

Multiview Analog FM Radio Underlay

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Abstract—Is it possible to reuse the frequency of a commercial FM station for short-range secondary FM transmission and be able to recover the secondary FM-modulated signal despite potentially strong and time-varying interference from the primary? The answer is yes, and this paper explains how this can be done, from a review of pertinent theory and prior art to transceiver design and laboratory experiments which demonstrate the concept using off-the-shelf programmable radios. This is the first successful demonstration of analog FM underlay without any coordination between the primary and secondary system. Interestingly, this only works in the analytic signal domain, because the FM signal has memory. As the spectrum at premium analog broadcasting frequencies becomes more valuable, this opens the door to a number of interesting communication scenarios, including emergency response.

Index Terms—Frequency modulation and demodulation, canonical correlation analysis, multiple-input multiple-output (MIMO), wireless communication, synchronization, software radio.

I. INTRODUCTION

It has been almost a century since the idea of frequency modulation (FM) was coined by E.H. Armstrong [1]. Since then, FM still plays a significant role in modern communications, with several applications including FM Radio Broadcasting, television sound transmission, two-way radio communications, wireless microphones, radar systems, and navigation systems.

As the number of connected devices has increased over time, the amount of spectrum available for use is rapidly decreasing. Spectrum sharing is therefore of paramount importance towards ensuring effective usage of premium channels, such as those used by legacy broadcasting services. Various spectrum sharing methods have been proposed and are generally classified as so-called *interweaving*, *overlay*, and *underlay* modalities; see e.g., [2], [3]. However, existing solutions require a high level of situational awareness to find and exploit transmission opportunities and/or to avoid destructive

interference. These tasks and objectives require significant computation and communication overhead, to the point of rendering solutions impractical – which partially explains the slow adoption of spectrum sharing innovations.

More recently, work in our lab has introduced a completely different approach [4] to spectrum underlay using signal repetition and canonical correlation analysis (CCA). CCA is a statistical technique for determining two linear combinations of the variables in two respective random vectors such that the resulting pair of random variables is maximally correlated [5]. The idea in [4] is important because the approach can work under powerful and time-varying primary interference, without any coordination, training, or channel state information. The repetition structure, when combined with multiple receive antennas, enables the use of CCA to find a shared latent space where the projected multichannel signal views are maximally correlated. The method in [4] was tested in the lab with digital linearly modulated primary and secondary signals.

In contrast, this paper presents the design and implementation of the CCA underlay concept to analog FM (nonlinear analog modulated) signals. The stronger primary user is a commercial FM station and the secondary user is a much weaker FM transmitter that hides under the commercial FM station. We demonstrate this new application using a secondary transceiver utilizing three USRP-2920 software-defined radios (SDRs): one to instantiate the secondary single-antenna transmitter and two for the secondary dual-antenna receiver. The secondary transmits at the same time and over the same bandwidth as the primary, but at low-enough power to stay well under the received signal strength of the primary FM station, *even within a distance of a few meters, i.e., within the lab*. The problem of interest is to reliably decode the secondary user at a receiver that is equipped with $M_b > 1$ antennas. To make things concrete, in the following we provide a mathematical formulation of the considered setting.

II. BACKGROUND

In this section, we provide a short introduction to two basic concepts that the proposed framework relies on: FM modulation/demodulation and underlay communication using Canonical Correlation Analysis. In the following subsections, we are considering the setting of interest as it was described in the previous paragraph.

A. FM based communications

Let $m_u(t)$ be the voice/audio message that user u transmits and f_c be the common carrier frequency. Then, in the context of FM-based communications, the transmitted signal of the u -th user is modeled as

$$s_u(t) = A_u \cos(2\pi f_c t + \phi_u(t)), \quad (1)$$

where A_u denotes the amplitude of the carrier signal of the u -th user. The phase term $\phi_u(t)$ can be expressed as

$$\phi_u(t) = 2\pi k_u^{(f)} \int_0^t m_u(\tau) d\tau, \quad (2)$$

where $k_u^{(f)}$ denotes the frequency sensitivity factor (also known as the modulation index) of the u -th user, and it controls the modulated signal bandwidth and noise immunity of the demodulated signal. For the rest of this paper, we absorb this scaling in the message signal itself and set $k_u^{(f)} = 1$ for brevity. Therefore, the signal at a multi-antenna receiver, $\mathbf{y}(t) : \mathbb{R} \rightarrow \mathbb{R}^{M_b}$, can be written as

