

# Real-Time High-Throughput Sonar Beamforming Kernels Using Native Signal Processing and Memory Latency Hiding Techniques



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# Introduction

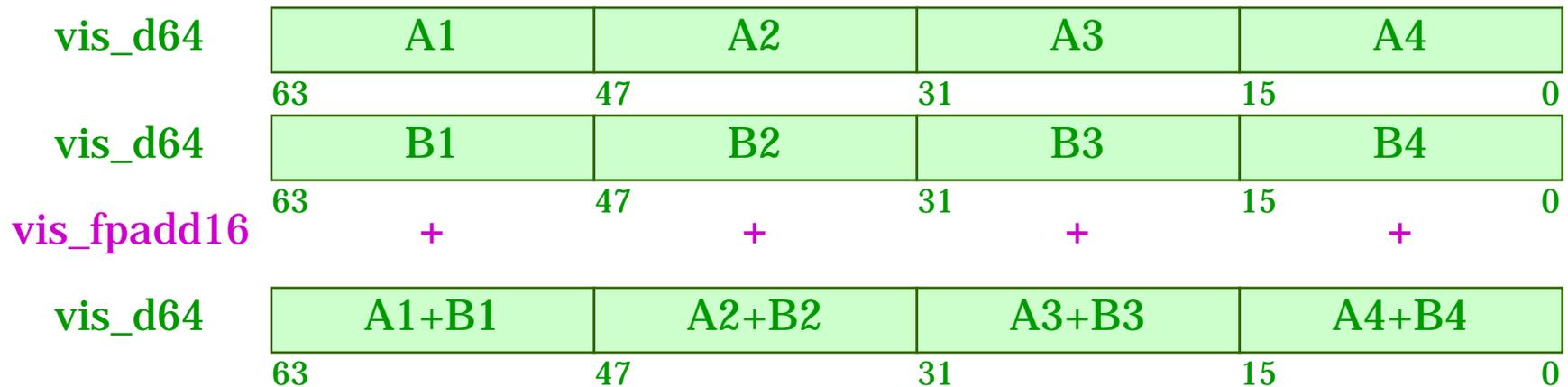
- **Sonar beamforming is computationally intensive**
  - **GFLOPS of computation**
  - **100 MB/s of data input/output**
- **Current real-time implementation technologies**
  - **Custom hardware**
  - **Custom integration using commercial-off-the-shelf (COTS) processors (e.g. 100 digital signal processors in a VME chassis)**
  - **Low production volume (50 units), high development cost**
- **Examine performance of commodity computers**
  - **Native signal processing, multimedia instruction sets**
  - **Memory latency hiding techniques**

# Native Signal Processing

- **Single-cycle multiply-accumulate (MAC) operation**
  - **Vector dot products, digital filters, and correlation**  $\sum_{i=1}^N x_i$
  - **Missing extended precision accumulation**
- **Single-instruction multiple-data (SIMD) processing**
  - ***UltraSPARC* Visual Instruction Set (VIS) and *Pentium MMX*: 64-bit registers, 8-bit and 16-bit fixed-point arithmetic**
  - ***Pentium III, K6-2 3DNow!*: 64-bit registers, 32-bit floating-point**
  - ***PowerPC AltiVec*: 128-bit registers, 4x32 bit floating-point MACs**
- **Must hand-code using intrinsics and assembly code**

# Visual Instruction Set

- **50 new CPU instructions for UltraSPARC**
  - **Optimized for video and image processing**
  - **Partitioned data types in 32-bit or 64-bit FP registers**
  - **Includes arithmetic and logic, packing and unpacking, alignment and data conversion, etc.**
- **Independent operation on each data cell (SIMD)**



