Cognitive Sub-Nyquist Collocated MIMO Radar Prototype with Clutter Removal

646804-BNYQ

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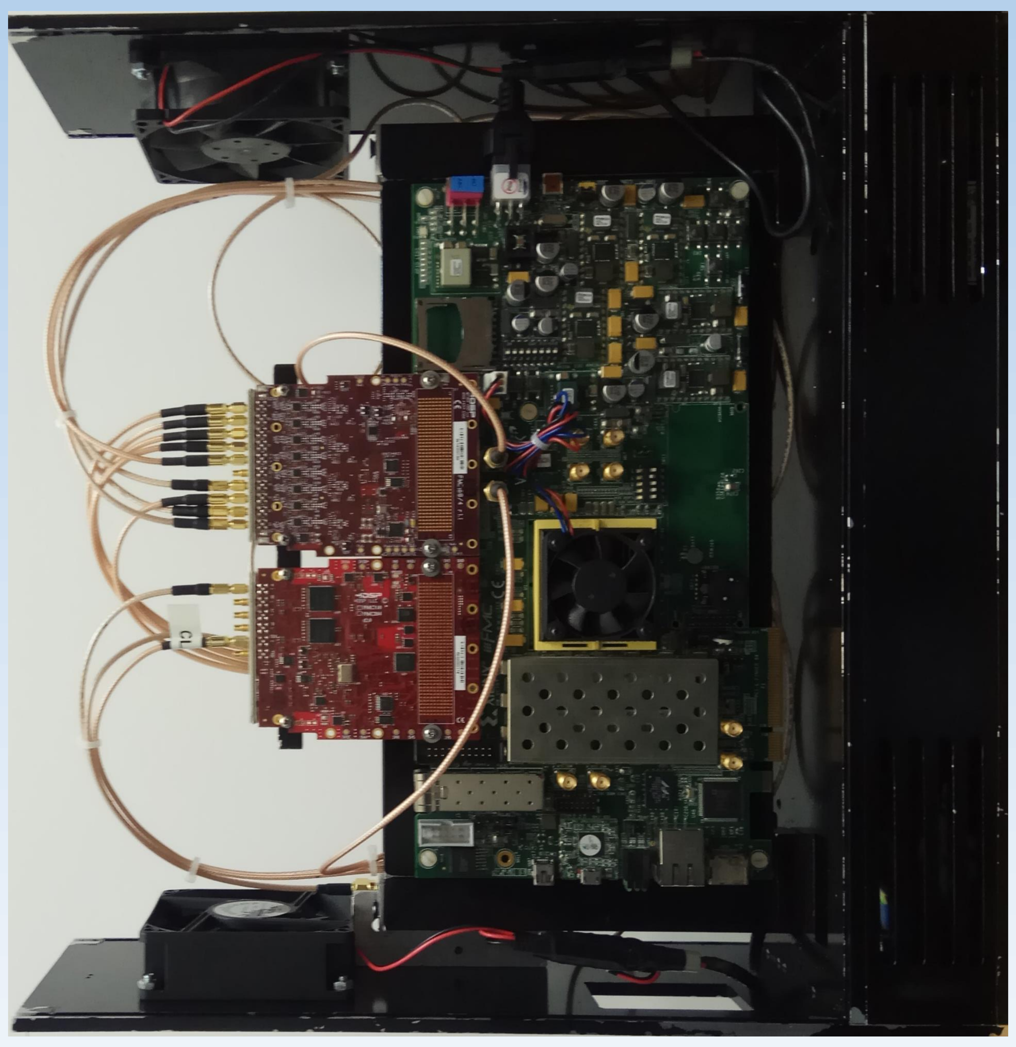
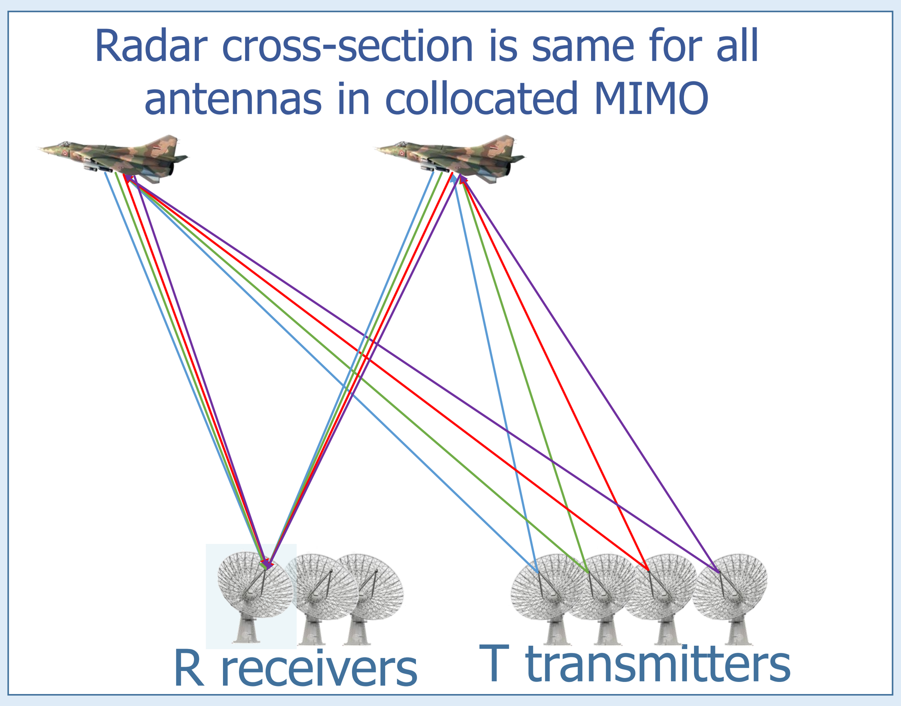
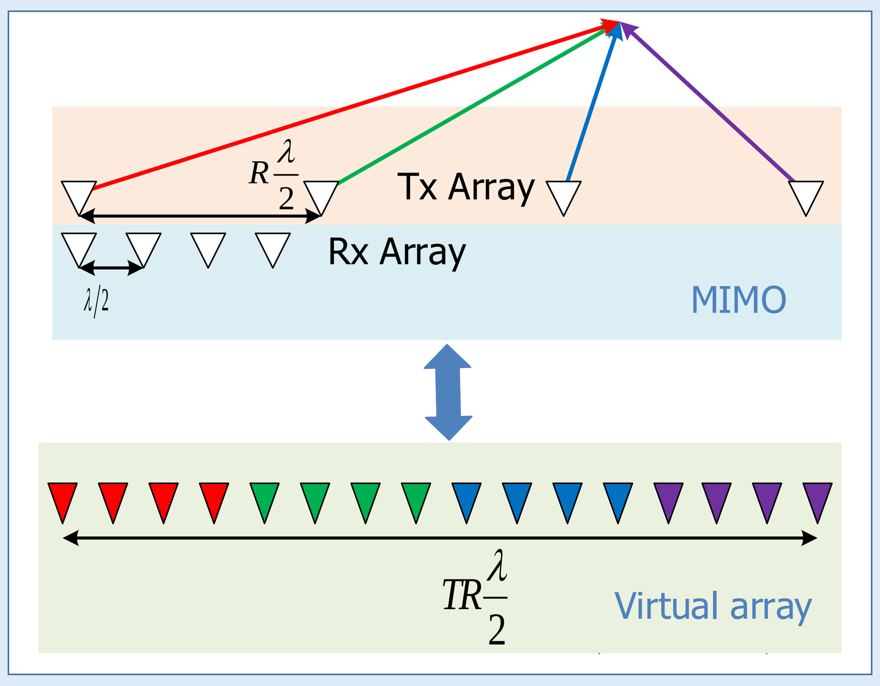


