The RFI 2022 Workshop at ECMWF, 14 – 18 February 2022
2022 URSI International Union of Radio Science

DDC Pool: Efficient down-conversion of signals for RFI monitoring

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Abstract

A method for simultaneous digital down-conversion of multiple signals detected in a wideband timeseries is introduced. An oversampled analysis filterbank channelizes the timeseries after which those channels containing signal fragments are synthesized to obtain a baseband waveform for each signal. The method is parameterized, parallelizable, and in this paper a prototype system is applied to a publicly available wideband dataset.

1 Introduction

Radio astronomy (RA) observatories may suffer degradation of the quality of the data from celestial sources due to the presence of radio frequency interference (RFI) from both terrestrial and satellite radio sources. Thus an RFI monitoring system that can identify RFI is an essential component of an RA observatory.

Obtaining the complex baseband timeseries of individually detected signals is desirable because more information can be gathered about the signal from its waveform rather than just its spectral shape and energy level, such as the modulation scheme and higher-order statistical cumulants. As well, when considering the radio frequency interference (RFI) monitor architecture illustrated in fig. 1 where the instantaneous bandwidth is very high (multiple GHz), it is not practical or economic to store a continuous stream of the wideband timeseries to disk. The value per storage unit is low and further analysis will require re-processing a massive and ever growing dataset. For this reason, we propose a system where only the complex baseband of the detected RFI is stored.

The tool for extracting a single signal from a wideband timeseries is the digital down-converter (DDC). There are several possible DDC architectures [1]. However, to efficiently extract multiple signals in parallel we propose a collection of dynamically-assignable synthesis filterbanks following the ideas in [2, 3, 4, 5]. We are calling the collection of DDCs a "DDC Pool".

Figure 1 shows a RFI monitor architecture which makes use of an analysis filterbank to generate channelized voltage streams. The voltage streams are squared to generate power spectra which is fed into a live spectrogram display as well as a signal detector. The channelized voltage streams are also fed into the DDC Pool along with the detected signal metadata.

2 Method

Rather than DDC architectures which process the entire wideband timeseries to downconvert each detected signal, the introduced method processes the wideband timeseries only once. The timeseries is channelized into oversampled channels using an analysis filterbank, then signals are identified in the time frequency spectrogram using a machine learning method. Using these detections and the oversampled channels, signals spread across multiple channels are synthesized to obtain their baseband waveforms.

We will now introduce our DDC method using simulated data. The simulation uses a 100 kHz wide timeseries as input to an 8 channel 2x oversampled analysis filterbank. Each channel output from the analysis filterbank has a sample rate of $(100\,\text{kHz} \div 8\ \text{channels}) \times \frac{2}{1} = 25\,\text{kHz}$. These simulation parameters were chosen for easy visualization and to show the software-defined parameterized nature of the method, however we envision an implementation of this system to span several GHz of bandwidth which is channelized into a frequency resolution appropriate for the observed RFI at a monitored site.

Figures 2 to 6 illustrate the various stages of the proposed system using simulated data.

2.1 Analysis filterbank

The wideband timeseries is channelized in a 2x oversampled polyphase filterbank (PFB) which we call the analysis filterbank. These channelized voltages are then squared into power spectra for signal detection and a live spectrogram display, as well as sent directly to the DDC Pool for detected signal synthesis.

Radio frequency (RF) signals can span multiple frequency channels of the analysis filterbank, as shown in fig. 2.