- **Inline function library provided for use from C/C++**

# Memory Latency Hiding

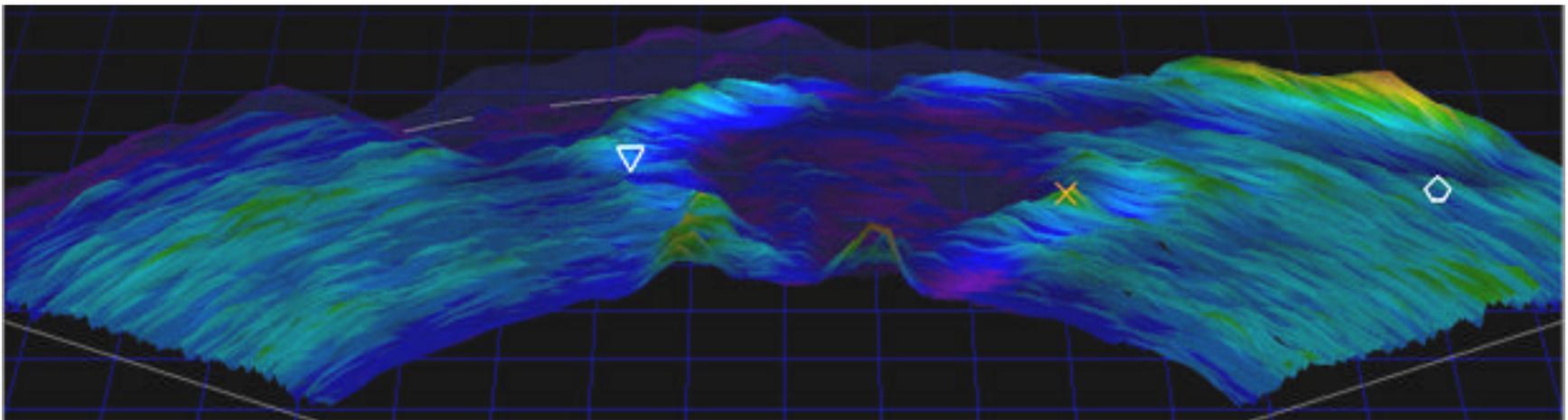
- **Fast processor stalls when accessing slow memory**
  - Cache memories can help to alleviate this problem
  - High-throughput streams of data amplify this problem
  - Software techniques can reduce the penalty
- **Technique: Loop unrolling**
  - Enlarges basic block size and reduces looping overhead
  - Can increase the time between data request and consumption
  - Low risk and no overhead, commonly used by compilers
- **Technique: Software pipelining**
  - Data load and usage overlapped from different loop iterations
  - Increases register usage and lifetimes, hard for compiler

# Software Data Prefetching

- **Non-blocking prefetch CPU instruction**
  - Issued at some time prior to when data is needed
  - Data at effective address is brought into cache
  - At a later load instruction, the data is already cached
- **Problems: overhead and “prefetch distance”**
  - Uses extra cache and issues extra instructions
  - Prefetch too far ahead: excessive cache usage, spillage
  - Not far enough ahead: stall at load instruction
- **Can be generated by a compiler**
- **Implemented in the UltraSPARC-II CPU**

# Sonar Beamforming

- **We evaluate two key kernels for 3-D beamforming**



- **Typically the computational bottleneck in sonar**
- **High throughput streams of data**
- **Goal: best performance using any means**

# Time-Domain Beamforming

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

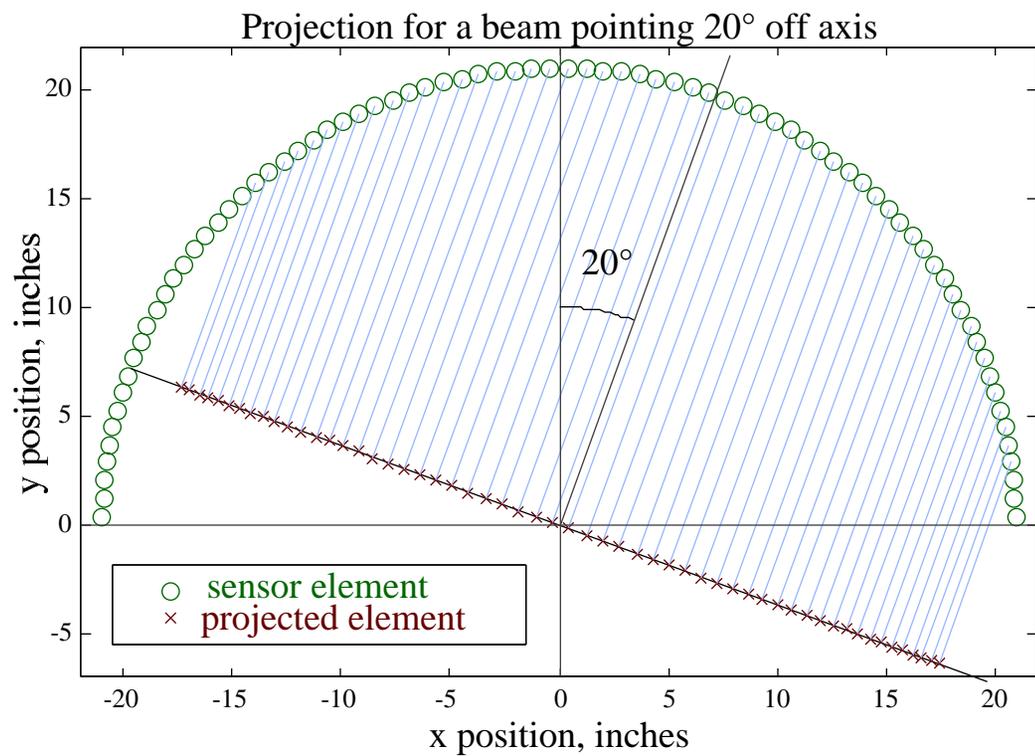
$$b(t) = \sum_{i=1}^M w_i x_i(t - \tau_i)$$