Theoretical Background

Conventional Collocated MIMO Radar



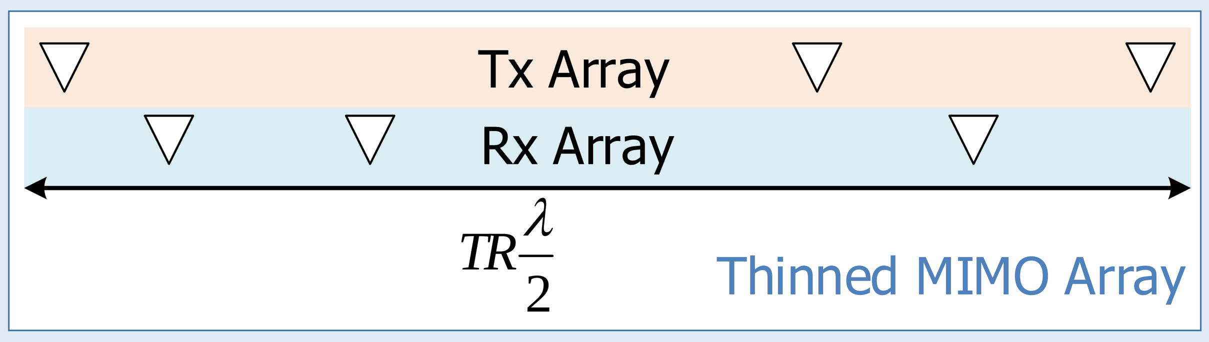
MIMO transmits orthogonal waveforms and processes linear combination of echoes received due to each waveform