A frequency-normalized polyphase raised-cosine filter with

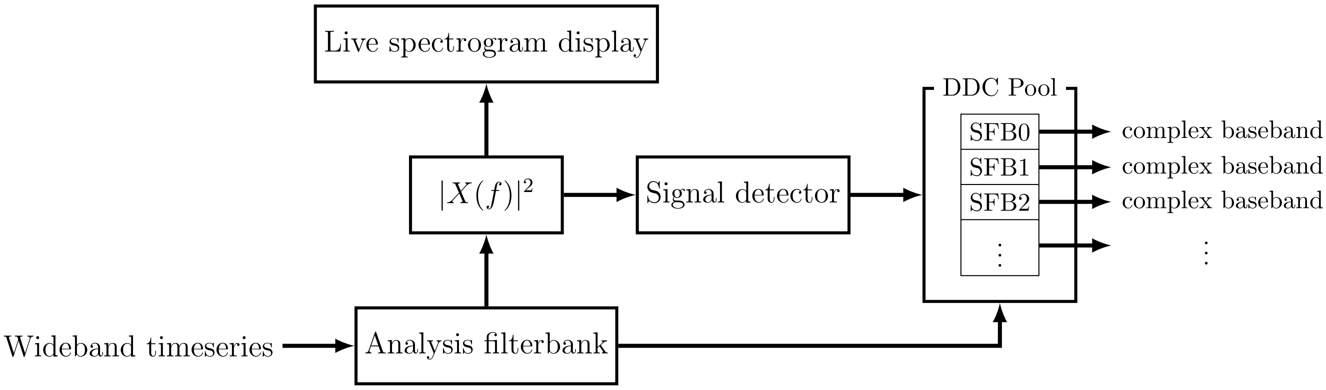


Figure 1. RFI monitor design concept block diagram

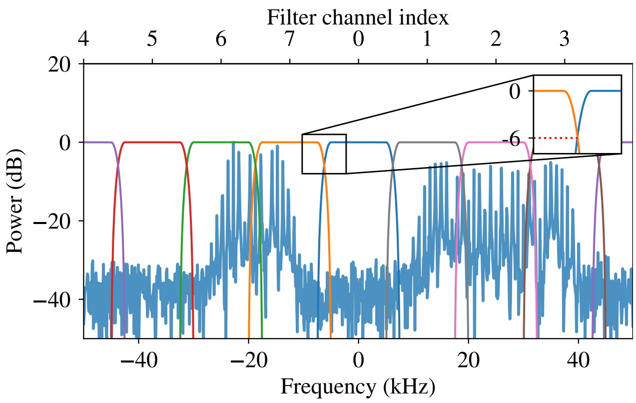


Figure 2. Input spectra with the oversampled filter overlaid showing the channels and −6 dB cross-over point

a roll-off factor (β) of 0.2 is applied to each of the M analysis filterbank channels as described by eq. (1).

$$h(n) = \text{sinc}(n)\frac{\cos(\pi\beta n)}{1-(2\beta n)^2}$$
$$n = \left(\frac{-N}{2M}, \frac{N}{2M}\right) \tag{1}$$

This ensures the oversampled channels cross at −6 dB so that signals can be reconstructed in voltage as per [3]. The stopband attenuation is a function of the number of taps (N) in the filter as well as the transition bandwidth (Δf) which proportional to β via eq. (2). For this demonstration we use 1201 taps yielding a stopband attenuation of $\approx$ 70 dB.

$$\beta = \frac{2\Delta f}{f_s} \tag{2}$$

For the simulation, the two frequency modulation (FM) signals shown in fig. 2 are each fragmented into multiple channels. The eight channels are shown in fig. 3 where the zeroth channel is centered over DC and the channels are indexed as they increase positively in frequency before wrapping to $-\frac{f_s}{2}$ and back up to DC. Note that there are eight channels each with a sample rate of 25 kHz spanning the 100 kHz bandwidth.

