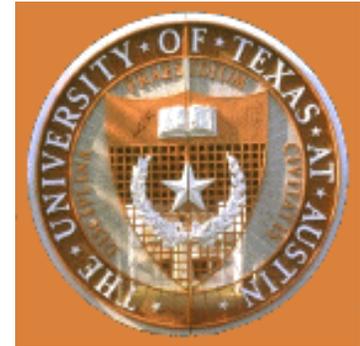


# Real-time Process Network Sonar Beamformer



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## Introduction

- ***Problem:*** Beamforming is computationally intensive
- ***Example:*** High-resolution sonar beamformers (GFLOPS)
  - Generation 1: expensive custom digital hardware (large state machines)
  - Generation 2: custom integration of programmable digital signal processors on commercial-off-the-shelf hardware (e.g. 120 DSPs in a VME rack)
- ***Objective:*** Unix workstation beamformers
  - Analysis: evaluate performance of beamforming kernels and systems
  - Modeling: capture parallelism, guarantee determinate bounded execution
  - Implementation: use portable, scalable software to achieve real-time performance on commodity hardware and lower development costs
- ***Solution:*** Real-time beamforming on workstations
  - Analysis: optimize kernels and profile beamformers to measure scalability
  - Modeling: Process Networks
  - Implementation: Real-time POSIX threads using C++ on symmetric multiprocessor UltraSPARC-II workstation with native signal processing

# Time-Domain Beamforming

- Delay and sum weighted sensor outputs
- Geometrically project the sensor elements onto a line to compute the time delays

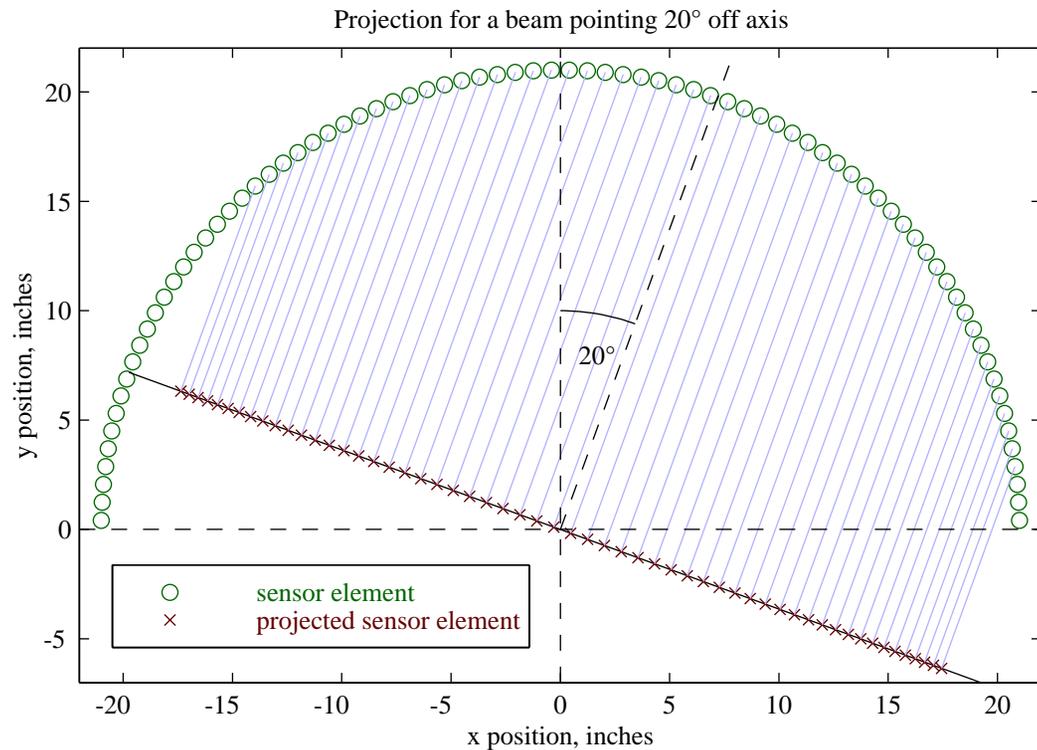
$$b(t) = \sum_{i=1}^M \alpha_i x_i(t - \tau_i)$$

