriate value for N depends on the amount of constraints placed upon the RPP's channel assignment problem.

Fig. 10 shows the best GCRA interference metric for ranking channels IBO over the range $1 \leq N \leq 5$ is the *pre-detection average power* with a maximum percent error of 5% for a comparison channel set of size four. This metric has a higher accuracy than the *post-detection average interference power* because that metric does not capture the duty cycle of the interference - both low and high duty cycle interference in a channel could have the same *post-detection average interference power* while the measured throughput could be significantly different. Another interesting result is that the two *interference energy* metrics do not attain higher prediction accuracy than the *post-detection average power* metric. The interference energy metrics include the effect of the duty cycle of the interference by time integrating the post-detection interference power within the FDMA channel.

VI. Conclusion

This paper describes the Greedy Channel Ranking Algorithm (GCRA) and quantified analysis of its measured performance in our SDR system. Our conclusion is that the GCRA can be used to accurately rank the best and worst sets of radio channels so that information can be used to solve the channel assignment problem in congested spectrum. The analysis of results quantifies the performance for using a variety of interference metrics to predict the relative performance of channels based on features extracted from measurements. Our analysis of results showed that the *pre-detection average interference power* metric and the *post-detection average interference power* had the highest prediction accuracies when ranking the channels IBO and IWO, respectively (experimental results for IWO not shown due to space constraints).

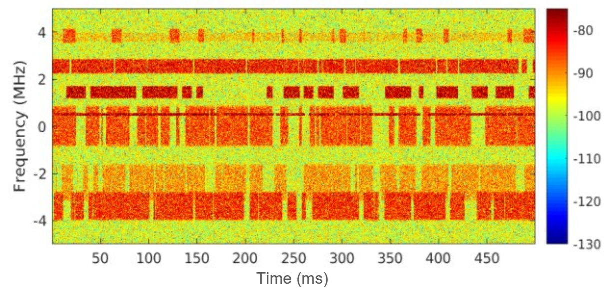

Fig. 8. 10 MHz spectrogram of eight randomly synthesized RF interferers

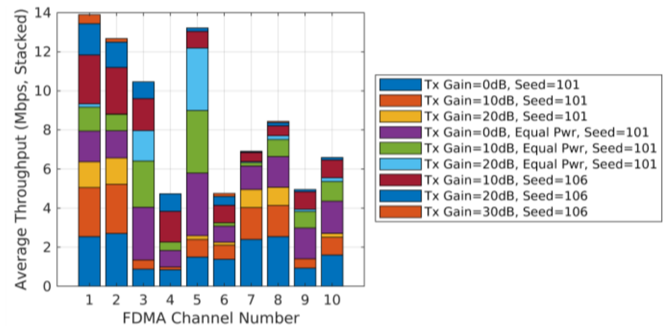

Fig. 9. Average throughput per FDMA channel (Mbps, stacked bar plot)

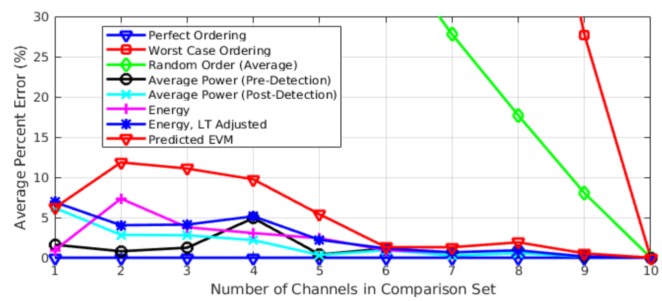

Fig. 10. Average percent error for throughput per channel set (In Best Order)

References

[1] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," in *IEEE Communications Surveys & Tutorials*, vol. 11, no. 1, pp. 116-130, First Quarter 2009.

[2] J. M. Peha, "Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio," in *Proceedings of the IEEE*, vol. 97, no. 4, pp. 708-719, April 2009.

[3] DARPA Spectrum Collaboration Challenge (SC2) Website, [online] Available: https://spectrumcollaborationchallenge.com/

[4] Clancy, T. Charles, "Dynamic Spectrum Access in Cognitive Radio Networks," PhD diss., 2006, University of Maryland, College Park, MD, Retrieved from https://www.cs.umd.edu/~jkatz/THESES/clancy.pdf

[5] A. N. Mody et al., "Machine Learning based Cognitive Communications in White as Well as the Gray Space," MILCOM 2007 - IEEE Military Communications Conference, Orlando, FL, USA, 2007, pp. 1-7.

[6] K. R. Dandekar et al., "Grid Software Defined Radio Network Testbed for Hybrid Measurement and Emulation," 2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON), Boston, MA, USA, 2019, pp. 1-9.

[7] Rohde and Schwarz, "Spectral Shape Detector, High Speed Spectral Shape Search", whitepaper, retrieved from http://www.rohde-schwarz-usa.com/rs/324-UVH-477/images/Spectral_Shape_Detector_High_Speed_Spectral_Shape_Search_V3.0.pdf

[8] Gaeddert, Joseph D., liquid-dsp, 2019, www.liquidsdr.org

[9] NLANR/DAST, iPerf, http://sourceforge.net/projects/iperf/