$b(t)$  beam output

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

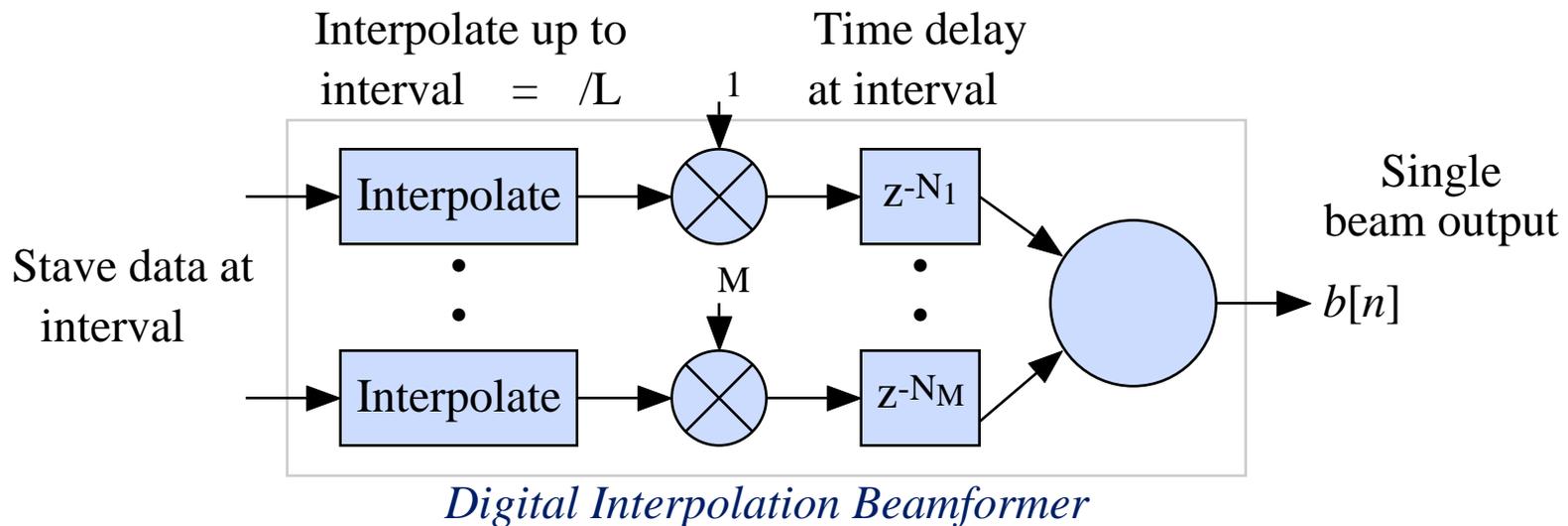
$\tau_i$   $i^{\text{th}}$  sensor delay

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



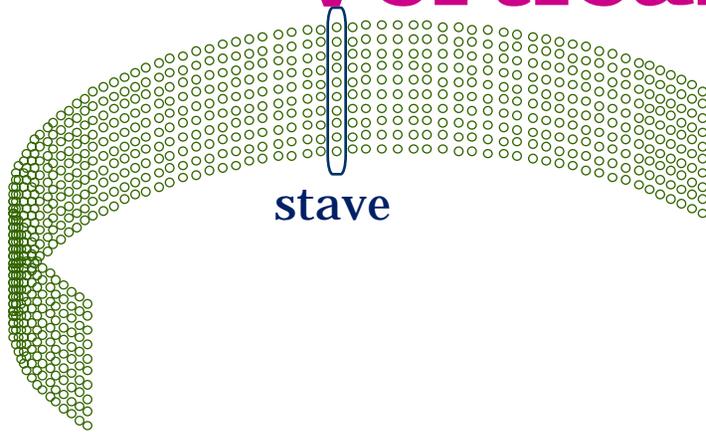
# Horizontal Beamformer

- **Sample at just above the Nyquist rate, interpolate to obtain desired time delay resolution**