$$\mathbf{y}(t) = \sum_{u=1}^2 \mathbf{h}_u A_u \cos(2\pi f_c t + \phi_u(t)) + \mathbf{w}(t), \quad (3)$$

with $\mathbf{h}_u \in \mathbb{R}^{M_b}$ denoting the channel vector w.r.t the u -th user at the receiver and $\mathbf{w}(t)$ denoting zero-mean spatially and temporally white Gaussian noise (AWGN).

As long as the power of the secondary user ($u = 2$) is significantly below the primary user's power, the resulting interference would not have a significant impact on primary reception. This is true for any modulation, and particularly so for FM where the demodulator locks on the phase of the dominant signal, a phenomenon known as capture which makes FM robust to moderate levels of adjacent- or co-channel interference. On the other hand, the power of the secondary user should be above the FM demodulation noise floor, otherwise any attempt for reliable communication would be futile even in the absence of the primary signal.

We would like to be in the position to synchronize with and recover the low-power secondary FM signal without any coordination between the two systems – i.e., they both transmit at will, without regard to one another. In the next subsection, we provide a short introduction to the framework of [4].

B. Underlay Communications via CCA

The authors of [4] considered the same underlay scenario - one strong primary user and one weak secondary user. By introducing simple repetition coding, i.e., the secondary user repeats its transmitted sequence once, in a back-to-back fashion, and using $M_b > 1$ receive antennas, they showed that it is possible to synchronize with the low-power secondary transmission and recover the secondary sequence reliably, over a broad range of signal to interference plus noise ratios.

Their starting point was the following observation. Consider a noiseless environment where only the two users are transmitting. Then, after assuming that a potential receiver is perfectly synchronized to the repeated transmission of N samples from the secondary user, the matrix of repeated in-phase / quadrature (I/Q) complex samples $\mathbf{Y} \in \mathbb{C}^{2N \times M_b}$ can be split into two consecutive blocks such that $\mathbf{Y} = [\mathbf{Y}_1; \mathbf{Y}_2]$. Then, for each matrix $\mathbf{Y}_r \in \mathbb{C}^{N \times M_b}$ the following model would hold

$$\mathbf{Y}^{(r)} = \mathbf{v}_1^{(r)} \mathbf{h}_1^{(r)T} + \mathbf{s} \mathbf{h}_2^{(r)T}, \quad (4)$$

where $\mathbf{v}_1^{(r)} \in \mathbb{C}^N$ denotes the subset of primary user's samples that appear in matrix $\mathbf{Y}^{(r)}$, $\mathbf{s} \in \mathbb{C}^N$ denotes the repeated samples of the secondary user, while vectors $\mathbf{h}_1^{(r)}, \mathbf{h}_2^{(r)} \in \mathbb{C}^{M_b}$ hold the coefficients that characterize the channels between the pairs, primary user - receiver and secondary user - receiver, respectively.

Several equivalent problem formulations can be used to pose the mathematical problem that CCA solves. The most fundamental one considers the problem of finding two vectors $\mathbf{q}^{(1)}, \mathbf{q}^{(2)} \in \mathbb{C}^{M_b}$ that maximize the correlation coefficient of vectors $\mathbf{z}^{(r)} = \mathbf{Y}^{(r)} \mathbf{q}^{(r)}$. Another equivalent and insightful problem formulation is the following one

$$\min_{\mathbf{q}^{(1)}, \mathbf{q}^{(2)}, \mathbf{g}} \sum_{r=1}^2 \left\| \mathbf{Y}^{(r)} \mathbf{q}^{(r)} - \mathbf{g} \right\|_2^2 \quad \text{s.t.} \quad \|\mathbf{g}\|_2 = 1, \quad (5)$$

