GNU Radio SDR Framework for Bistatic Sensing Using 5G NR Zadoff-Chu and SSB Waveforms

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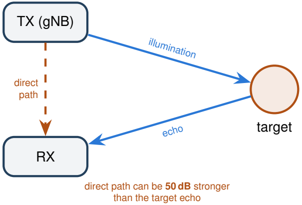
Why sense with 5G waveforms?

Integrated sensing and communications

- Reuse communication infrastructure for sensing i.e. no dedicated radar transmitter, spectrum or site
- Passive coherent location: detect targets using opportunistic signals



5G NR is a good illuminator

- Physical layer fully specified by 3GPP
- Synchronization signals are deterministic: a receiver can regenerate them without decoding user data
- Exactly what a matched filter needs

Same receiver architecture irrespective of TX signal - the hard part is doing it in real time.

The real-time problem

A sensing receiver must *continuously*:

1. suppress a direct-path signal orders of magnitude stronger than the echo,
2. matched-filter the residual,
3. reject static clutter,

... all while keeping pace with the sample stream.

- $f_s = 30.72\,\text{MS/s}$; $N_{ZC} = 16\,381$
- $\Rightarrow T_{PRI} = 0.533\,\text{ms}$
- $\Rightarrow \approx$ 1876 range profiles/s sustained

Why GNU Radio

- Streaming scheduler matches the problem
- Each stage becomes a reusable block
- Same chain runs in simulation and on hardware

Scope of this work

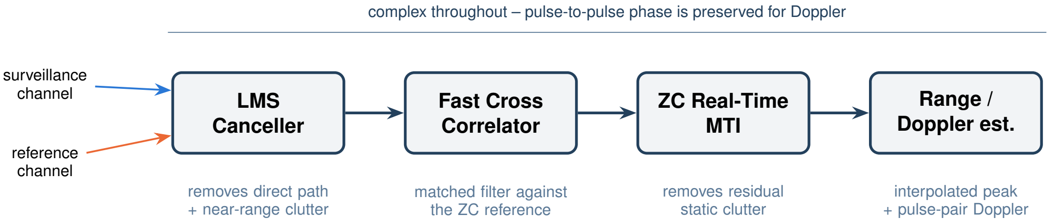
Cooperative bistatic testbed - transmitter under our control.

Not opportunistic sensing of a live commercial gNB.

Contributions

1. A complete **streaming sensing chain in GNU Radio**, as three reusable out-of-tree blocks running in real time at 30.72 MS/s:
   `LMS Canceller` → `Fast Cross Correlator` → `ZC Real-Time MTI`
2. A **waveform argument**: the standard SSB duty cycle is a few percent, so we radiate an extended Zadoff-Chu pilot continuously and show in simulation why it beats the full SSB burst
3. **Simulation characterisation** – drone target at four bistatic excess ranges (19.5–195.3 m), TCR above 35 dB
4. **Over-the-air validation**: a walking human tracked across a 38 m corridor, extended ZC compared against the 5G NR PSS

Processing chain



Each stage is one GNU Radio block. The same chain is used in simulation and over the air.

Stage 1 - adaptive cancellation

Complex LMS driven by the reference channel:

$$e[n] = y_{surv}[n] - \sum_{k=0}^{K-1} w_k[n]\, y_{ref}[n-k]$$

$$w_k[n+1] = w_k[n] + \mu\, y_{ref}[n-k]\, e^*[n]$$

What the tap count K means

- The filter converges to the stationary part of the surveillance channel over K delay bins
- A moving target carries time-varying phase, is poorly modelled by fixed weights, and survives

Two operating points

	Simulation	**Over the air**
K	1	5
μ	10^{-3}	10^{-7}
span	lag 0 only	$\approx$ first 20 m

- $K = 1$ in simulation leaves targets at $\tau_s \geq 2$ provably untouched
- $K = 5$ indoors also suppresses strong static returns near the antennas

Stages 2 and 3 - matched filter and clutter rejection

FFT matched filter

$$R[\tau] = \mathcal{F}^{-1}\{\mathcal{F}\{e[n]\} \cdot \mathcal{F}^*\{s[n]\}\}$$

- $N_{FFT} = 32\,768 \geq 2N_{ZC} - 1 \Rightarrow$ linear correlation
- Reference spectrum precomputed once
- Output kept complex - no magnitude taken

Exponential-average MTI

$$b_m[\tau] = (1-\alpha)b_{m-1}[\tau] + \alpha R_m[\tau]$$
$$\tilde{R}_m[\tau] = R_m[\tau] - b_m[\tau]$$

α must be matched to the target

$$f_{3dB} = \frac{\alpha}{2\pi T_{PRI}}$$

	α	f_{3dB}
Drone ($f_d \approx 160$ Hz)	0.10	29.9 Hz
Human ($f_d \approx 16$-24 Hz)	0.01	2.98 Hz

- $\alpha = 0.10$ would put a *walking human* below cutoff and attenuate it

Stage 4 - range and velocity estimation

Range:

- OTA testbed is quasi-monostatic (45 cm baseline), so the sum $\approx 2R$ and the target-range bin is $\Delta R = c/2B = 4.88\,\text{m}$
- Resolution is fixed by bandwidth; accuracy is improved by interpolating the peak

$$\delta = \frac{1}{2} \frac{|R[k-1]| - |R[k+1]|}{|R[k-1]| - 2|R[k]| + |R[k+1]|}$$

Single snapshot - no target motion required.