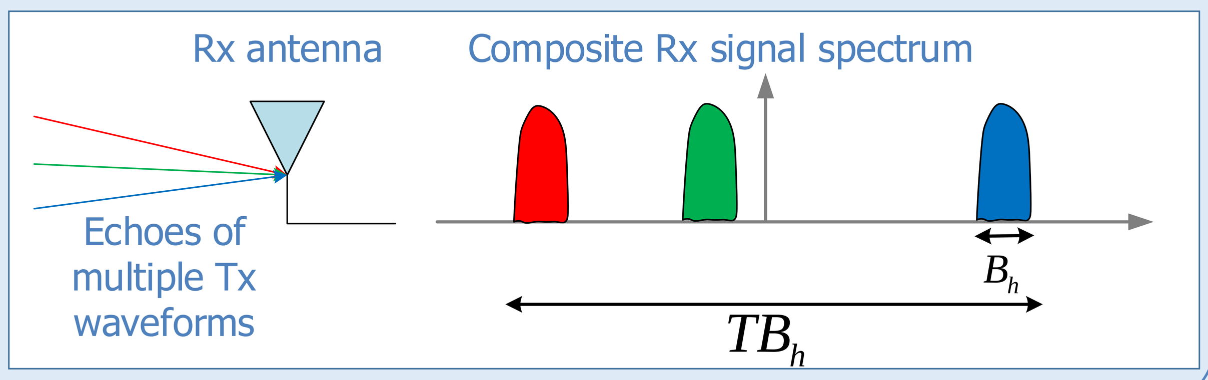
MIMO array with fewer elements has same spatial resolution as a virtual array with more elements

Sub-Nyquist Collocated MIMO Radar

Spatial Sub-Nyquist
Thinned random array that preserves the azimuthal resolution as a virtual ULA



Spectral Sub-Nyquist
Reduced sampling rate at each receiver that preserves the range resolution as with bandwidth TB_h



Signal Model and Xampling

- Received signal at the qth antenna after demodulation:

$$x_q(t) = \sum_{m=0}^{M-1} \sum_{l=1}^{L} h_m(t-\tau_l) e^{j2\pi\beta_{mq}\nu_l}$$

(L: Total number of targets; τ_l: Target time delay; β_{mq}: Element location factor; ν_l: Target azimuth)

- Fourier coefficients of the mth transmitter channel at the qth receiver:

$$y_{m,q}[k] = \sum_{l=1}^{L} \alpha_l e^{j2\pi\beta_{mq}\nu_l} e^{-j\frac{2\pi}{\tau}k\tau_l} e^{-j2\pi f_m \tau_l}$$

(f_m: Operating frequency; α_l: Target reflectivity)

- Xampling retrieves the Fourier coefficients from low rate samples

Recovery algorithm: Matrix OMP

- Goal: Recover delay, azimuth and reflectivity from $y_{m,q}[k]$
- In matrix form, the Fourier coefficients for the mth transmission:

$$\boldsymbol{Y}^m = \boldsymbol{A}^m \boldsymbol{X} (\boldsymbol{B}^m)^T$$

($\boldsymbol{A}^m$: Range dictionary; $\boldsymbol{B}^m$: Azimuth dictionary)

- Solve

$$\text{minimize } \|\boldsymbol{X}\|_0 \quad \text{subject to } \boldsymbol{Y}^m = \boldsymbol{A}^m \boldsymbol{X} (\boldsymbol{B}^m)^T, \quad 0 \le m \le M-1$$

($\boldsymbol{X}$: Sparse reflectivity matrix; non-zero values at target location)

- Use OMP for simultaneous sparse matrix recovery

Clutter Model

The received signal $r_q(t)$ at the qth antenna is $r_q(t)=x_q(t)+y_q(t)+n_q(t)$ where $n_q(t)$ is the spatially and temporally white Gaussian noise.

- The echo from C clutter targets is

$$y_q(t) = \sum_{p=0}^{P-1}\sum_{m=0}^{M-1}\sum_{c=1}^{C} \alpha_c h_m(t-p\tau-\tau_c) e^{j2\pi\beta_{m,q}\phi_c} e^{j\nu_p p\tau}$$

- The clutter amplitude in the angular range $[\theta-\epsilon, \theta+\epsilon)$ is

$$\alpha_c = \frac{1}{2\pi}\int_{\theta-\epsilon}^{\theta+\epsilon} S_c(\theta)d\theta$$

- The clutter correlation function is

$$E[S_c(\theta)S_c^*(\theta')] = R_{S_c}(\theta-\theta')$$

- After normalization becomes

$$Y_{m,q,p}[k] = \frac{\tau}{\left|H_m\left(\frac{2\pi}{\tau}k\right)\right|^2} \tilde{Y}_{m,q,p}[k+f_m\tau] = \sum_{c=1}^{C} \alpha_c e^{j2\pi\beta_{m,q}\phi_c} e^{-j\frac{2\pi}{\tau}k\tau_c} e^{-j2\pi f_m\tau_c} e^{j\nu_c p\tau}$$

