A Sub-Nyquist Radar Prototype: Hardware and Software

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Abstract

We introduce a full hardware implementation and demo of a sub-Nyquist radar receiver. Our system demonstrates pulse-Doppler radar transmission and reception at sub-Nyquist rates. Specifically, we sample the received radar signal at 1/20 the Nyquist rate, while still perfectly detecting the targets in the delay-Doppler plane. In addition our system filters clutter interference from the sub-Nyquist samples by implementing a clutter rejection algorithm, with all the processing done at the low rate. In this prototype system, we use the Xampling framework in order to reduce the sampling rate at the ADC. After sampling, the entire signal, recovery process and clutter filtering are performed on the low rate samples without having to return to the Nyquist rate. With our hardware and algorithm we are able to obtain good detection performance even in low SNR. To our best knowledge this is the first sub-Nyquist radar system illustrating delay-Doppler detection implemented in hardware.

1. Introduction and Motivation

Current state-of-the-art radar systems, sample at the signal's Nyquist rate, which can be hundreds of MHz. This results in high demands on the system front-end hardware as well as high computational loads caused by the large number of samples. In our demo we present a sub-Nyquist radar receiver prototype that samples and processes pulse-Doppler radar signals at sub-Nyquist rates. Using the Xampling [1] method, the sampling rate is 20 times lower than the signal's Nyquist frequency while attaining the same detection abilities as a standard Nyquist radar. In addition our system filters clutter interference from the sub-Nyquist samples by implementing a clutter rejection algorithm, with all the processing done at the low rate.

In Xampling, we use an analog-to-digital convertor (ADC) which performs analog prefiltering of the signal before taking point wise samples. These compressed samples ("Xamples") contain the information needed to recover the desired targets' parameters and to filter the clutter by using a small number of Fourier coefficients. All of the processing is performed in the Fourier domain after FFT on the low rate samples.

Our approach is based on the observation that there are 3 main parameters to recover [2]: amplitude, delay and Doppler frequency for each target. Our radar prototype is capable of extracting these parameters out of low SNR samples and clutter interference from the low rate samples.

Our hardware prototype implements a multi-channel topology consisting of 4 channels, each comprising a bandpass crystal filter with a random effective carrier frequency. This allows to obtain a wide spread of Fourier coefficients of the signal in an efficient manner. The proposed recovery algorithm then uses these coefficients to recover the delays and Dopplers and filter the clutter. Using crystal filters, which have extremely narrow transition bands, we are able to obtain sufficient amount of information from the signal, while substantially decreasing the total sampling rate.

The system we consider generates non-fluctuating point targets, sparsely populated in the radar's unambiguous time-frequency region. The system shows reception and detection of the targets in the delay-Doppler plane using both the Nyquist rate samples and the sub-Nyquist samples and compares their performance in real time. Clutter is also added to the desired signal as well as noise.

To the best of our knowledge this is the first demonstration of a radar system operating at sub-Nyquist rates. While past works have discussed the applications of compressed sensing (CS) algorithms to this type of problem, how to sample such signals with existing hardware, and perform all the required signal processing on the low rate samples, has not been previously demonstrated.

2. Algorithm Description

In this section we present in short the targets recovery algorithm. A detailed description of the basic algorithmic steps can be found in [5]. In classic radar processing [3], time delays and amplitudes of the target are first estimated using a matched filter, and then the Doppler frequency is recovered using an FFT. Finally the clutter interference is reduced using statistical estimation. In our sub-Nyquist algorithm we reverse this order and start by filtering the clutter interference. This is done in the Fourier domain, after performing an FFT over the slow time. In the Fourier domain, we then show that our problem can be reduced to a specific class of CS problem, in the joint delay Doppler plane. To enhance the SNR before applying CS, we use a Doppler focusing method, introduced in [5], which can be implemented on the low rate samples and provides an optimal SNR enhancement, just like the matched filter does, even though it is applied to the low rate samples. After Doppler focusing, we arrive at a simple delay-only CS problem which can be solved efficiently. In our hardware, we solve it using OMP. The basic processing steps are summarized in Figure 1.

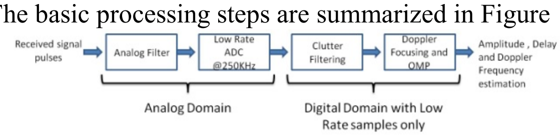

Figure 1 Recovery algorithm stages.

a. Analog filtering and sampling

In order to recover the incoming pulse parameters we use only a small subset of the signals Fourier coefficients, which is the key to allowing for sub-Nyquist sampling. Our analog front-end is designed to extract the required Fourier coefficients in a hardware efficient way, while still spreading them out enough so that the performance of our CS algorithms is sufficiently good. To this end we use 4 narrow bandpass filters, randomly spread over the signals bandwidth, followed by 4 low rate samplers. In our demo, we consider signals with bandwidth of 20Mhz, and sample using 4 ADCs, each of 250KHz.

b. Clutter interference removal

Unlike real targets, clutter interference is a stochastic process with a PSD function varying with respect to the Doppler frequency. Using the PSD function, a set of optimal filters in the sense of signal to clutter ratio improvement - IF, can be constructed for each Doppler frequency [4]. The set of filters coefficients is obtain by:

$$\underline{w}_{opt} = M^{-1}\underline{S}$$

Where w the filter coefficient vector, M is the covariance matrix of received signal and S is a vector of doppler frequencies. An important part of our demo is to show that standard clutter rejection methods can be integrated into our sub-Nyquist prototype. We implement clutter rejection in the frequency domain, on our low rate samples. As we show, only small adjustments are necessary to incorporate the clutter algorithms into our sub-Nyquist prototype due to the fact that all of our processing is Fourier-based.

c. Estimating target's parameters

After the samlpes are cleaned of clutter, we implement our CS-based recvoery algorithm on the Fourier samples.