known as the MAX-VAR formulation of CCA [6]. Assume that matrices $\mathbf{Y}^{(r)}$ follow the model in (4) and that they are full column rank. Then the intersection of their ranges/column spaces will be one-dimensional and spanned by the vector of repeated samples, $\mathbf{s}$. In other words, the optimal solution of problem (5), denoted $\mathbf{g}^o$ will be a scaled version of $\mathbf{s}$, $\mathbf{g}^o = \lambda \mathbf{s}$, for a $\lambda \in \mathbb{C}$ [7]. Regarding its practicality, it was recently shown that problem (5) w.r.t. vector $\mathbf{g}$ can be posed as the problem of recovering the principal component of a matrix [8]. More specifically, after letting matrices $\mathbf{U}^{(r)} \in \mathbb{C}^{N \times M_b}$ form orthonormal bases of the ranges of matrices $\mathbf{Y}^{(r)}$, respectively, then it can be shown that an optimal vector $\mathbf{g}^o$ would be a left principal vector

of matrix $\mathbf{M} = [\mathbf{U}^{(1)} \ \mathbf{U}^{(2)}] \in \mathbb{C}^{N \times 2M_b}$. As a result, an estimate of $\mathbf{s}$ can be obtained at complexity that is linear in N .

III. PROPOSED SYSTEM MODEL AND PROBLEM STATEMENT

The design of the CCA-based secondary transceiver for FM underlay communication and the verification of its functionality and efficiency by conducting real-life experiments with USRP radios are the main contributions of this paper. Let us start with the first one. Two issues make the design of CCA-based FM underlay non-obvious: inducing repetition of the modulated secondary signal, since FM modulation has built-in memory; and mining the received signal for the right repetition timing, which is challenging when operating under a powerful commercial FM station. We first consider the first issue.

A. Designing the secondary FM-based transmitter

When a software radio is used as FM transmitter, the secondary message signal $m_2(t)$ is generated from pulse-shaped discrete-time baseband audio samples

$$m_2(t) = \sum_{n=1}^N v_2[n]p(t - nT_s), \quad (6)$$

Upsampling is used to better approximate the integral used for FM modulation. Towards this end, a rational resampler is employed in GNU radio, and we adopt this approach here as well. If L denotes the interpolation factor and M denotes the decimation factor, then the rational resampler adjusts the sampling rate to $F'_s = \frac{L}{M}F_s$, where $F_s = \frac{1}{T_s}$.

The simplest way to introduce repetition to the FM-modulated waveform is to repeat the baseband signal sample block before resampling and FM modulation. If the original message $m_2(t)$ is of duration T_o , this will create an extended message $\tilde{m}_2(t)$ of duration $2T_o$ and the property

$$\tilde{m}_2(t) = \tilde{m}_2(t - T_o) = m_2(t - T_o), \text{ for } t \in [T_o, 2T_o]$$

Note however that FM modulation has memory, as the running integral of $\tilde{m}_2(t)$ is used to modulate the phase. For $t \in [T_o, 2T_o]$ the modulated signal can be written as

$$\begin{aligned} \tilde{s}_2(t) &= \Re \left\{ e^{j2\pi \left(f_c t + \int_0^t \tilde{m}_2(\tau) d\tau \right)} \right\} \\ &= \Re \left\{ e^{j2\pi \left(f_c t + \int_0^{T_o} \tilde{m}_2(\tau) d\tau + \int_{T_o}^t \tilde{m}_2(\tau) d\tau \right)} \right\} \\ &= \Re \left\{ e^{j\theta} e^{j2\pi \left(f_c t + \int_{T_o}^t \tilde{m}_2(\tau) d\tau \right)} \right\}, \end{aligned}$$

where $\Re\{\cdot\}$ extracts the real part of its argument and $\theta := 2\pi \int_0^{T_o} \tilde{m}_2(\tau) d\tau$. It follows that

$$\tilde{s}_2(t) = \Re \left\{ e^{j\theta} e^{j2\pi \left(f_c t + \int_0^t \tilde{m}_2(\tau) d\tau \right)} \right\}, \forall t \in [T_o, 2T_o].$$

Following downconversion, the complex baseband-equivalent model of the analytic signal at the SDR receiver is therefore proportional to

$$\tilde{s}_2(t) = \Re \left\{ e^{j\theta} e^{j2\pi \int_0^t \tilde{m}_2(\tau) d\tau} \right\}, \forall t \in [T_o, 2T_o].$$