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Technical Features

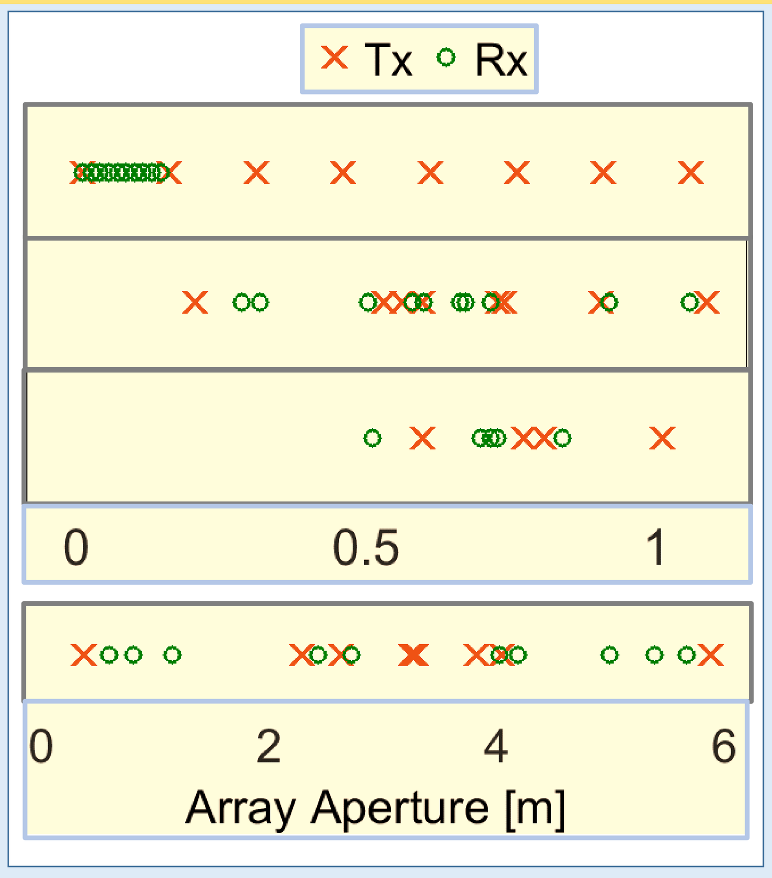
- Prototype array configurations:

Mode 1: Filled uniform array, 8x10

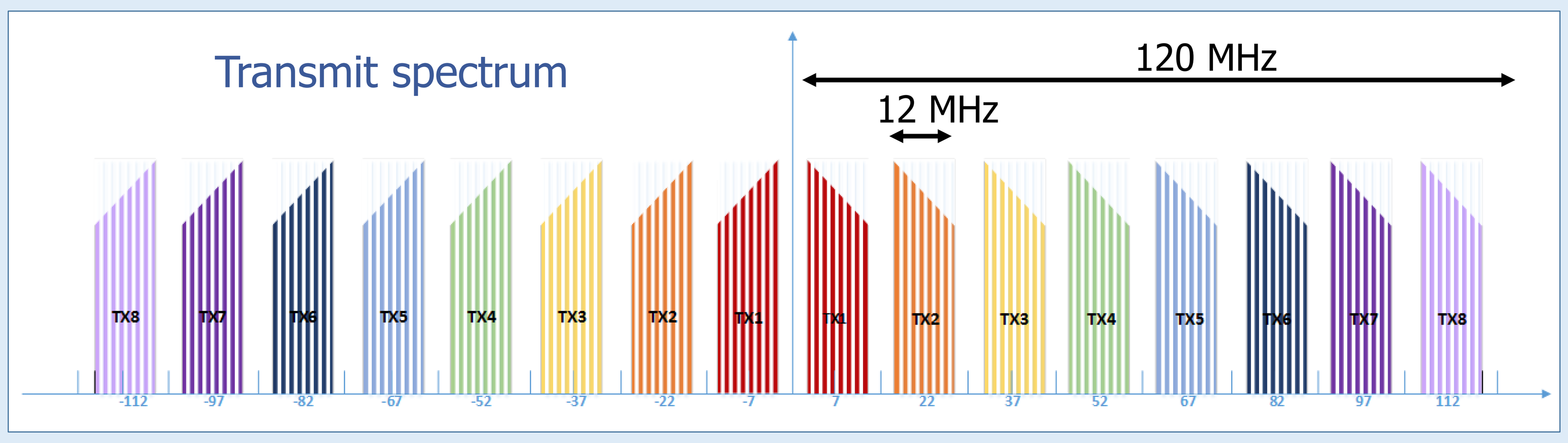
Mode 2: Filled random array, 8x10

Mode 3: Thinned random array, 4x5 (~Virtual 8x10 ULA)
Spatial sub-Nyquist mode

Mode 4: Thinned random array, 8x10 (~ Virtual 20x20 ULA)

