Lightweight Instrumentation and Analysis using OpenSHMEM Performance Counters

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Outline

- Introduction and Motivation
- Existing Approaches
- Performance Counter APIs
- Design and Implementation of a Collector
- Experimental Analysis
- Conclusion and Future Work
Introduction and Motivation

• Effective performance profiling and analysis tools for PGAS applications have been challenging
  – One-sided high-throughput usage model
  – Scale of parallel applications
  – Rate and volume of communication operations generated

• Tracing is the most common approach
  – Captures a log of each operation for offline analysis
  – Instrumentation introduce overhead and impact dynamic behavior of applications

• Can an alternative lightweight instrumentation approach be devised that skip library interposition, yet achieve detailed profiling for communication performance?
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Existing Approaches

- A number of tools provide communication tracing and analysis for OpenSHMEM applications
  - Collect detailed information
  - Plug-in/out capabilities
  - User-friendly interfaces
- Can generate per-operation overhead
- Requires library interposition
- Using hardware performance counters, e.g. PAPI is challenging for process-level application performance analysis
Our Approach

• Performance profiling using network and library counters through well-defined SHMEM APIs

• Associate performance information to process level as well as contexts within a process

• Simplest design of collector that impose low overhead to the application runtime

• Profiling analysis and optimization strategies proposed in this work can be applicable for other PGAS models
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OpenSHMEM Performance Counters

- Unsigned 64-bit integers
- Follow C language rules for unsigned integer arithmetic
- Monotonically increasing over the duration of program execution
- Incremented 0 or more times by SHMEM operations
  - One single large put operation can be fragmented to several smaller writes
  - Operation performed through shared memory rather than fabric
Implementation in Sandia OpenSHMEM

- Different design choices available for APIs based on operation type, input arguments, and return values

- Two class API for per-context counters
  - Operations reading data from a symmetric object (get, fetch AMO)
  - Operations writing data to a symmetric object (put, non-fetch AMO)

- Each context utilizes
  - Middleware level counters for issued operations
  - Fabric level event counters for completed operations

- Tracks number of fabric operations that have completed in the local memory
  - Associated with local process instead of a particular context
Proposed APIs

/* Retrieve write operation counters */
int shmemx_pcntr_get_issued_write(shmem_ctx_t ctx, uint64_t *cntr_value);
int shmemx_pcntr_get_completed_write(shmem_ctx_t ctx, uint64_t *cntr_value);

/* Retrieve read operation counters */
int shmemx_pcntr_get_issued_read(shmem_ctx_t ctx, uint64_t *cntr_value);
int shmemx_pcntr_get_completed_read(shmem_ctx_t ctx, uint64_t *cntr_value);

/* Retrieve target operation counters */
int shmemx_pcntr_get_completed_target(uint64_t *cntr_value);

/* Retrieve all operation counters */
int shmemx_pcntr_get_all(shmem_ctx_t ctx, shmemx_pcntr_t *pcntr);

Object to hold all counter values
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Design of a Collector

- Simple design choices to collect the performance counter data
- Initiated as a thread to run alongside with the calling PE
- Sampling Interval defines the rate at which the data is collected; controlled by a runtime parameter
- Samples are timestamped and stored in memory
- Samples are discarded when there has been no change in the counter values since the last collection
- By default, collects the data for SHMEM_CTX_DEFAULT
- Additional contexts can be added and removed during runtime; maximum number of allowable contexts can be controlled via a runtime parameter
- Stored samples are dumped in a simple CSV format
Example program utilizing the Collector

shmem_init();
...
shmem_ctx_create(&ctx);
for (rem_pe = 0; rem_pe < npes; rem_pe++) {
  shmem_ctx_put(ctx, dest, src, nelems, rem_pe);
}
...
shmem_finalize();

shmem_init_thread(SHMEM_THREAD_MULTIPLE, &tl);
start_collect();
shmem_ctx_create(&ctx);
register_context(ctx);
for (rem_pe = 0; rem_pe < npes; rem_pe++) {
  shmem_ctx_put(ctx, dest, src, nelems, rem_pe);
}
remove_context(ctx);
stop_collect();
shmem_finalize();

Contexts must not be created with
SHMEM_CTX_PRIVATE/
SHMEM_CTX_SERIALIZED
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Experimental Setup

- Cluster with 14 compute nodes
  - Intel® Xeon® E5-2699 V3, 36 cores/node @ 2.3 GHz
  - 64 GB DDR4 memory
  - Intel® Omni-Path Fabric

- Performance counter APIs are implemented on top of Sandia OpenSHMEM (SOS), git #908682ee

- Applications
  - Integer Sort (ISx)
  - Stencil from Parallel Research Kernel (PRK)
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  ▪ Communication Schedule
  ▪ Overlap
  ▪ Load Balance
  ▪ Weak Scale Analysis
  ▪ Overhead
‒ Conclusion and Future Work
Communication Schedule

