The development and practical study of a grey space detector for cognitive radio

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Outline

Key Definitions

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Key Definitions Continued

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Objective

The objective of our detector is to find grey space within a portion of the UHF TV band (470-698 MHz) that is partially occupied by a digital television signal (DTV).

Detection Process

- Step 1: Filtering
- Step 2: Multitaper Spectral Estimation
- Step 3: Harmonic F test
- Step 4: Noise Floor Estimation
- Step 5: Signal to Noise Ratio
- Step 6: Signal Placement

Step 1: Filtering

- Analog high-pass filter
- Image-rejecting mixer
- Amplification
- Analog bandpass filter
- Digitization
- Digital bandpass filter

Step 2: Multitaper Spectral Estimation

- Digital signal data $x(n)$, use a discrete Fourier transform (using the FFT) - $S(f) = \left|\sum_{n=0}^{N-1} x(n)e^{-i2\pi fn}\right|^2$
- We window the Fourier transform in order to reduce bias, giving $S_m(f) = \left|\sum_{n=0}^{N-1} d(n) \cdot x(n)e^{-i2\pi fn}\right|^2$
- We use the orthogonal family of DPSSs and compute K of transforms on the same input data sequence; denote these windows as $d_w(n)$, for $w = 0, 1, \ldots, K-1$
- The spectrum estimate is a weighted combination of the K windowed Fourier transforms; $\overline{S}(f) = \sum_{k=0}^{K-1} c(k)S_{d_k}(f)$

Step 3: Harmonic F test

The purpose of the F-test is to find line components in the spectrum that derive from periodic signals. The F-test tests the null hypothesis that no line components exist at a given frequency.

Step 3: Harmonic F test continued

The statistic for the F-test follows a F (2,2K-2,P) distribution and is computed by:

$$F(f) = (K-1)\frac{|\hat{B}(f)|^2 \sum_{k=0}^{K-1} |U_k(0)|^2}{\sum_{k=0}^{K-1} |X_k(f) - \hat{B}(f)U_k(0)|^2}, \tag{1}$$

$$\hat{B}(f) = \frac{\sum_{k=0}^{K-1} U_k(0)X_k(f)}{\sum_{k=0}^{K-1} |U_k(0)|^2}, \tag{2}$$

$$X_k(f) = \sum_{t=0}^{N-1} v_t^{(k)}(t)e^{-2i\pi ft}, \tag{3}$$

$$U_k(-f) = \epsilon_k V_k(f)e^{-2i\pi f(1/2(N-1))}, \tag{4}$$

Step 3: Harmonic F test continued

Where X_k is the eigencoefficient, ϵ_k is equal to 1 for k even and i for k odd, the U_k are the Slepian-defined real eigentapers, and the V_k the notation of the complex eigentapers. If the F statistic is above $F(2, 2k-2, p)$ we will reject the null hypothesis. For our data we use $F(2, 12, p)$.

Auxiliary Classification

- To use this test for detection, we determine the presence of either the DTV pilot tone or analog luma carrier.
- To ensure that the signals are not unlicensed devices that are transmitting in these channels at the carrier frequencies, auxiliary classification must be performed.
- For digital signals with high SNR, evaluating the bandwidth of the signal will suffice. To calculate the bandwidth of a DTV signal, we determine where the guard bands are located. Finding when the power of the signal begins to decrease determines the location of the guard bands. To account for randomness and content-dependent modulation, the data should be averaged in 50 to 100 kHz blocks when trying to find the drop in power.

Auxiliary Classification continued

- In the case of low SNR signals, we cannot determine the bandwidth of our signal using the decrease in power in the guard bands since this is masked by the noise floor. Other auxiliary methods need to be explored.
- The necessity of auxiliary classification can be avoided through regulation. Not allowing secondary signals to transmit at the pilot carrier frequency would remove any confusion concerning DTV classification.

Step 4: Noise Floor Estimation

- A robust estimate of location for the amplitude of the channels not occupied by TV signals will give an accurate estimate of the background noise for the occupied channels.
- A trimmed mean taken across all of the unoccupied channels will not be effected by undetected low powered systems that may be transmitting.
- For this project a 25% trimmed mean was used.