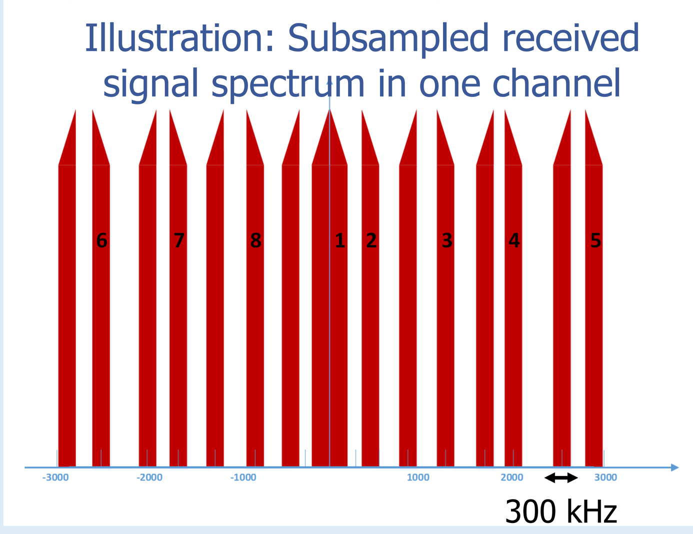


- Cognitive transmission of eight 300 kHz bands within each 12 MHz Tx BW



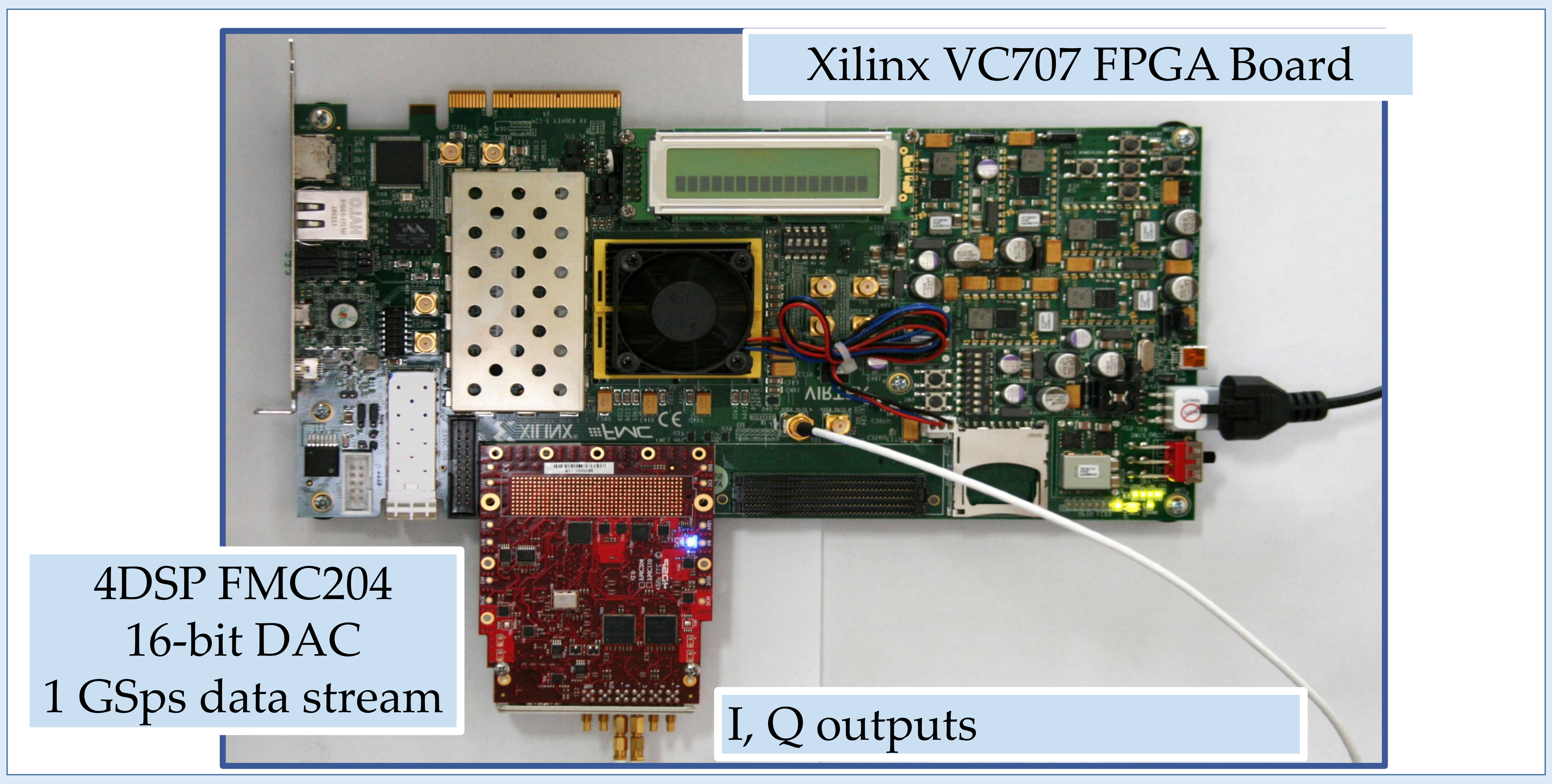
- Sub-Nyquist processing of subsampled 12 MHz spectrum

Nyquist BW, 8 Tx channels: 120 MHz
Sub-Nyquist BW, 1 Tx channel: 3 MHz
Sub-Nyquist BW, 4 Tx channels: 12 MHz
Reduction Factor: 10% (12 of 120 MHz)