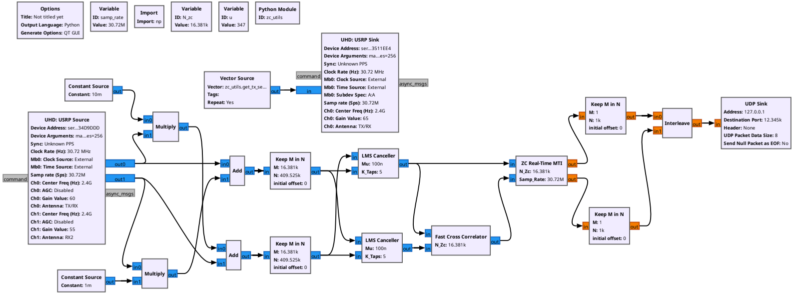
Velocity: pulse-pair estimator

$$\hat{f}_d = \frac{1}{2\pi T_{PRI}} \arg\left\{ \sum_m \tilde{R}_{m+1}[\tau^\star]\tilde{R}_m^*[\tau^\star] \right\}$$

- Doppler *resolution* over 3 pulses is poor ($\approx$39 m/s): two targets cannot be separated
- Doppler *accuracy* for one dominant target is a few Hz at realistic SNR

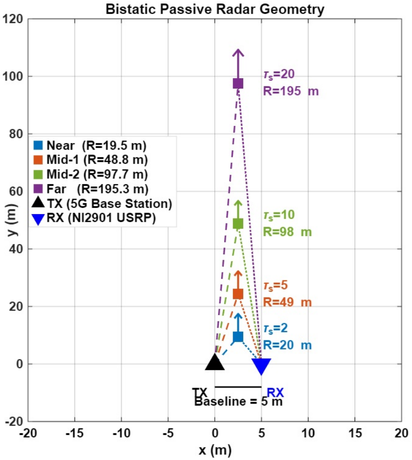
No coherent CPI over the air - by design.

GNU Radio implementation



- `LMS Canceller` runs first, at full rate
- Stream is decimated ahead of the correlator and MTI
- MTI output streamed over UDP for peak detection

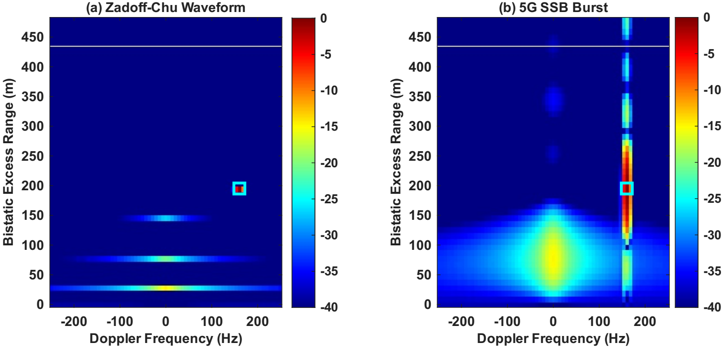
Simulation configuration



Parameter	Symbol	Value
Carrier	f_c	2.4 GHz
Sample rate	f_s	30.72 MS/s
ZC length / root	N_{ZC}, u	16 381 / 347
PRI	T_{PRI}	0.533 ms
Pulses per CPI	M_{CPI}	256
Direct-path ratio	DPR	50 dB
Drone RCS	σ	0.05 m^2
Drone speed	v	10 m/s

	Near	Mid-1	Mid-2	Far
τ_s	2	5	10	20
R_{bi} (m)	19.5	48.8	97.7	195.3

Why the ZC reference and not the full SSB



- **(a) ZC:** one clean target cell against a flat floor
- **(b) SSB:** same target, plus an OFDM-induced ridge across *all* range bins

Equal mean transmit power. The SSS and PBCH symbols are not CAZAC and the cyclic prefix adds periodic self-similarity - such a ridge would mask weaker returns at other ranges.

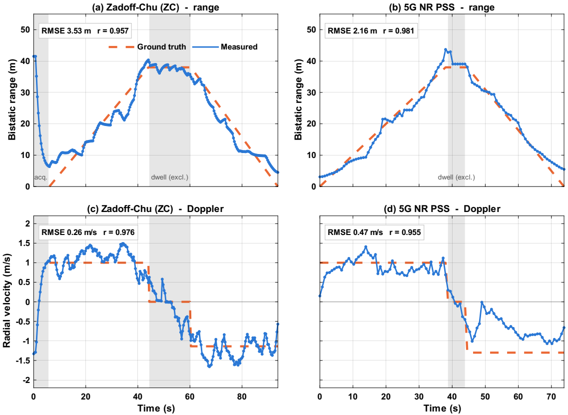
Over-the-air testbed

- Two NI USRP-2901: one transmits the continuous pilot, one is the two-channel sensing receiver
- Locked to a common **rubidium reference** - without it, LO drift appears as spurious Doppler
- Double Ridge Horn anetnnas on a 45 cm baseline along a **38 m** corridor
- Wired reference, with a controlled emulated impairment rather than an ideal replica

Experiment

One person walks to the far end, waits, walks back. Repeated for **extended ZC** and for the **5G NR PSS**.

Both waveforms track the walk end to end



- Measured range and velocity follow the constant-speed reference over the whole corridor. Range correlation > 0.95 for both waveforms
- Neither loses the target through the turn at the far end. Shaded spans (acquisition transient, far-end dwell) are excluded

Conclusions

- A complete bistatic sensing chain - LMS cancellation, FFT matched filtering, exponential-average MTI - runs **in real time at 30.72 MS/s** as three reusable GNU Radio out-of-tree blocks
- In simulation the chain recovers a drone target across **19.5-195.3 m** of bistatic excess range with **TCR above 35 dB**
- An extended Zadoff-Chu reference gives a markedly cleaner range-Doppler map than the full SSB burst at equal transmit power
- Over the air the chain tracks a walking human across a **38 m corridor** with both waveforms

Selected references

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Thank You

Any Questions?

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