Step 5: Signal to Noise Ratio

- We estimate the average amplitude for the DTV channel to determine if the channel is fully occupied.
- Taking a trimmed mean of the head of the DTV channel will provide an accurate measure of the signal strength.
- Reporting both the signal strength and noise floor estimates and ensuring both are in the same units, such as dBm, we find the SNR to be,

$$dB_{SNR} = dB_{Signal} - dB_{Noise}. \tag{5}$$

Step 6: Signal Classification

- To determine if the Signal is classified as grey space or black space depends on the choice of SNR limit.
- The Threshold of Visibility (TOV) for the DTV signal is 15dB. To ensure that our transmissions are not affecting any receivers that are at or above the TOV, we need to set our limit for grey space distinctly lower.
- Our limit depends on the power and distance to be serviced by our cognitive device. To ensure quality of service to the primary users, regulations on these limits should be made. For this project an extra SNR drop of 10 dB is required.

Step 6: Signal Placement

- To avoid the need for auxiliary classification and confusion for other cognitive systems, not transmitting at the classification frequencies is necessary.
- Using schemes that sub divide the band to allow for flexibility towards the number of users and modulation methods is the practical solution for signal placement.
- The currently proposed scheme in the IEEE 802.22 standard is for *orthogonal frequency-division multiple access* (OFDMA) with 48 sub-channels across the 6 MHz band for white space.

Experiment Overview

- To test our grey space detector on real world data, we sampled the radio frequency (RF) environment at Queen's university. We used a Channel Master 3671 crossfire antenna designed for digital television systems.
- **Note:** For robust detection an omnidirectional antenna would be required. This would ensure that no channels are classified incorrectly.
- We placed our antenna on the roof of Jeffery Hall, at Queen's University. This location caused less attenuation from obstructions like buildings and vehicles.

Experimental Overview continued

- We aligned the antenna in the direction of the TV transmitter of interest. To ensure we observed DTV signals, we took data sets with our antenna aligned towards three US cities: Watertown, Rochester and Syracuse.
- Dr. David J. Thomson designed and built the analog radio system employed. The system includes an image-rejecting mixer had a tunable carrier frequency for adjustable heterodyning, an IF filter with a fixed bandwidth of $100 - 150$ MHz and signal amplifiers.
- We incurred amplitude modulation due to a reflection in the coaxial cable. The reflection was caused by running both a spectrum analyzer and the analog to digital converter simultaneously with a coaxial "T" junction.

Regional Map

Figure: Kingston and surrounding areas.

Experimental Overview continued

- The signal is then digitized. We sampled the data at 100 MHz for 3 ms, giving us $300,000$ data points for each data set. We collected five data sets, testing different locations and frequencies.
- The digital grey space detector was coded in Matlab. The detector determined the classification of all of the channels found within the 50 MHz simultaneously. The detector had four possible classifications for each channel; no TV data, grey space, black space, or analog signal.

Results: Data set#1

Frequency (MHz)	500	506	512	518
Classification	Grey	No TV	Black	No TV
Frequency (MHz)	524	530	536	542
Classification	No TV	Black	Black	No TV

Table: Data Set#1: Syracuse, 500-550 MHz.

Analysis: Data set#1

- The four detected DVT signals had well defined pilot tones visible on the left edge of the band in the multitaper spectral estimate. The pilots are also visible on the F-test.
- There were DTV transmitters in Syracuse operating at 500, 530 and 536 MHz. There was also a DTV channel in Watertown transmitting at 512 MHz.
- There was visible attenuation in the multitaper spectral estimate from the coaxial reflection.

Date Set#1 plots

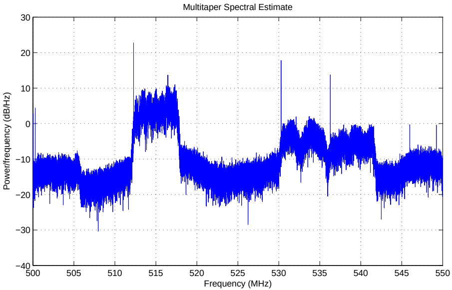

Figure: Data Set#1: Syracuse, 500-550 MHz.

Date Set#1 plots

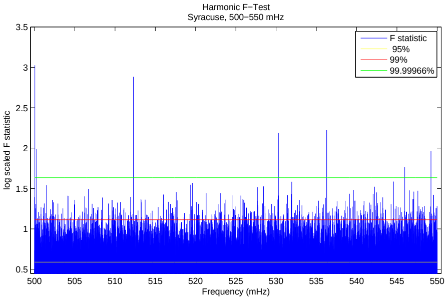

Figure: Data Set#1: Syracuse, 500-550 MHz.

Results: Data set#2

Frequency (MHz)	500	506	512	518
Classification	No TV	No TV	Black	No TV
Frequency (MHz)	524	530	536	542
Classification	No TV	Grey	No TV	No TV

Table: Data Set#2: Watertown, 500-550 MHz.