The signal inside the brackets in the above expression is the complex baseband-equivalent model of the analytic signal at the SDR receiver. Hence repetition of the baseband signal samples does not exactly repeat the modulated waveform; it also changes its phase by a constant angle θ that depends on the integral of the original message signal. *While this changes the waveform in the time domain when we take the real part, when we work with the analytic signal (computed using the Hilbert transform) this phase shift is immaterial, as it introduces a complex multiplicative constant.* This can be absorbed in the complex baseband-equivalent channel. In other words, CCA only needs the repeated signal to manifest itself in the measured subspace; it does not care whether the exact same signal or a scaled / phase shifted version of the same signal appears in the retransmission. This is a key point, which dictates that CCA should be performed on the complex analytic signal before FM demodulation. It is not guaranteed to work with the real-valued baseband signals, or the signals after demodulation.

IV. SECONDARY FM RECEIVER

The secondary FM receiver uses an unsupervised protocol to mine the received data streams for secondary repetition patterns, which it then processes using CCA in complex baseband. This yields an oversampled sequence of complex baseband signal samples. The angle of this sequence is then accessed, phase unwrapped, differenced and subsampled to get to the original sampling rate $\frac{1}{T_s}$. The details of the lab implementation are discussed next.

V. LABORATORY IMPLEMENTATION AND DEMONSTRATION

A speech sample of 8.5 seconds was recorded with a known sampling frequency. The resulting length of the speech signal was 409000 samples with a playback

sampling frequency of 48000 Hz. The audio samples are then divided into 20 packets of 20450 samples. Each packet is repeated back-to-back, meaning there is no artificial delay added between repetitions. Because CCA assumes a constant channel during each packet transmission (which can change for the repetition), the length of the packets was chosen from empirical observations to ensure that the channel remains constant per packet.

Then the packetized and resampled repetitions are stored and fed into the WBFM Transmit block in GNU Radio [9]. The software defined radios (SDR) utilized for testing were N2920 models. The single transmitter acting as the secondary user is illustrated in Fig. 1a and the multi-antenna receiver is shown in Fig. 1b. The two receiver SDRs are connected with a MIMO cable to guarantee synchronized received data streams. The sampling rate of the SDRs at the transmitter and receiver are set at 500000 samples per second (Sps). The carrier frequency of the secondary transmitter and the receiver were set to 97.5 MHz, where a known local FM station (acting as a primary user) operates. The secondary transmit power is set to -75 dBm, with a power difference of 30 dB between the primary and secondary signals, as empirically measured at the receiver. The receiver collects samples in complex baseband representation, filters them using a 50 kHz low-pass filter, and stores them for post-processing. The post-processing is done in MATLAB, utilizing the repetition structure to detect the start of the secondary transmission.

A CCA-based synchronization algorithm for detecting the starting time index of a packet was used, and it works as follows. Starting at the beginning of the received complex baseband data streams from both received antennas, signal views are constructed at each index $i \in \{0, \dots, L_{Data} - L_{packet} - L_{window} - 1\}$. Here L_{Data} represents the length of each received data stream, L_{packet} is the packet size, and L_{window} is a window whose size we choose to balance detection performance and complexity. After multiplying the constructed signal views with the optimal dimensionality reducing operators $\mathbf{q}^{*(1)}$ and $\mathbf{q}^{*(2)}$ the reduced views are produced. The packet starting index is determined to be where the correlation coefficient between these reduced views is maximized (see Fig. 2). After finding the starting index, signal views are constructed on that particular timing and using CCA the common component $\mathbf{g}^*$ is determined. That common component contains the secondary FM modulated signal (see Fig. 3a). Then FM demodulation is performed and the secondary audio signal is reconstructed. The proposed experimental setup was arranged and audio was recovered across several trials. To test the quality of the recovered underlay audio signal, the

Pearson correlation coefficient between that recovered audio and the original one was calculated. Across trials the best correlation was found to be 0.98, which indicates an effective reconstruction¹. If FM demodulation is performed at the time index estimated from CCA, the primary's audio signal can be successfully reconstructed. This demonstrates that CCA is able to reconstruct the underlay's signal without impacting the primary (commercial FM station's) performance. Indeed, if one demodulates the received signal using the standard GNU radio FM demodulator, the commercial station comes across loud and clear, without any perceptible interference. This is as expected, since the underlay signal is 30 dB below the commercial FM station, as measured at the receiver.