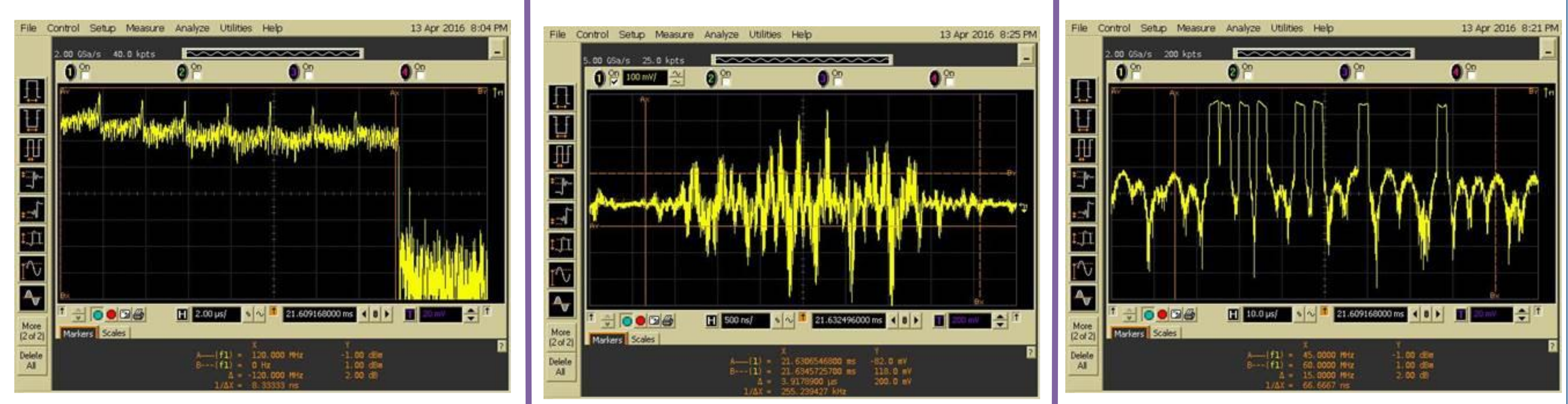
Transmit Waveform Generator

- Virtex-7 XCVX486T FPGA based digital waveform generator serializes all receivers separately into I and Q analog channels



- Transmitter outputs

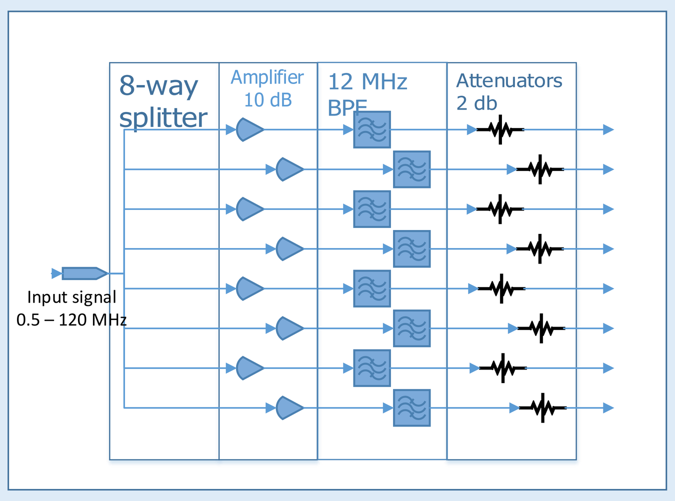
120 MHz spectrum of all 8 transmitters	Pulse from one transmitter	Spectrum of one transmitter



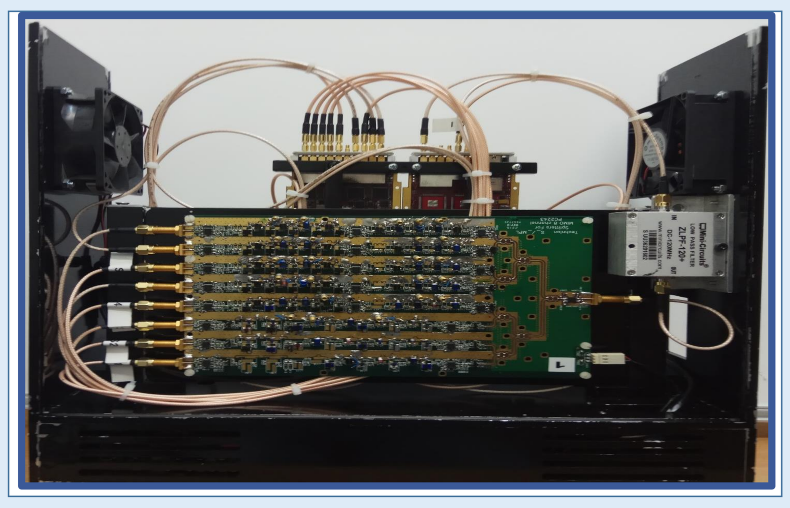
3 MHz guardband between adjacent channels	Transmit signals differ in carrier frequencies	Only eight 300 kHz slices are transmitted