Analysis: Data set#2

- The antenna was now facing Watertown and the only changes in the classification were those of the Syracuse channels. We were using a directional antenna a change in power was to be expected.
- The change in results without changing the actual signals strength or location showed that using directional antennas was *not* an appropriate way to sense the RF environment for cognitive radio.

Results: Data set#3

Frequency (MHz)	602	608	614	620
Classification	No TV	No TV	analog	No TV
Frequency (MHz)	626	632	638	644
Classification	No TV	Black	No TV	No TV

Table: Data Set#3: Watertown, 600-650 MHz.

Analysis: Data set#3

- There was an analog signal at 614 MHz, which is the frequency at which Kingston's TVO channel operates. The three carriers of the analog signal were visible in the MTM estimate. The luma and chroma carriers also appeared in the F-test.
- The DTV signal that was detected as black space at 632 MHz was being transmitted from Watertown.

Date Set#3 plots

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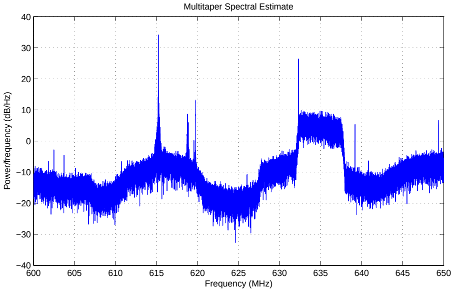

Figure: Data Set#3: Watertown, 600-650 MHz.

Date Set#3 plots

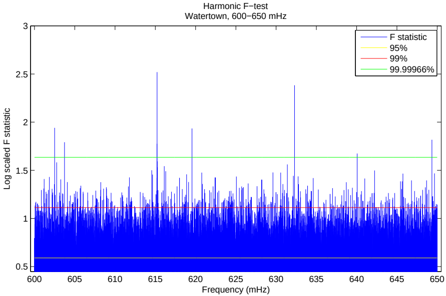

Figure: Data Set#3: Watertown, 600-650 MHz.

Results: Data sets#4#5

Frequency (MHz)	530	536	542	548
Classification	Grey	No TV	No TV	No TV
Frequency (MHz)	554	560	566	
Classification	Analog	No TV	Analog	

Table: Data Set#4: Rochester, 525-575 MHz.

Frequency (MHz)	626	632	638	644
Classification	No TV	Black	No TV	No TV
Frequency (MHz)	650	656	662	668
Classification	Grey	Grey	No TV	Grey

Table: Data Set#5: Rochester, 625-675 MHz.

Analysis: Data sets#4&#5

- The signals classified as grey space were coming from Rochester and Syracuse. The fully occupied signals were coming from Watertown.
- In data set five we saw that at low power the guard bands of the DTV signals were not distinguishable from the background noise.
- The positioning of the pilot signals was sufficient for properly classifying a DTV signal in our data.

Date Set#5 plot

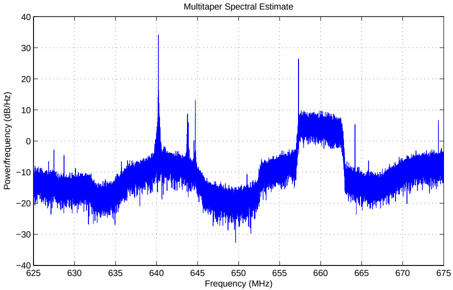

Figure: Data Set#5: Rochester, 625-675 MHz.

Remarks

- The SNR limit may be lower than required for most situations
- The signals found to be grey space were all at least 145 km away from our antenna, similar to a Grade B contour.
- Once cognitive radio systems begin operation, without regulations on in-band transmission allocation, mis-classification is plausible. To avoid this, regulations are required to keep cognitive radio systems from transmitting signals on or near the frequency locations for carrier tones.

Remarks continued

- The FCC's regulations and IEEE 802.22 standard are designed for implementation in rural areas. The data used in this experiment was taken from an urban center.
- When used in combination with a reliable white space detector, the grey space detector provides an increase in spectrum available for reuse.

Future Work

- To ensure minimal interference by systems using grey space detection, rigorous testing of potential systems must be performed.
- Implementation of the system specifications to determine precise SNR limits is needed.
- Development of robust and accurate attenuation models for TV signals and secondary systems will further help define a precise SNR limit.
- To minimize interference and help with classification, detailed regulation of grey space methods and uses needs to legislated.

Future Work continued

- Regulation of modulation types, allocation schemes and pilot carrier avoidance are all needed to make grey space detection practical.
- Optimized code for grey space detection must be developed to allow the systems to operate as close to real time as possible.
- Also in an effort to get closer to real time transmission rates and minimal delays during sensing, the development of parallel operation of sensing and sending is needed.