Comparison of Efficient FPGA-Oriented Direction-of-Arrival Algorithms on an RFSoC 4x2 Board

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1. Motivation & Contribution

GNSS can be degraded by **jamming, spoofing, urban multipath,** and indoor attenuation. Radio-frequency signals of opportunity can complement it by providing a **direction-of-arrival (DoA)** measurement. FPGA DoA studies are difficult to compare because their array geometry, snapshot length, hardware, arithmetic, and metrics differ.

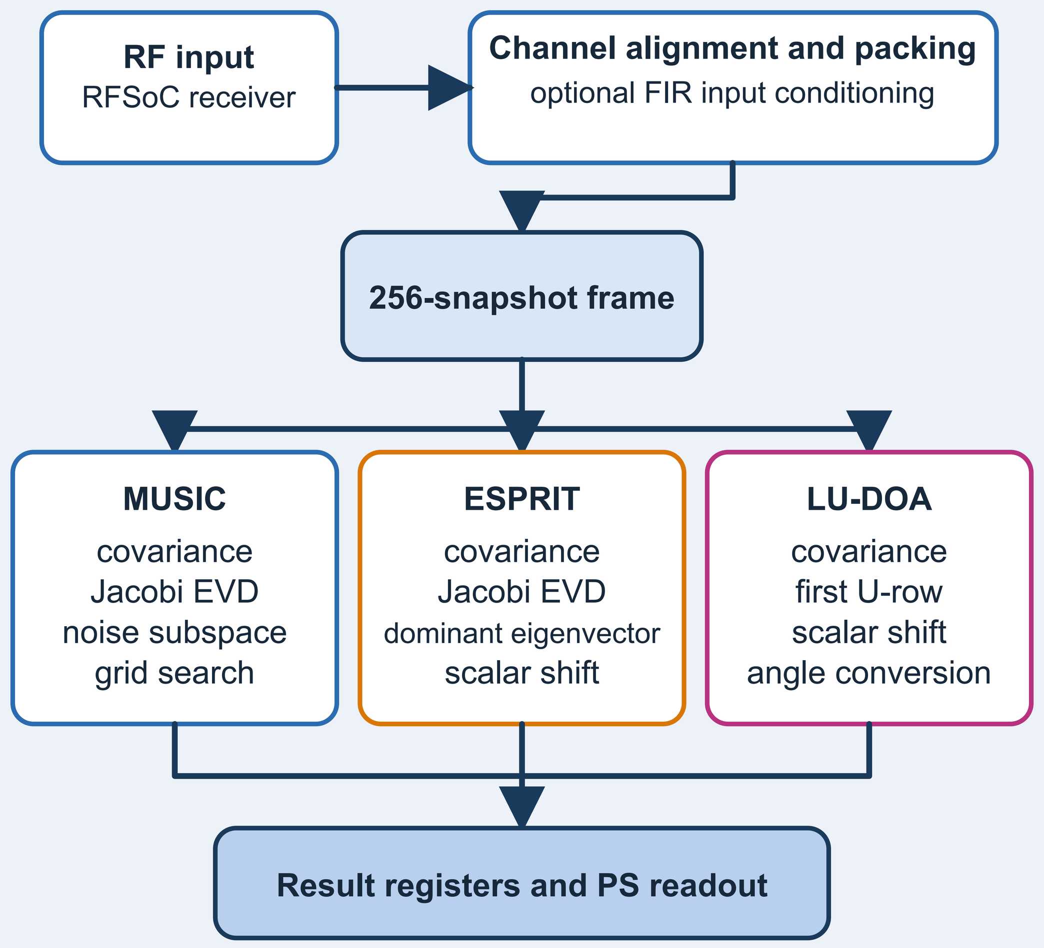
The main contribution is a common RFSoC- and HLS-based comparison of three existing DoA estimators.

Common comparison conditions:

- four-element uniform linear array (ULA)
- single narrowband source at 2.480 GHz
- 256 snapshots per estimate
- identical captured RF frames
- q16.8, q18.8, q20.8, and q24.8 kernels
- 125 MHz Vitis HLS/Vivado implementation

2. Implementation Overview

Three parallel kernels process the same four-channel frame. Each contains the common covariance logic and produces one broadside DoA estimate.



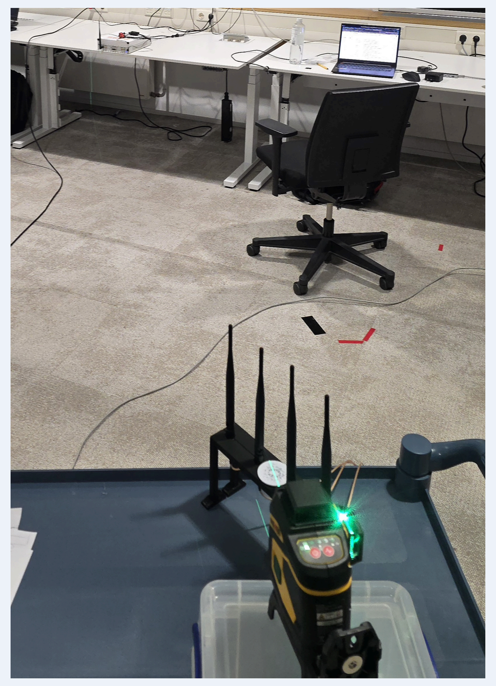
Implemented RFSoC/HLS processing flow.