$b(t)$  beam output

$x_i(t)$   $i^{\text{th}}$  sensor output

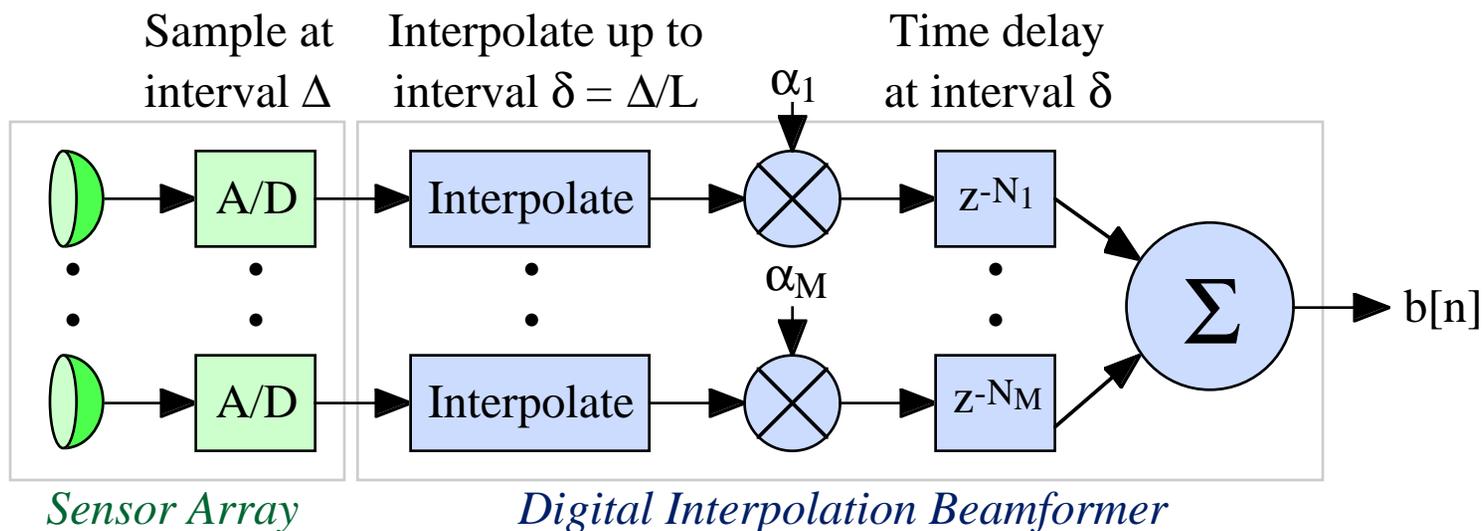
$\tau_i$   $i^{\text{th}}$  sensor delay

$\alpha_i$   $i^{\text{th}}$  sensor weight



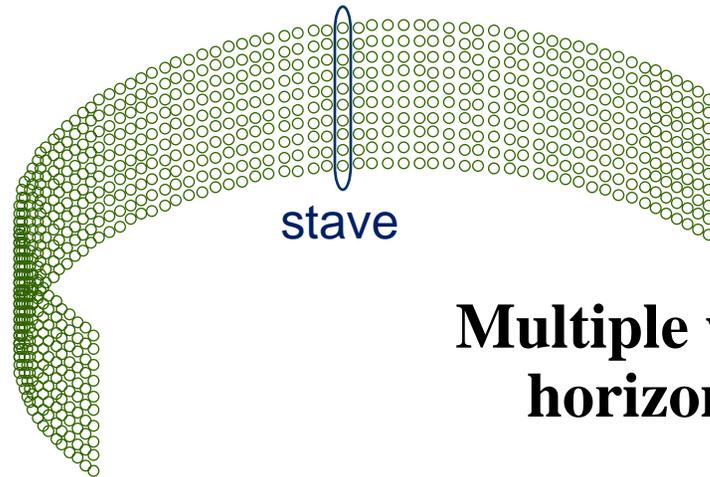
## Interpolation Beamforming

- Quantized time delays perturb beam pattern
- Sample at just above the Nyquist rate
- *Interpolate* to obtain desired time-delay resolution



- **Kernel implementation on UltraSPARC-II**
  - Highly optimized C++ (loop unrolling and SPARCompiler5.0EA)
  - Currently operating at 60% of peak, which is 2 FLOPs per cycle