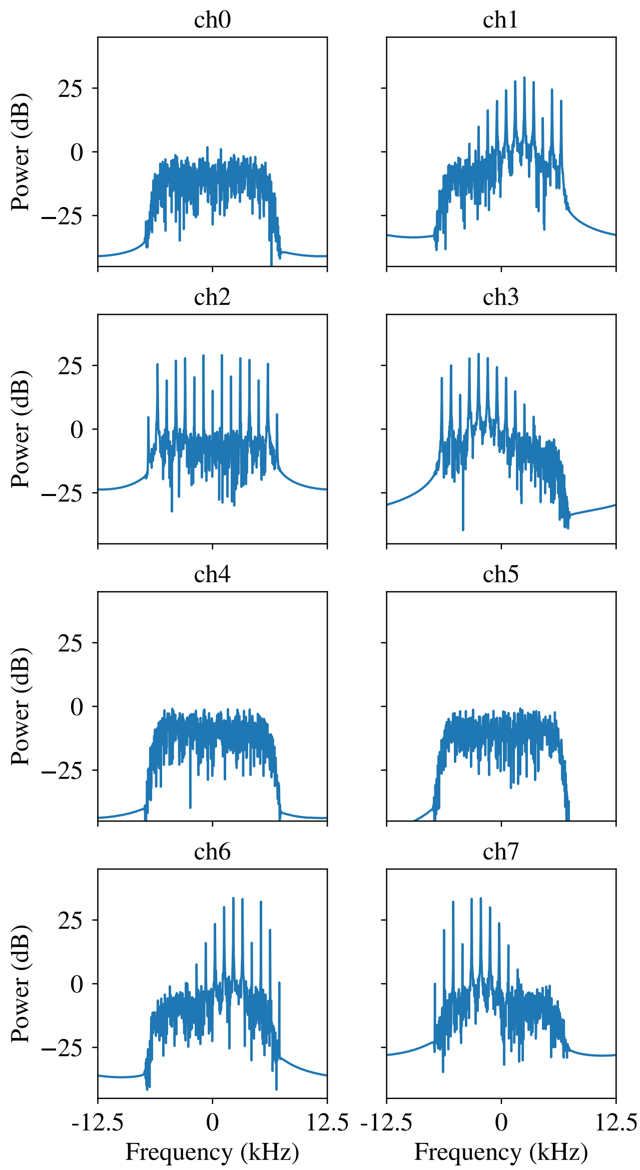


Figure 3. Spectra of 2x oversampled channels output from analysis filterbank

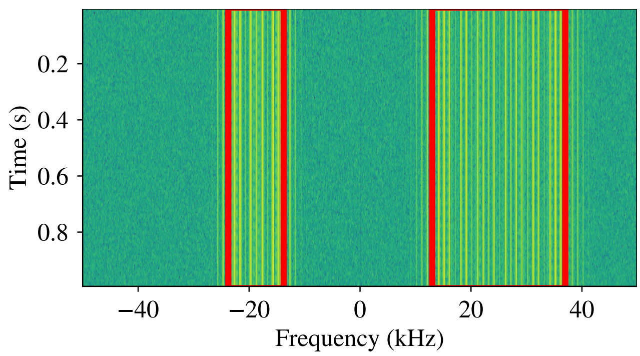


Figure 4. Detected bounding boxes

2.2 Signal detections

The output of the analysis filterbank is squared to produce power spectra. Signal detections are done on these power spectra, using the algorithm introduced in [6], yielding predicted bounding boxes in time/frequency space. These bounding boxes are illustrated on the simulated data with red in fig. 4.

2.3 DDC Pool

Analysis filterbank channels intersecting a bounding box are fed to a synthesis filterbank which reconstructs the signal time series.

As shown in fig. 1, the DDC pool is fed with the bounding boxes detected in the power spectra where signal structure has been destroyed along with the oversampled voltage channels from the analysis filterbank where signal structure is preserved. The DDC pool handles the logic to pass only those voltage channels which overlap with a bounding box to a synthesis filterbank.

2.3.1 Synthesis filterbank

Figure 5 illustrates the processing steps which take place in the synthesis filterbank. The inputs are those analysis filterbank channels containing fragments of a signal destined for synthesis. Each of these M_s channels has a sample rate of $2\frac{f_s}{M}$ with M being the number of channels output from the analysis filterbank and f_s being the sample rate of the timeseries fed into the analysis filterbank input.

The channels are fed into the synthesis filterbank in order of increasing frequency.

Padding

The padding process first checks whether M_s is even or odd. This defines the number of zero-valued channels used for padding: one is appended for an odd number of input channels while two are appended for an even number of input channels. These zero-valued padding channels ensure that the Fast Fourier Transform (FFT) and PFB always have an even channel count and that during the FFT the channel that wraps from $\frac{f_s}{2} \rightarrow -\frac{f_s}{2}$ is zeros, preventing any signal fragments from being wrapped to the wrong spectral locations.

At the output of the padding block there are M_p channels where

$$M_p = \begin{cases} M_s \bmod 2 = 0, & M_s + 2 \\ M_s \bmod 2 \neq 0, & M_s + 1 \end{cases} \tag{3}$$

When M_s is odd, the single padding channel is inserted before the 0-th index. When M_s is even, paddings channel are added before the 0-th index and after the M_s-th index, effectively sandwiching the M_s input channels between two channels of zeros.

From this point forward, the processing steps within the synthesis filterbank will operate on M_p channels.

Align

The channels are aligned going into the FFT by first inverting their order then shifting them all by one index such that the channel containing the DC bin is kept in the center of the FFT.