Finally, the Relative Mean Square Error (RMSE) was calculated for the recovered audio, which is

$$\text{RMSE}_{\text{dB}} = 10 \log_{10} \left(\frac{\left(\sum_{i=1}^N (y(i) - \hat{y}(i))^2 \right)}{\sum_{i=1}^N y(i)^2} \right)$$

where $y(i)$ is the true audio signal and $\hat{y}(i)$ is the recovered audio. The RMSE measures the relative error between the recovered underlay audio and the original one and was found at best to be -14.91dB. This value demonstrates a high degree of accuracy in the audio recovery process, underscoring the effectiveness of CCA in decoding weak transmission signals.

VI. CONCLUSIONS

This paper demonstrated a practical application of multi-view CCA on real FM signals. By utilizing CCA, a secondary user's transmission was recovered when operating at the same time and frequency as a much stronger commercial FM station, without significantly impacting the commercial FM transmission. The proposed secondary transmission scheme was a back to back repetition scheme of packets of audio. Using this transmission scheme at the secondary and at least 2 antennas at the receiver, the secondary audio information was recovered in a time-efficient manner with little error using CCA. The receiver only needs to know the size of packets sent and the sampling frequency of the original audio to accurately reconstruct the original signal.

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¹The audio files of the original, reconstructed and primary's signal can be found in the following [Github link](#).



(a) Transmitter



(b) Receiver

Fig. 1: Experimental setup. Receiver antennas are synchronized using a MIMO cable, and each SDR connects to one antenna.

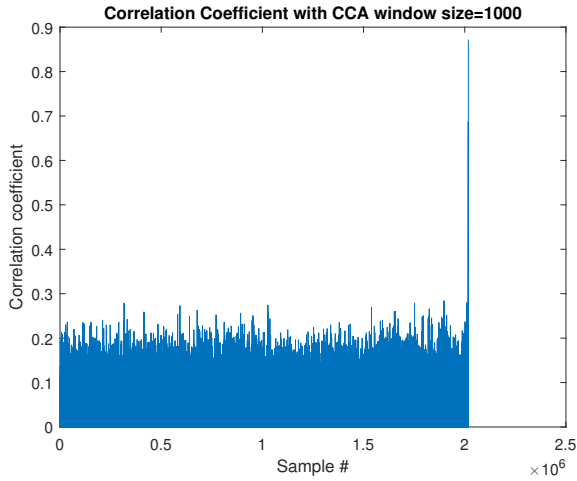
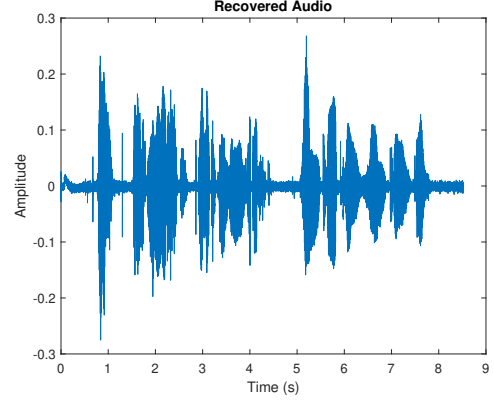
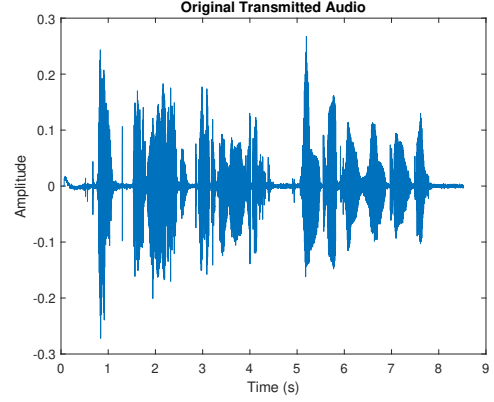


Fig. 2: Coefficients of canonical correlation between two sliding windows on the received signal, before demodulation, for detecting the start of the secondary transmission.

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(a) Recovered audio signal of the secondary user.



(b) True audio signal of the secondary user.

Fig. 3: Recovered and true audio signal of the secondary user. The correlation coefficient between the two is 0.98, while the RMSE is -14.91 dB.

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