# Vertical Beamforming



**Multiple vertical transducers for every horizontal position**

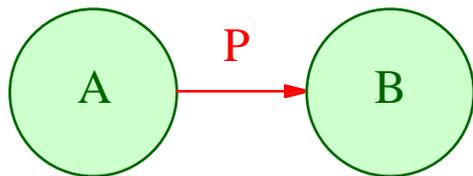
- **Each vertical sensor column is combined into a *stave***
  - No time delay or interpolation is required
  - Staves are calculated by a simple *integer* dot product
  - Integer-to-float conversion must be performed
  - Output data must be interleaved
- **Kernel implementation on UltraSPARC-II**
  - Native signal processing with Visual Instruction Set (VIS)
  - Software data prefetching to hide memory latency and keep the pipeline full

# Formal Design Methodology

- The *Process Network* model [Kahn, 1974]

- Superset of dataflow models of computation
- Captures concurrency and parallelism
- Provides correctness
- Guarantees determinate execution of the program

- A program is represented as a directed graph



- Each **node** is an independent process
- Each **edge** is a one-way queue of data

- Blocking reads, non-blocking writes, infinite queues
- Scheduling for bounded queues is possible [Parks, 1995]
  - Blocking reads and writes
  - Dynamically increase queue capacities to prevent *artificial deadlock*
- Fits the thread model of concurrent programming

## Process Network Implementation

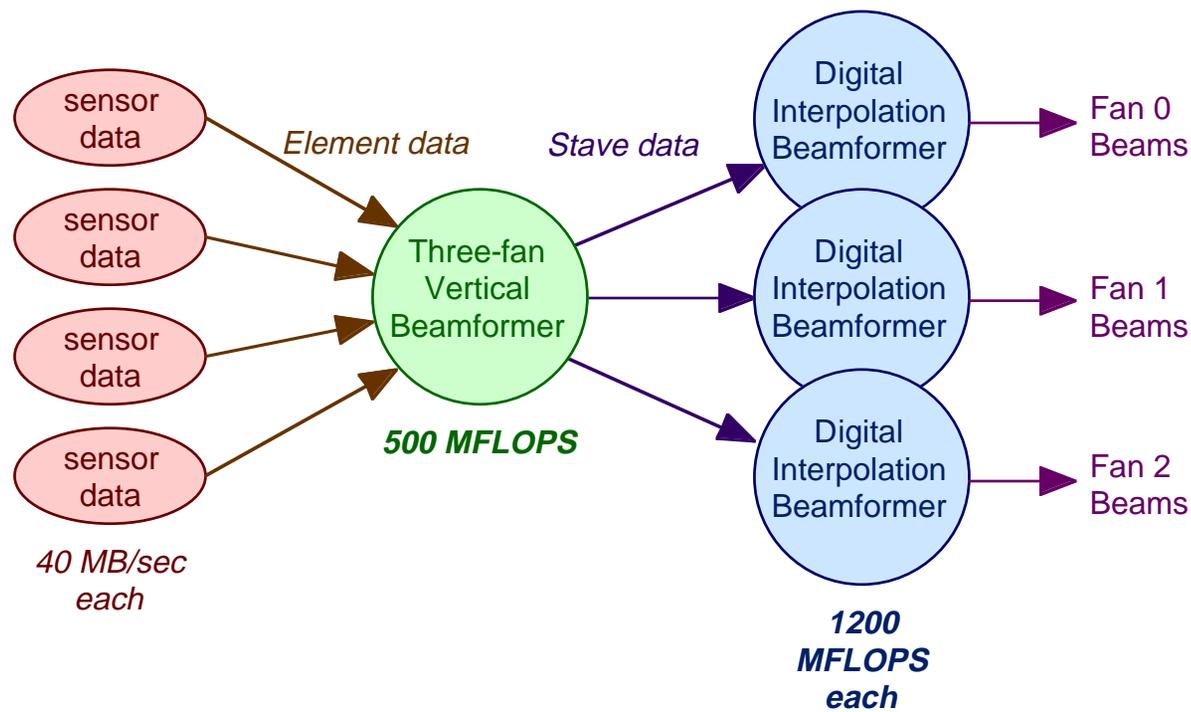
- **Each node corresponds to a thread**
  - Implemented in C++ using POSIX Pthreads
  - Low-overhead, high-performance, scalable
  - Granularity larger than a thread context switch (~10 us)
  - Symmetric multiprocessing operating system dynamically schedules threads
  - Efficient utilization of multiple processors
- **Optimize queues for high-throughput signal processing**
  - Nodes operate directly on queue memory, avoiding copying
  - Queues use mirroring to keep data contiguous