FFT

A M_p-point FFT is done.

Circular shift

The channels output from the FFT process are each phase rotated for alignment into the polyphase filter. Since the channels are oversampled, each must be shifted by $e^{-j2\pi k\frac{M}{2}}$ where k is the channel index. This shift bring the channel centers back to a spacing of f_s/M.

This can be accomplished by applying a complex rotator to each channel, or by applying the discrete Fourier transform (DFT) time shift property,

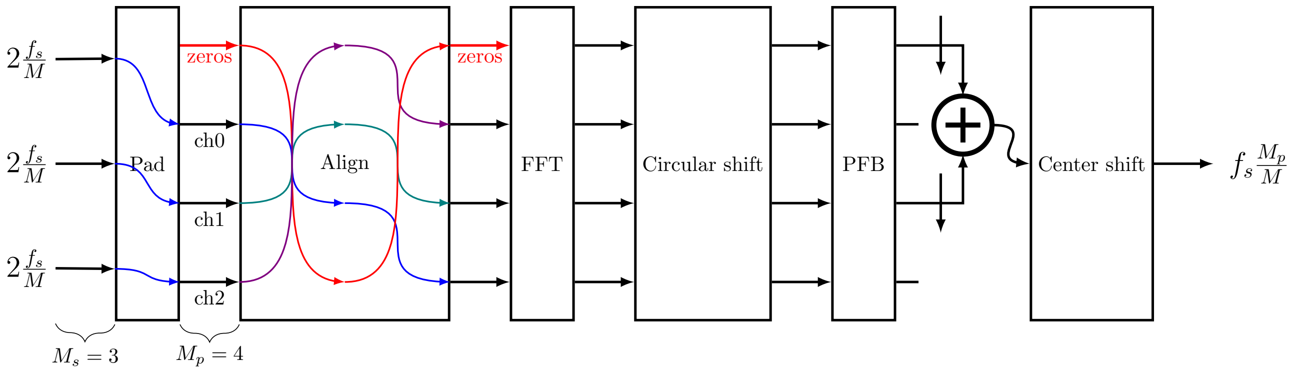
$$x(n-m) = X(k)e^{-j2\pi km} \tag{4}$$

such that each channel is simply delayed by $k\frac{M}{2}$ samples.

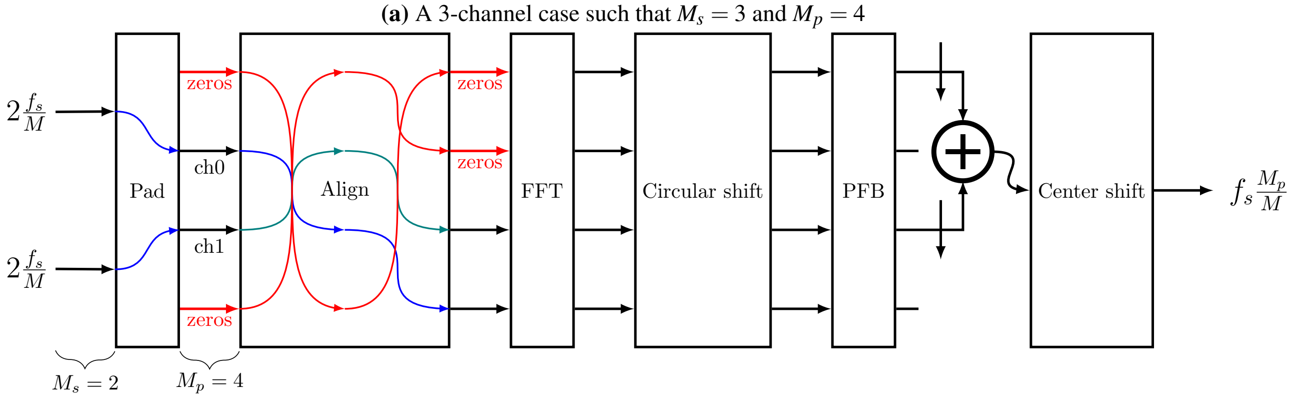
PFB

The next step is to apply the polyphase filter. The filter is a Nyquist filter (as in the analysis filterbank) with the same roll-off factor $\beta = 0.2$ but where $M = \frac{M_p}{2}$. Equation (1) can then be written as eq. (5).