Analog Pre-Processor (APP) Board

APP filters the receiver data into eight channels



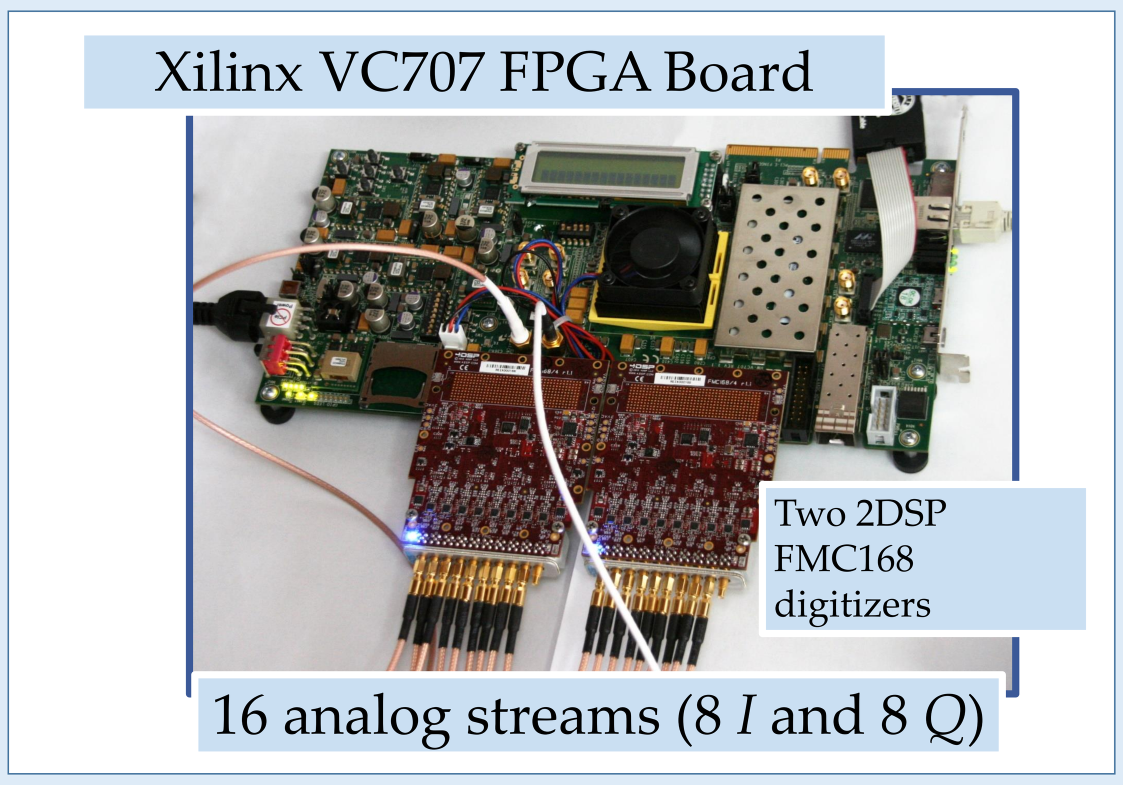
The APP card is mounted in a chassis



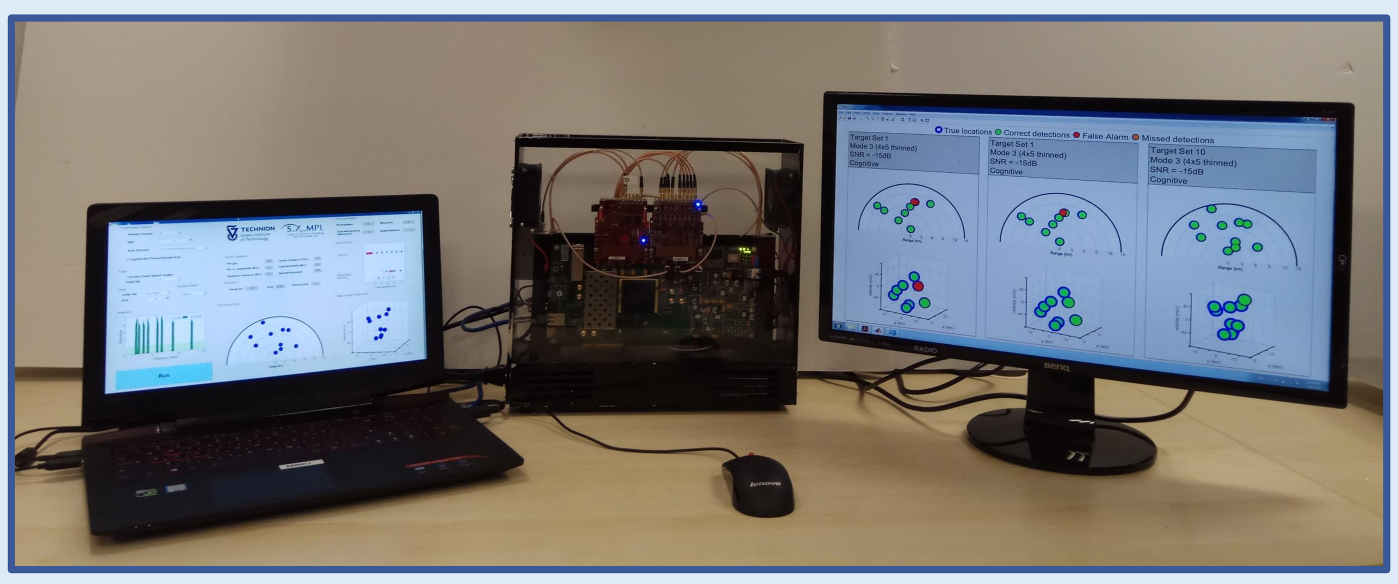
BPFs have ~30 dB stopband attenuation to mitigate subsampling noise