From [5] :

$$\Psi_{\nu}\left[k\right] \cong \frac{P}{\tau} H\left(2\pi k / \tau\right) \sum_{l=0}^{L-1} \alpha_l e^{-j2\pi k \tau_l / \tau}$$

While Ψ_{ν} are the Fourier coefficients for Doppler frequency ν, P is SNR scale, α_l, τ_l, ν_l are amplitude, delay and Doppler frequency of the l_{th} target. H is transmitted pulse's function. From equation above, Doppler focusing can be performed on the low rate sub-Nyquist samples and estimate for every ν up to PRF, amplitude and delay using OMP

3. System Implementation

Our hardware consists of two parts. The first part is a multi-channel crystal receiver which filters Fourier coefficients needed for the digital recovery, in a practical and efficient way. This approach makes use of four parallel channels which sample distinct bands of the radar signal spectrum, as illustrated in Fig.2a. Each band is filtered, demodulated to baseband and then sampled it at its Nyquist rate of 250 KHz. As crystal filters operate only at specific central frequencies, we have to perform two stages of modulation. First the desired band is up-converted to the pass-band of the filter and then, after filtering, it is demodulated to baseband. Finally the signal is filtered with a LPF that serves to suppress the modulation image. A photo of our 4-channel receiver analog board is shown in Fig.2b.

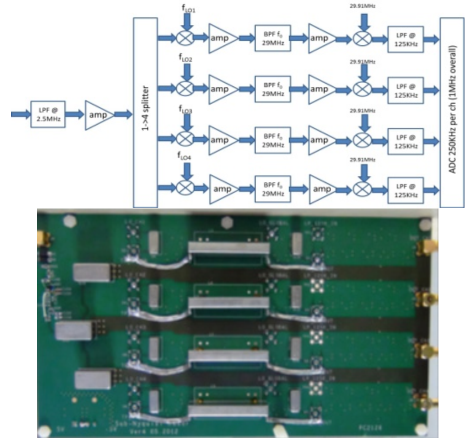

Figure 2 a. (top) crystal receiver block diagram , 2b. (bottom) crystal receiver picture

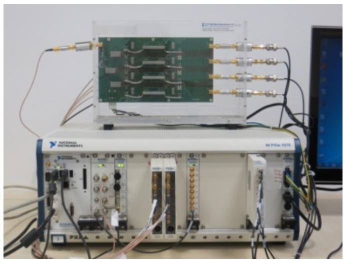

Figure3 the PXI chassis and crystal receiver

The second part of our system is a National Instruments PXI chassis as shown in figs 3 and 4. It contains a controller which runs the AWR simulation that produces a variety of realistic scenarios and also the recovery algorithm,, an Arbitrary Waveform Generator (AWG) which is fed with the scenarios created by the AWR and transmits them, 2 FPGA based sine wave generators which generate 5 sine waves to be fed into the mixers LO input at the analog PCB described above, low rate ADC samples the analog PCB outputs at 250KHz and a clocking and synchronization unit which is able to send a start trigger simultaneously to all units. This combination of the crystal filter PCB and the synchronized generator on the PXI chassis behave as a unique analog filter bank with zero phase delay between output channels.

The combination of the analog crystal receiver and the PXI chassis allows our system to be flexible, so that we can choose other Fourier coefficients easily by changing $LO_{1\text{-}4}$ frequencies in the GUI. Furthermore we can create various scenarios with different parameters for targets, noise level and clutter models using the AWR simulation system and feed any scenario into the AWG.

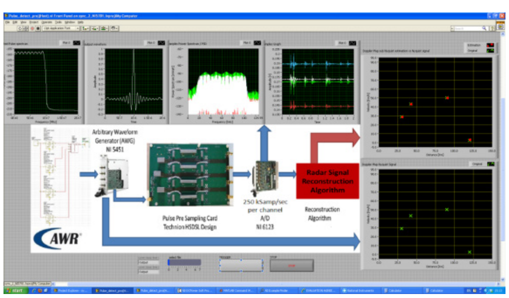

Figure4 recovery SW GUI, at the most left graph is the transmitted signal in frequency and time domain, in the middle two graphs showing the sampled data in frequency and time domain. In the most right there are two delay Doppler maps; the lower one obtained at the Nyquist rate and the is the result of our sub-Nyquist receiver

As illustrated in Fig. 4, in the demo itself, we will input various different scenarios of targets with different delays and Dopplers. We will then show in real time their sampling through our board of Fig. 2, and the recovery using the system in Fig. 3. The demo pane, shown in Fig. 4, illustrates the process: We show in real time the input signal in frequency and time, the subsampled channels, and the delay Doppler maps obtained both at the sub-Nyquist rate and the Nyquist rate for comparison. All of the processing is performed in real time from the true sub-Nyquist samples.

A link to Demo system web page :
http://webee.technion.ac.il/people/YoninaEldar/hardware_demo_radar.php , video:
http://www.youtube.com/watch?feature=player_embedded&v=h66uPzEOs_s
the videos in link above does not include clutter processing which has been added recently and will be presented in coming Demo.

4. Conclusion and Future work

We presented a sub-Nyquist radar prototype based on the Xampling methodology which has almost the same abilities of operational radar. We have been able to reduce the total sampling rate by a factor of nearly 20 while maintaining reasonable detection ability and high ability to clean the clutter from samples. Moreover we have successfully integrated the CDP (Clutter Doppler Processing) technique originally developed for Nyquist systems into our Sub-Nyquist algorithm. Future work will develop an addition for staggered PRI, and extensions to MIMO radar.

References

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