$$\begin{gathered} h(n) = \mathrm{sinc}(n)\frac{\cos(\pi\beta n)}{1-(2\beta n)^2} \\ n = \left(\frac{-N}{M_p}, \frac{N}{M_p}\right) \end{gathered} \tag{5}$$



(a) A 3-channel case such that $M_s = 3$ and $M_p = 4$



(b) A 2-channel case such that $M_s = 2$ and $M_p = 4$

Figure 5. Block diagram of synthesis filterbank processing steps

As described in [7], the filter for each branch of the PFB is zero-stuffed and the second half of the channels have the filter taps delayed by 1 sample as illustrated by example in eq. (6) where $h(n)$ is the result of eq. (5) and $M_p = 4$.

$$\begin{aligned} h(n) &= [x_0, x_1, x_2, x_3, x_4, x_5, x_6, x_7] \\ h_0(n) &= [x_0, 0, x_4, 0] \\ h_1(n) &= [x_1, 0, x_5, 0] \\ h_2(n) &= [0, x_2, 0, x_6] \\ h_3(n) &= [0, x_3, 0, x_7] \end{aligned} \tag{6}$$

Decimation

With the filter applied, every $\frac{M_p}{2}$ samples is summed resulting in the output sample rate being decimated to $f_s \frac{M_p}{M}$.

Center shift

Finally, if M_s is odd the center frequency of the input bandwidth (the bandwidth covered by the M_s input channels) is frequency shifted to 0 Hz on the synthesized spectrum. This is only necessary when M_s is odd; when M_s is even the "sandwiching" zero-valued padding channels don't cause an offset from the input center frequency.

The shift when needed is always proportional to M_p as $e^{j\pi \frac{n}{M_p}}$ where n is the sample index.

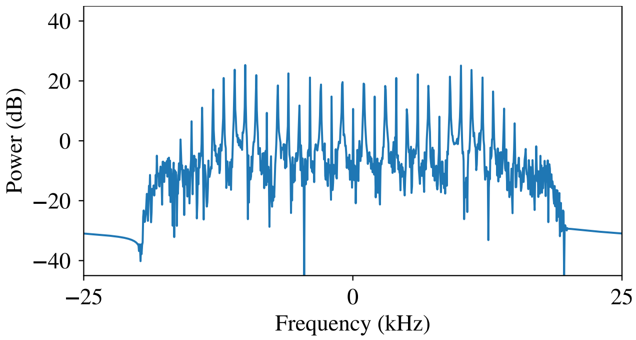
2.4 Postprocessing

Note that the final stage of the synthesis filterbank, the center shift, does not consider the center frequency of the signal, but of the input channels. The synthesis filterbank does not consider the concept of a detected signal and only synthesizes input channels. In the common case where a detected bounding box is not centered with respect to the analysis filterbank channels, a second shifting operation is required after the synthesis filterbank to shift the center of the detection box to 0 Hz.

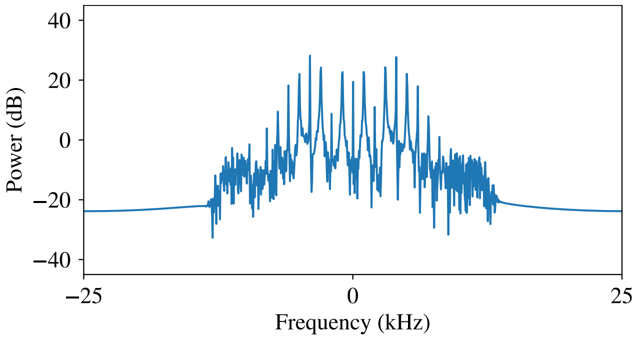
Another effect of the zero-valued padding channels is that it changes the sample rate of the synthesized signal relative to the 2x oversampled fragments. This can be handled by a simple decimation process if desired.

2.5 Output

Figure 2 shows one FM signal centered at -18.75 kHz spanning 2 of the 8 channels and another centered at 25 kHz spanning 3 of the 8 channels. Figures 6a and 6b then show the signals synthesized spectra. In the 3-channel case the synthesis filterbank has added a fourth channel of zeros while in the 2-channel case it has added 2 channels of zeros. The output sample rate considers these padding channels, so in both the 2 and 3 channel cases is 50 kHz. This is because following eq. (3), in both cases ($M_s = 2, M_s = 3$) the



(a) Synthesized channels 1, 2 and 3



(b) Synthesized channels 6 and 7

Figure 6. Synthesized FM signals

total number of channels synthesized, including padding channels, is 4 ($M_p = 4$).

