Direct Pulse-Density-Modulated Bitstream Operators for Efficient Beamforming With Large Sensor Arrays

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From tracking fetal heartbeats in ultrasound to pinpointing voices in noisy crowds, acoustic beamforming plays a vital role in healthcare, consumer technology, and public safety. Beamforming steers an array of sensors to isolate target sounds. Although adding sensors improves performance, it significantly increases the computational cost of extracting spatial information from highly redundant data, with common algorithms having complexities between O(n^2) and O(n^3), where n is sensor count. While prior work has focused on algorithmic and array improvements, this work presents a novel approach that directly beamforms Pulse-Density-Modulated(PDM) bitstreams from digital microphones to exploit their high time resolution and 1-bit quantization. These PDM operators replace complex multi-bit adders and multipliers with simple logic gates. By shifting the delay and sum operations forward and operating on 1-bit data, this method reduces complexity from O(n^2), or worse, to O(1) and massively improves efficiency while maintaining distortion-free audio within audible frequencies. To validate PDM beamforming, I built a 16-mic acoustic imaging system that directly beamforms 256 simultaneous rays in real time—like a global shutter. Implemented on an XC735T FPGA, this system achieves 4 ms latency and 0.188° angular resolution, running 300x faster than real-time with 33x more angular precision than traditional beamforming, surpassing initial goals. To prove silicon feasibility, I fabricated these operators as custom ASICs on the Skywater 130nm process. Based on these results, PDM beamforming can significantly outperform traditional beamforming, enhancing efficiency and precision in industrial applications, medical imaging, and more while reducing costs and hardware demands.

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