- **Modeled as a sparse FIR filter**
  - **Forming 61 beams from 80 elements with 2-point interpolation**
  - **3000 index lookup plus 6000 floating-point MACs per sample**
  - **At each sample: 12 Kbytes of data, coefficient size of 36 Kbytes**

# Vertical Beamformer



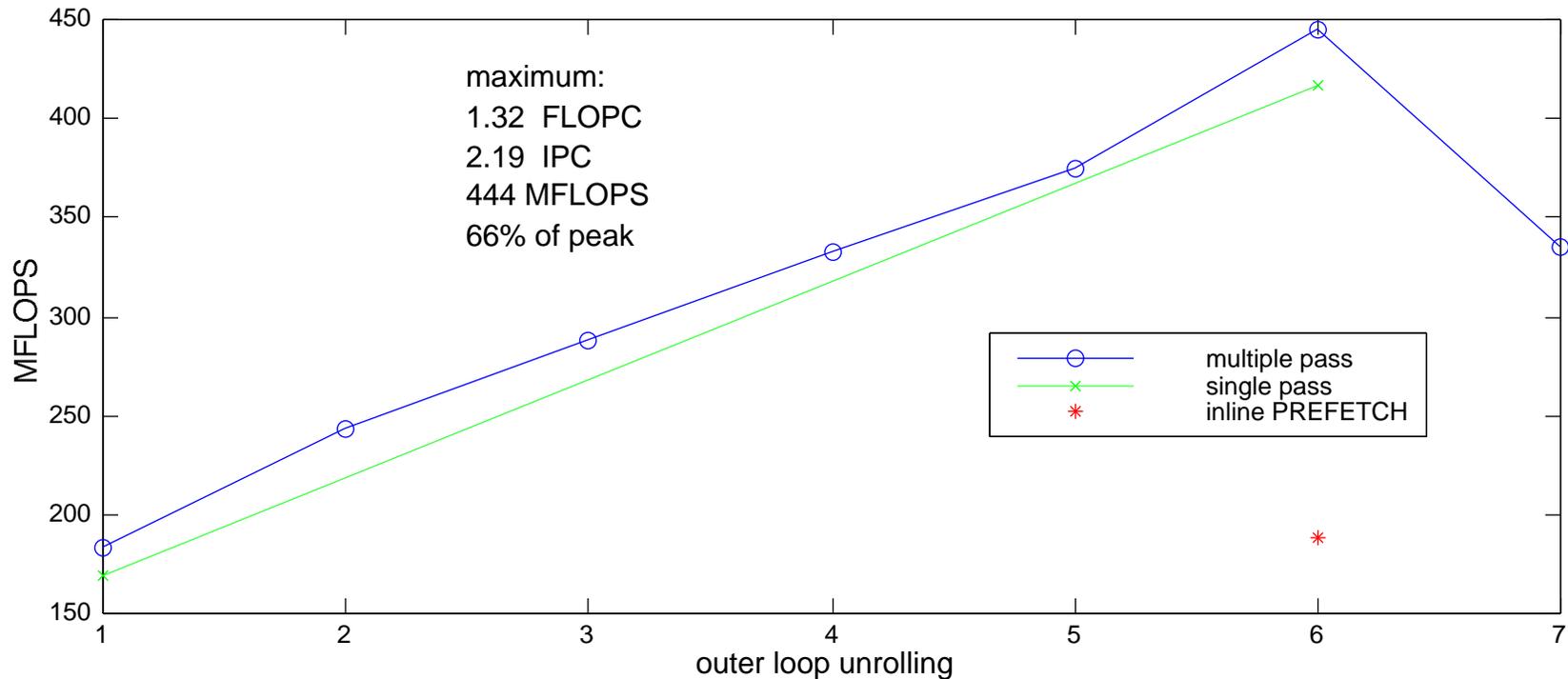
***Multiple vertical transducers  
for every horizontal position***