- Compensates for the lack of circular address buffers
- Queues trade-off memory usage for overhead
- Virtual memory manager maintains data circularity

## System Implementation

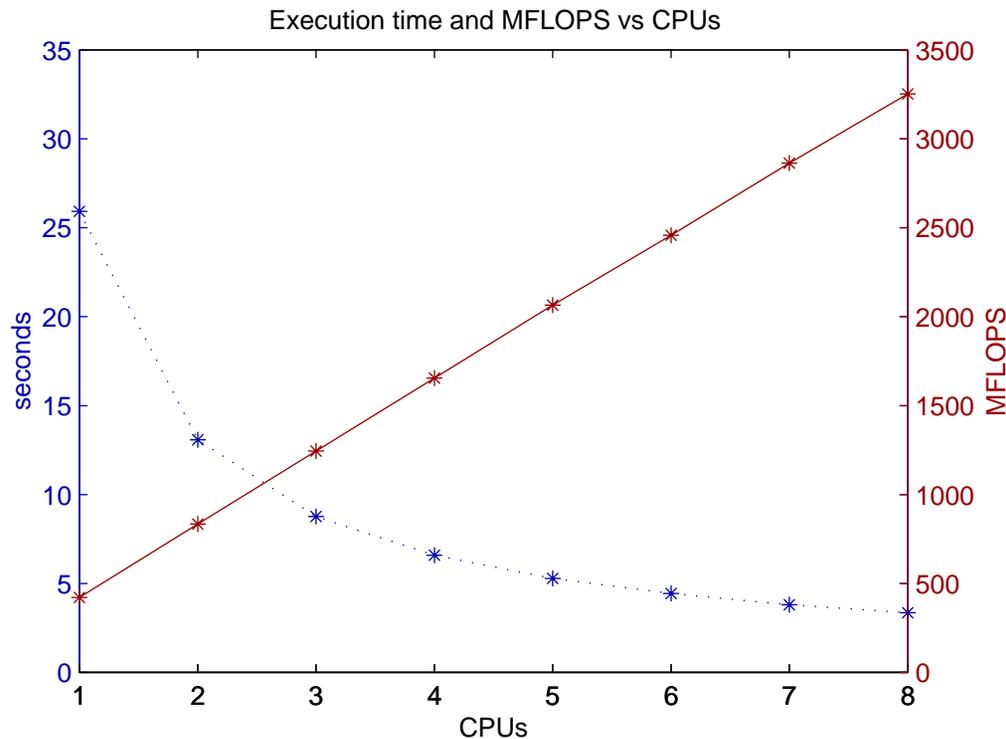
- Vertical beamformer forms 3 sets of 80 staves from 10 vertical elements per staff
- Each horizontal beamformer forms 61 beams from the 80 staves, using a two-point interpolation filter
- 4 GFLOPS total computation



## Performance Results

- 100 trial mean execution time for 2.6 seconds of data
- Sun Ultra Enterprise 4000 with eight 336-MHz UltraSPARC-IIs, 2 Gb RAM, running Solaris 2.6

| Implementation  | Time (s) | MFLOPS | Mbytes |
|-----------------|----------|--------|--------|
| thread pool     | 3.607    | 3024.8 | 832    |
| process network | 3.354    | 3252.8 | 654    |



- Process network is 7% faster than thread pool, overhead is small
- Process network uses 20% less memory with lower latency
- Process network scalability is nearly linear
- Will continue to scale with additional CPUs
- Real-time performance achievable with 12 CPUs

## Conclusion

- **Third generation beamformers:** *Workstation* hardware
  - Commodity hardware saves development/manufacturing costs
  - Multiprocessor servers, native signal processing
  - Upgradable hardware, Moore's Law
- **Software model:** *Process Networks*
  - Captures parallelism, guarantees determinate bounded execution
  - Portable, reusable, scalable C++ code
  - High-performance, low overhead POSIX threads
  - Symmetric multiprocessing operating system
- **The example 4-GFLOPS 1-Gb 3-D sonar beamforming system does execute in real time using a Sun Ultra Enterprise 4000 server with twelve 336 MHz UltraSPARC-II CPUs with 14.5% to spare**

<http://www.ece.utexas.edu/~allen/Beamforming/>