# Xampling-Enabled Coexistence in Spectrally Crowded Environments

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*Abstract*—**We present a composite suite of technologies for spectral coexistence of existing communication and radar systems using the Xampling framework. For a stand-alone communication system, we consider a cognitive radio (CRo) that receives multiband signals with unknown carrier frequencies and directions of arrival, and demonstrate joint spectrum sensing via CompreSsed CArrier and Direction-of-arrival Estimation (CaSCADE) with an L-shaped configuration of two uniform linear arrays. For radars operating in bands with widespread spectral interference, we present an X-band prototype of cognitive sub-Nyquist multiple input multiple output (MIMO) radar (SUMMeR). The prototype allows sampling in both spatial and spectral domains at sub-Nyquist rates and cognitively transmits over multiple narrow subbands. Finally, we demonstrate Spectral Coexistence via Xampling (SpeCX) technology that shows joint operation of both - cognitive radio and cognitive monostatic radar - over a common spectrum. Our solutions to individual and joint operation of communication and radar systems supersede existing spectrum sharing technologies that require a compromise over performance of one of the systems.**

**Keywords—spectrum sharing, sub-Nyquist, MIMO, cognitive radar, cognitive radio**

## I. INTRODUCTION

The unhindered operation of radar and communication ("comm", hereafter) systems that share spectrum with other services has captured a great deal of attention in recent years. The interest in such spectrum sharing systems is largely due to electromagnetic spectrum being a scarce resource and almost all services having a need for a greater access to the spectrum. With the allocation of available spectrum to newer comm technologies, the radio-frequency (RF) interference in radar and comm bands is on the rise. Spectrum sharing systems are, therefore, being investigated in order to use the information from coexisting radar, wireless and navigation services to manage this interference. In general, existing solutions consider either radar or comm as a primary system to be optimized while allowing degradation in the performance of the other.

In this demo, we present a holistic approach to the spectrum sharing problem where the radar and comm systems efficiently utilize the available spectrum without any deterioration in their capabilities. Our systems are based on the recently proposed Xampling framework [1] that samples and processes analog inputs at rates far below Nyquist. The inherent structure of radar and comm signals is sparse facilitating the use of compressed sensing (CS) [6] techniques for signal recovery. Our demo has three components: an advanced cognitive radio (CRo) capable of blind spectrum sensing; a state-of-the-art cognitive radar (CRr) system in multiple input multiple output (MIMO) configuration performing sub-Nyquist sampling in both spatial and spectral domains; and finally an actual spectrum sharing prototype where CRo and CRr transmit, receive and operate over a common spectrum. We describe each of these systems and their advantages over existing solutions in the following sections.

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## II. CASCADE: A COGNITIVE RADIO ENHANCEMENT

Our CRo demo implements the CompreSsed CArrier and Direction-of-arrival Estimation (CaSCADE) system [2]. Here, we first consider cyclostationary detection to overcome the traditional energy detection in low SNR regimes. Moreover, to cope with fading and shadowing, we show that collaborative sensing, centralized as well as distributed, allows for correct support detection by a network of CRs, when each CR performing independent sensing would fail. Last, in order to exploit both frequency and spatial sparsity we implement a joint direction of arrival (DOA) and spectrum sensing algorithm. Our prototype is based on a sub-Nyquist system referred to as the modulated wideband converter (MWC). We show signal reconstruction in a blind setting, i.e., the carrier frequencies of the transmissions are unknown. A multiband input signal of Nyquist rate $f_{Nyq}$ = 6 GHz with total bandwidth occupancy of 120 MHz is sampled at an overall rate of 480 MHz, i.e. only 8% of the Nyquist rate. Our CRo abilities surpass the IEEE 802.22 CRo standard that considers Nyquist rates below 1 GHz. Our new prorotype extends our basic CRo system to cyclostationary detection, collaborative sensing and joint DOA and spectrum sensing. The hardware is a wireless system with transmitters and receivers consisting of 2 L-shape uniform linear arrays (ULAs) (Fig. 1).

## III. COGNITIVE SUMMER: SUB-NYQUIST MIMO RADAR

Our CRr prototype realizes the sub-Nyquist multiple input multiple output radar (SUMMeR) [3] system with capabilities of cognitive transmission [4]. The prototype allows sampling in both spatial and spectral domains at rates much lower than dictated by the Nyquist sampling theorem. It realizes an X-band MIMO radar receiver that can be configured to have a maximum of 8 transmit and 10 receive antenna elements. The orthogonality of MIMO waveforms is achieved via frequency division multiplexing (FDM). The Xampling framework is used for signal recovery in range and azimuth. Real-time experiments show recovery capabilities with per channel SNR as low as -5 dB for two spatial sub-Nyquist configurations consisting of 4 X 5 and 8 X 10 thinned random arrays. The thinned 4 X 5 array achieves the detection performance of its filled array counterpart with a spatial and spectral reduction of 50% and 87.5% respectively. The radar transmits in eight narrow subbands per transmit channel utilizing only 20% of the available full band without losing the range resolution of a conventional MIMO radar. The prototype is implemented using a Xilinx VC707 FPGA board for digitizer and sampler and a custom-built analog pre-processor (Fig. 2).