3 Application

We apply the synthesis filterbank to extract short segments of complex baseband signals for further classification using machine learning (ML) methods. We have found segments of 128-1024 complex time samples are suitable for this task, although longer segments could be synthesized. In the following example, 256 synthesized samples are extracted for each detection.

In fig. 7, we show three signals detected in time-frequency space from the publicly available dataset at [8]. Below that are the synthesized spectra and the corresponding complex baseband waveforms. The waveform synthesis can be validated visually by inspecting the symbols and seeing that the FSK2 (black) signal clearly switches between two frequencies, the PSK4 (orange) signal has four peaks at $1+0j$, $0+1j$, $-1+0j$ and $0-1j$, and the FSK4 (blue) signal switches between four frequencies.

The synthesized signal has been centered with respect to the synthesis bandwidth following the steps in section 2.4. This corrects for the residual frequency offset between the analysis filterbank channels center frequencies and the detection box center frequency. There may still be a residual frequency offset caused by error in the bounding box detection algorithm.

Table 1. Information on synthesized signals shown in fig. 7

	Black	Orange	Blue
Number of synthesized channels	4	8	5
Number of padding channels	2	2	1
Modulation type	FSK2	PSK4	FSK4

4 Conclusions

We have introduced the DDC Pool concept and prototyped it. This is an efficient DDC method which makes use of an over-sampled channelization process as input to the DDC Pool. We validated it on a publicly available wideband timeseries from which the complex baseband waveforms of detected signals were all extracted.

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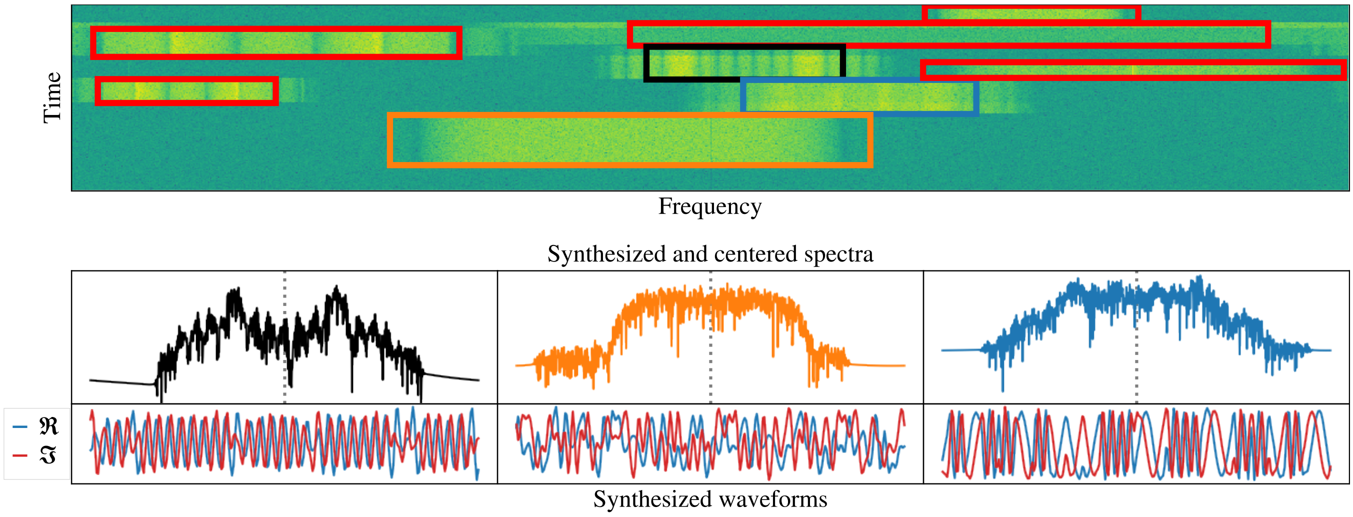

Figure 7. Waterfall plot (top) showing detection boxes with some of the signals synthesized (bottom)

[8] N. West, "SPAWC21 Wideband Dataset," May 2021, type: dataset. [Online]. Available: https://opendata.deepsig.io/datasets/SPAWC.2021/spawc21_wideband_dataset.zip