- **Vertical columns combined into 3 **stave** outputs**
  - **Multiple dot products (30 MACs per stave per sample)**
  - **Convert integer to floating-point for following stages**
- **Ideal candidate for the Visual Instruction Set (VIS)**
  - **Use integer dot products (16x16-bit multiply, 32-bit add)**
  - **Highest precision (and slowest) VIS mode**
  - **Coefficients must be scaled for best dynamic range**

# Tools Utilized

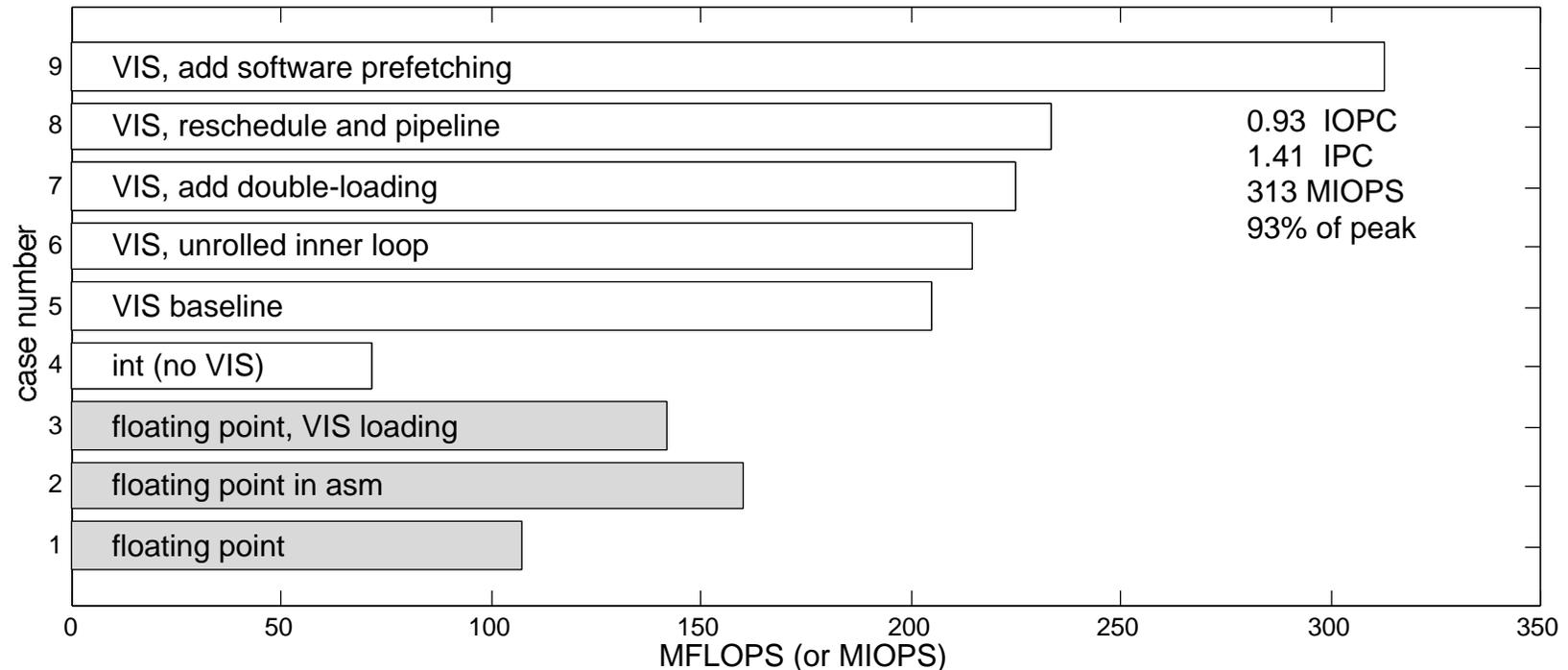
- **Sun's SPARCompiler5.0**
  - **Automated prefetch instruction generation?**
  - **Inline assembly macros for VIS instructions**
  - **Wrote assembly macros for prefetch and fi tos instructions**
- **Shade: pfi count (prefetch instruction counter)**
- **INCAS (It's a Nearly Cycle-Accurate Simulator)**
- **perf-monitor: hardware performance counters**
- **Benchmarks on a 336 MHz UltraSPARC-II**

