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Real-time, Wide-field Imaging with Large Aperture Arrays

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Real-time processing is crucial for detecting and monitoring fast, explosive phenomena such as fast radio bursts (FRBs) and prompt emissions from gravitational wave (GW) merger events on millisecond timescales. It also enables sub-arcsecond localization, which is essential for understanding their progenitors and underlying physical mechanisms. The likelihood of serendipitous discoveries and effective transient monitoring increases with high time resolution, wide fields of view, and instantaneous data processing. As a result, several wide-field aperture arrays in radio astronomy, including SKA-low, ASKAP, CHIME, CHORD, MWA, and LOFAR, have integrated real-time processing as a core design feature. Advances in low-cost antennas and high-performance computing have further driven the expansion of these large-scale, data-intensive arrays, often comprising thousands to tens of thousands of elements.

However, key challenges persist, particularly in computational efficiency and bandwidth management for fast transient science. Traditional correlator-based methods scale steeply as $O(N^2)$, making real-time processing at millisecond timescales difficult. This often necessitates trade-offs in spatial resolution or field of view, limiting discovery potential. Another critical constraint in large-N arrays is power consumption, especially for proposed lunar-based low-frequency arrays, where power is severely restricted despite the availability of high-performance computing.

Addressing these challenges requires both ultra-fast imaging techniques [1] and power-efficient hardware. Direct imaging methods [2], which bypass pairwise correlations, offer promising alternatives. The E-field Parallel Imaging "Correlator" (EPIC) [3, 4, 5] is one such approach, achieving computational efficiency as low as $O(N \log N)$—a significant advantage for large-N, dense arrays. A working EPIC prototype is deployed on the LWA-Sevilleta station [4] using GPUs and is regularly available to LWA users.

This work explores an FPGA-based implementation of EPIC as an alternative to GPU-based processing. GPUs face memory bandwidth bottlenecks when handling gridding and short FFTs with low-bitwidth data, making FPGA architectures particularly well-suited for these tasks. A fully parallel FFT can efficiently utilize FPGA resources, offering significant power savings. We evaluate the power consumption of FPGA-based implementations and assess their suitability for future applications, including SKA-low, low-frequency VLBI with aperture arrays, and lunar-based arrays. This research represents a critical step towards improving the efficiency and feasibility of large-scale aperture arrays in radio astronomy.

References

[1] N. Thyagarajan, “Comparison of fast, hybrid imaging architectures for multi-scale, hierarchical aperture arrays,” *PASA*, **42**, e001, January 2025, doi:10.1017/pasa.2024.121

[2] M. Morales, “Enabling Next-Generation Dark Energy and Epoch of Reionization Radio Observatories with the MOFF Correlator,” *PASP*, **123**, 1265, November 2011, doi: 10.1086/663092.

[3] N. Thyagarajan et al., “A Generic and Efficient E-field Parallel Imaging Correlator for Next-Generation Radio Telescopes,” *MNRAS*, **467**, 715, May 2017, doi: 10.1093/mnras/stx113.

[4] H. Krishnan et al., “Optimization and commissioning of the EPIC commensal radio transient imager for the long wavelength array,” *MNRAS*, **520**, 1928, April 2023, doi: 10.1093/mnras/stad263.

[5] K. Masui et al., “Algorithms for FFT Beamforming Radio Interferometers,” *ApJ*, **879**, 16, July 2019, doi: 10.3847/1538-4357/ab229e.