Efficient Real-time Imaging with Large-*N*, Dense Interferometer Arrays

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There are several aperture arrays in radio astronomy with the key design objective of real-time processing. Real-time processing is essential for discovering and monitoring fast, explosive phenomena such as FRBs and prompt emission from GW-generating merger events on millisecond timescales and to localise them with sub-arcsecond precision to characterise the nature of their progenitors and the underlying physical mechanisms. For effectiveness in making serendipitous discoveries and monitoring of transient phenomena, these arrays are also required to have wide fields of view and high time-resolution. Due to availability of relatively low-cost antennas and powerful computing, these arrays are becoming increasingly large (typically consisting of several to tens of thousands of array elements) and data-driven. Examples include CHIME and CHORD, ASKAP, MWA, LOFAR, LWA, and the upcoming SKA-low.

Some key challenges in the form of efficient handling of computational load and output bandwidth remain, especially in fast transient science applications, because the complexity of traditional correlator-based approaches not only scales steeply as $O(N^2)$, but the data also have to be processed and transmitted on millisecond timescales. Hence, they often compromise on some key requirements such as spatial resolution or field of view, thereby severely curtailing the instrument's discovery potential. Another key constraint in such large-*N* arrays is power consumption. For example, lunar-based low frequency arrays are being considered which have stringent limits on power even if powerful computing is available.

These requirements necessitate not only innovative and ultra-fast approaches to imaging but also use of power-efficient hardware. Approaches relying on direct imaging [1] based on the principle of avoiding pairwise correlations between array elements such as the E-field Parallel Imaging "Correlator" (EPIC) [2, 3, 4] have emerged as promising alternatives. They hold significant advantage for large-*N* dense array layouts and can be as efficient as $O(N \log N)$. A working prototype of EPIC is deployed on the LWA-Sevilleta station [3] using GPUs, and offered commensally to LWA users regularly.

This work explores an FPGA-based implementation of EPIC as an alternative to GPU-based approaches. The challenges of implementing gridding and short FFTs with low-bitwidth data on GPUs, owing to memory bandwidth bottlenecks, make FPGA architectures particularly attractive for these tasks. Notably, a fully parallel FFT optimally utilises the FPGA fabric. The study delves into the relative power consumption of FPGA-based implementations and assesses their suitability for future applications, such as SKA-low, low-frequency VLBI using aperture arrays, and upcoming Lunar arrays. This research represents a critical step towards enhancing the efficiency and applicability of large-scale aperture arrays in the field of radio astronomy.

References

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