Digital Receiver

- Two 16-bit eight-channel digitizers for I and Q streams
- Sub-Nyquist sampling rate: 7.5 MHz/channel
- Signal BW with guard-bands: 15 MHz/channel

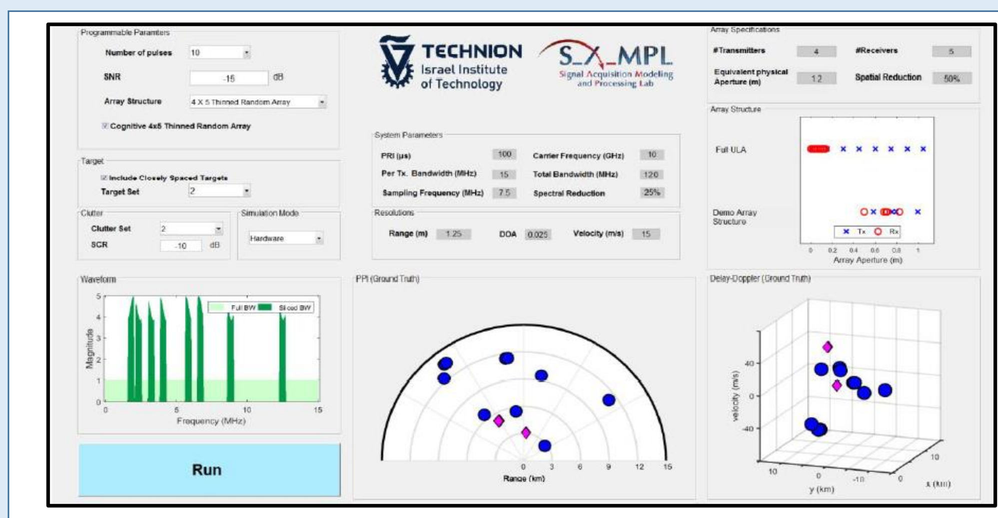


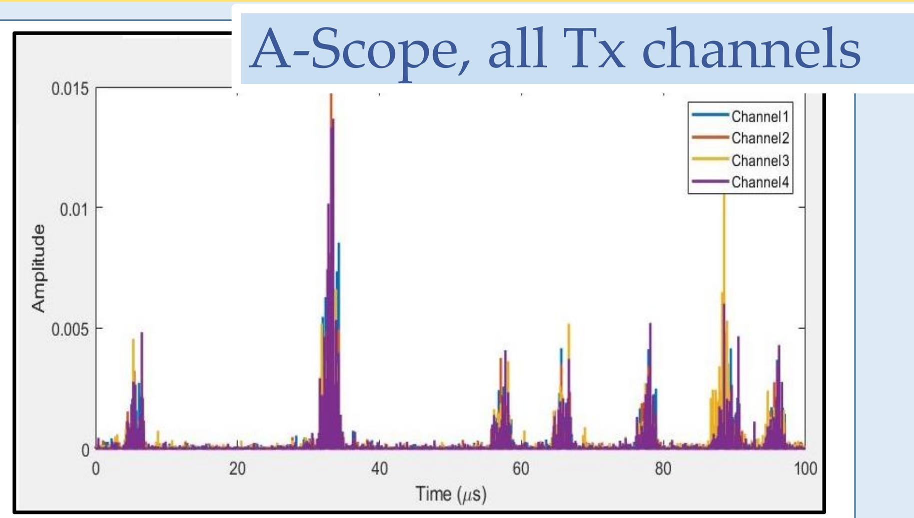
User Interface and Measurement Results (Mode 3, 4x5 Array)



Prototype with user control and measurement output

- Selectable scenarios, including closely-spaced targets
- Mode 3: 4x5 sub-Nyquist array resolution performance same as the virtual ULA (Mode 1)
- Mode 4: 8x10 sub-Nyquist array shows higher resolution performance than virtual 20x20 ULA





User Input Interface