# Horizontal Kernel Performance



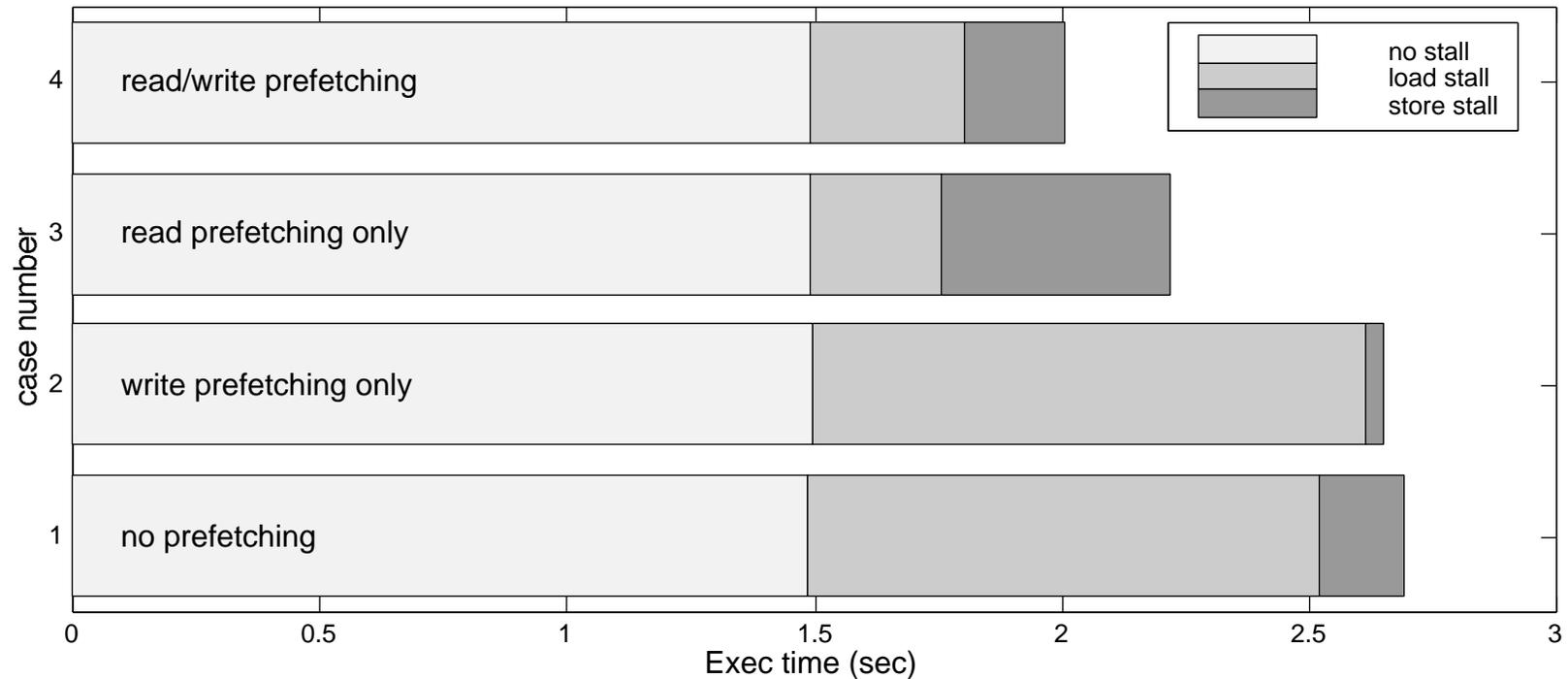
- **Hand loop unrolling gives speedup of 2.4**
- **Multiple passes improve cache usage (93% / 97%)**
- **Inline PREFETCH “breaks” compiler optimization**

# Vertical Kernel Performance



- **VIS offers a 46% boost over floating-point**
- **Software prefetching gives an additional 34%**
- **104 MB/s data input, 62.7 MB/s data output**

# Vertical Prefetch Statistics



- **Breakdown of execution time**
- **Execution cycles (no stall) constant across trials**
- **Internal cache statistics do not change**

# Conclusion

- **Beamforming kernel results:**
  - **Horizontal beamformer kernel: 444 MFLOPS, 66% of peak**
  - **Vertical beamformer kernel: 313 MFLOPS, 93% of peak**
  - **Loop unrolling: 2.4 speedup in horizontal kernel**
  - **VIS: 1.46 speedup in vertical kernel**
  - **prefetching: 1.34 speedup in vertical kernel**
- **Near-peak performance can be achieved, but**
  - **Kernel optimization is difficult and time consuming**
  - **Compiler did not generate prefetch instructions**
- **For high-throughput real-time signal processing, general purpose CPUs can be an attractive target**