Selected References

[1] R. Schmidt, "Multiple emitter location and signal parameter estimation," *IEEE TAP*, 1986.
[2] R. Roy, A. Paulraj, and T. Kailath, "ESPRIT," *Proc. MILCOM*, 1986.
[3] A. A. Hussain et al., "FPGA hardware implementation of DOA estimation algorithm employing LU decomposition," *IEEE Access*, 2018.
[4] Y. Jung et al., "Scalable ESPRIT processor for direction-of-arrival estimation of FMCW radar," *Electronics*, 2021.
[5] S. Lahti et al., "An efficient high-level synthesis implementation of the MUSIC DoA algorithm for FPGA," *DDECS*, 2024.

3. Experimental Setup

- Indoor LOS laboratory (7 m × 10 m)
- Ettus USRP narrowband transmitter
- RFSoC 4x2 receiver approximately 4 m away
- Nine angles from $-60°$ to $60°$
- Laser/protractor alignment; uncertainty $\pm 1°$
- 145 capture runs; **3,589,597 output rows**
- Filtered and unfiltered receiver branches



Physical measurement setup.

4. Captured-Data Accuracy

Algorithm	Central RMSE	Large-angle RMSE	Overall RMSE	Overall P99
MUSIC	1.11°	10.06°	6.85°	15.00°
ESPRIT	1.23°	14.98°	10.17°	23.10°
LU-DOA	1.37°	32.20°	21.62°	82.47°

Central: $|\theta| < 45°$; large-angle: $|\theta| \geq 45°$. Errors in degrees.

The algorithms are similar near broadside. Their main differences appear at larger steering angles, where sign-mirror estimates increase the error tails.

MUSIC provides the strongest full-range angular robustness, while LU-DOA produces the largest edge-angle error tails.

5. Timing & Update Rate

Algorithm	Fastest format	Latency	Update rate
MUSIC	q20.8	21.656 µs	46.2 kHz
ESPRIT	q20.8	21.664 µs	46.1 kHz
LU-DOA	q20.8/q24.8	4.336 µs	230.2 kHz

MUSIC and ESPRIT have almost identical timing because both retain covariance and EVD-based processing.

LU-DOA has approximately five times lower latency than the fastest MUSIC and ESPRIT configurations.

6. Fixed-Point Sweep

Central-angle RMSE across internal kernel formats:

Algorithm	q16.8	q18.8	q20.8	q24.8
MUSIC	1.17°	1.14°	**1.08°**	1.12°
ESPRIT	1.31°	1.24°	1.18°	**1.16°**
LU-DOA	1.52°	1.43°	1.36°	**1.29°**

Wider arithmetic improves ESPRIT and LU-DOA most consistently. MUSIC performs best at q20.8.

7. Input Conditioning

A 219-tap, 20 MHz low-pass FIR was evaluated before the estimators.

RMSE	MUSIC	ESPRIT	LU-DOA
Filtered	4.32°	7.23°	27.53°
Unfiltered	8.59°	12.35°	13.52°

Filtering reduces MUSIC and ESPRIT RMSE, but increases LU-DOA RMSE. The FIR path adds **34,640 LUTs, 243,744 FFs, and 880 DSPs**.

Filtering is an estimator-dependent receiver trade-off, not a universal improvement.

8. Implemented FPGA Resources

Post-implementation DoA kernel resources at the fastest common format, **q20.8**. Shared receiver resources and FIR filters are excluded.

Algorithm	LUT	FF	DSP	BRAM36 / 18
MUSIC	42,616	25,908	243	10 / 6
ESPRIT	46,028	27,599	198	5 / 0
LU-DOA	12,587	9,552	51	5 / 0

At q20.8, LU-DOA uses approximately **70% fewer LUTs**, **63% fewer FFs**, and **79% fewer DSPs** than MUSIC.

LU-DOA has the lowest latency and resource cost across every evaluated word length.

9. Conclusions

MUSIC: strongest full-range angular robustness.

ESPRIT: intermediate accuracy, with timing and resources close to MUSIC.

LU-DOA: lowest latency and resource usage, but larger edge-angle error tails.

The results show a clear trade-off between full-range angular robustness and hardware cost.

10. Limitations & Future Work

Limitations: three algorithms, four-element ULA, one source, controlled indoor measurements, and kernel-level timing.

Future work:

- larger arrays and other geometries
- dedicated phase/gain calibration
- multiple simultaneous sources
- outdoor signals-of-opportunity measurements
- integration into a passive-positioning pipeline