## IV. SpeCX: A Spectrum Sharing Solution

Our spectrum sharing solution enables interference-free operation of a surveillance radar and a communication system within a common spectrum. Both systems dynamically share information with each other and optimize their spectral resources to the changing RF environment. The communication system is a CRo that is capable of sensing its bands of interest using very low sampling and processing rates. The radar system is also modeled as a cognitive system that employs a Xampling-based sub-Nyquist receiver and transmits in several narrow bands occupying a fraction of the conventional radar bandwidth [5]. The main contribution of this work is the amalgamation of two previous concepts, CRo and CRr, and their adaptation to solve the spectrum-sharing problem. Our prototype (Fig. 3) demonstrates the spectral coexistence via Xampling (SpeCX) technology [6] through real-time experiments.

The CRo system uses the proprietary MWC board that implements the sub-Nyquist analog front-end receiver. The card first splits the wideband signal into 4 hardware channels, with an expansion factor of 5, yielding 20 virtual channels after digital expansion. In each channel, the signal is then mixed with a periodic sequence (truncated versions of Gold Codes). The CRo blind-senses the spectrum from sub-Nyquist samples and provides the radar with spectral occupancy information. Equipped with this spectral map as well as a known radar environment map (REM) detailing typical interference with respect to frequency, the radar transmitter chooses narrow frequency subbands that have minimal interference in signal transmission. The CRr receiver samples and processes only these subbands. By exploiting the sparsity of the target scene, CRr achieves the same range resolution as a conventional wideband signal while transmitting and processing only a few narrow spectral bands. Due to space constraints, we use basic prototypes of CRo and CRr in our SpeCX hardware. However, each of these systems can be replaced by their advanced counterparts such as CaSCADE or cognitive SUMMeR in a realistic scenario.

Our solution has several advantages. It optimizes the radar's performance without interfering with existing comm transmissions. Unlike conventional spectrum sharing radar, the SpeCX radar does not lose the range resolution despite using less bandwidth for transmission. Both CRo and CRr receivers use very low sampling rates. The received signal SNR of the radar is enhanced via cognitive transmission. The CRo is capable of sensing both DoA and spectra-of-interest in highly congested spectral environments. Our technology is applicable even when CRr extends to array configurations such as MIMO, and when CRo operates in a networked configuration.

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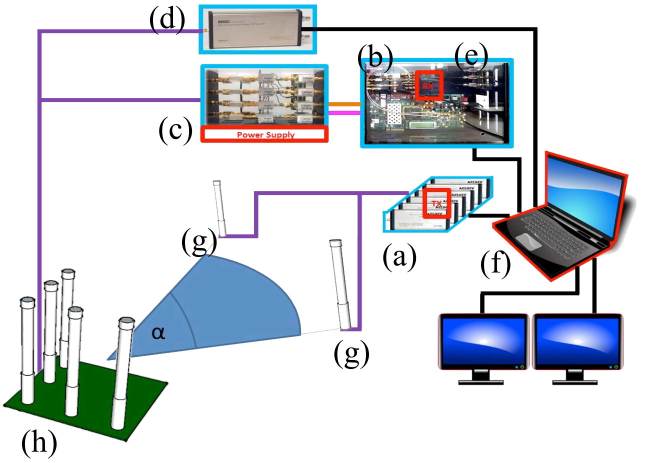


Fig. 1. MWC CR wireless + DOA system prototype: (a) Vector Signal Generators, (b) FPGA mixing sequences generator, (c) MWC analog front-end board, (d) spectrum analyzer, (e) ADC, (f) DSP, (g) Transmit antenna, (h) 2 ULAs in L-shape array.

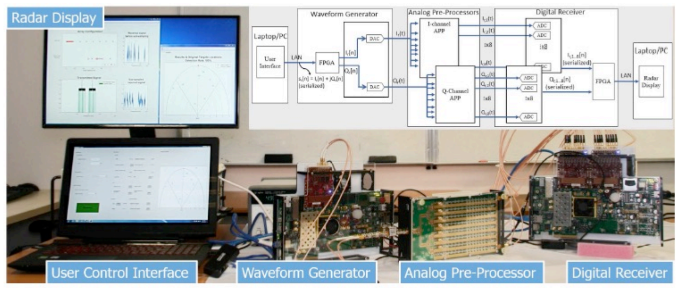


Fig. 2. Cognitive sub-Nyquist MIMO prototype and user interface. The analog pre-processor module consists of two APP cards mounted on opposite sides of a common chassis. The inset shows the simplified block diagram of the system. The subscript r represents received signal samples for $r^{th}$ receiver. Wherever applicable, the second subscript corresponds to a particular transmitter. The square brackets (parentheses) are used for digital (analog) signals.

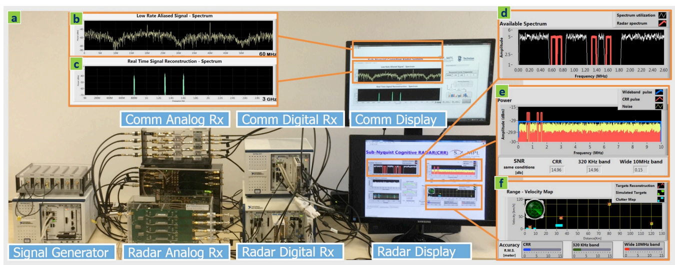


Fig. 3. (a) SpeCX prototype. The system consists of a signal generator, a CRo comm analog receiver including the MWC analog front-end board and the FPGA mixing sequences generator, a comm digital receiver, a CRr analog and receiver. SpeCX comm system display showing (b) low rate samples acquired from one MWC channel at rate 120 MHz, and (c) digital reconstruction of the entire spectrum from sub-Nyquist samples. SpeCX radar display showing (d) coexisting comm and CRr, (e) CRr spectrum compared with the full-band radar, and (f) range-velocity display of detected and true locations of the targets.