• Defines the next target PE in an all-to-all key exchange for each PE

• ISx implements three different communication scheduling pattern
  – Round-Robin (default): Chooses the next PE based on the given PE’s rank and loops over a circular array of PEs
  – Incast: Iterates over an array of PEs from 0, 1, 2, ... n
  – Permute: Iterates over a random array of PEs

• Target counter progression follows different trend for different communication schedule

• Divide the total number of PEs into four groups to highlight the differences in progression
Permute and Incast follow a similar pattern caused by an implementation bug in Permute communication schedule; created the same random array of PEs across all PEs.
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Overlap

• Observe the dynamic differences between the posted and completed operation counters
• Analyze the opportunities to introduce communication overlap
• Use ISx for this analysis and apply different optimization strategies based on the counter values
• Focus on the counter changes in the key exchange routine through
  – Pending read/write operations
  – Issued write operations w.r.t. completed read operations
Pending Operations with default ISx

- Pending operation counters (difference between the issued and completed counter values) over execution time
- Both read (left) and write (right) counter values reveal only one pending operation at any given time – presenting the opportunity for the usage of non-blocking APIs
Pending Operations with Non-blocking Put

- Replace Blocking Put with Non-blocking API
- Pending read operations are unchanged as no overlap is introduced; Pending write operations increase to at most 14 during the key exchange execution
- Further overlap is possible through non-blocking read (non-blocking fadd AMO)

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Non-blocking AMO in ISx key exchange

```c
for (int i=0; i<shmem_n_pes(); i++) {
    int dest_pe = peers_iter(i);
    long long dest_offset = shmem_longlong_atomic_fetch_add(
        &bucket_offset, bucket_sizes[dest_pe], dest_pe);
    shmem_int_put_nb(&bucket_keys[dest_offset], ..., dest_pe);
}
```

Loop fission

```c
for (int i=0; i<shmem_n_pes(); i++) {
    int dest_pe = peers_iter(i);
    shmem_longlong_atomic_fetch_add_nbi(&bucket_offset,
        bucket_sizes[dest_pe], &destOffsets[dest_pe], dest_pe);
}
shmem_quiet();
for (int i=0; i<shmem_n_pes(); i++) {
    int dest_pe = peers_iter(i);
    shmem_int_put_nb(&bucket_keys[dest_offsets[dest_pe]], ..., dest_pe);
}
```

shmem_quiet() ensures the completion of all fetches
Pending Operations with Non-blocking AMO

- Both pending read and write operations increase to almost 128 (total number of PE)
- Loop fission ensures read and write operations overlap within themselves
- `shmem_quiet` ensures the completion of all fetches, but prevents any overlap between read and write

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Overlap between Read and Write

- Plot issued write v/s. completed read to present any overlap between read and write
- In both iterations, write and read progress independently and thus, no overlap

- Replace `shmem_quiet` with individual `wait_until` to wait for each non-blocking `fadd` to complete before invoking the corresponding `shmem_put`
- Both the iterations exhibit overlap between read and write with `wait_until` at the end of the loop execution

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Overlap with Threads

- Alternative approach to pipeline the all-to-all exchange
  - Distribute loop iterations to multiple threads
  - Launch the threads in parallel

- Use OpenMP threads to the key-exchange routine
  - Create a pool of contexts to be used by different threads
  - Each thread utilizes its own context to invoke SHMEM APIs

- Apply OpenMP threads on both implementations of ISx (with and without loop fission)

```c
#pragma omp parallel num_threads(T) {
    int thread_id = omp_get_thread_num();
    int PEs_per_thread = shmem_n_pes() / T;
    for (int i = thread_id * PEs_per_thread; i < (thread_id + 1) * PEs_per_thread; i++) {
        int dest_pe = peers_iter(i);
        long long dest_offset = shmem_longlong_atomic_fetch_add(ctx_pool(thread_id),
                                                               &bucket_offset, bucket_sizes[dest_pe], dest_pe);
        shmem_int_put_nb(ctx_pool[thread_id], &bucket_keys[dest_offset], ... , dest_pe);
    }
}
```
Pending Operations with Non-blocking Put and Two Threads

- Pending read operations are similar to the non-threaded implementation as they use the blocking API; per thread, it does not increase more than once.
- Pending write operations increase more than that of non-threaded implementation; with multiple threads, overlapping among different write operations can be increased.

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Overlap with Non-blocking Put, AMO and Two Threads

- Apply OpenMP threads on the two distributed loops of key exchange with wait-until
- Both warm-up and trial iterations exhibit more overlap with multiple threads
- Increased pipelining between read and write operations compared to the non-threaded implementation

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Load Balance

• Utilize performance counters to detect load balance across all PEs
• Focus on the final operation counter value
• Use Stencil kernel (128 PEs with grid size of 1000 and 100 iterations)
• Observe put and get counters as well as target counter
Load Balance

- Grid of PEs with 8 rows and 16 columns; PEs with less neighbors (edge) have less load compared to the PEs with more neighbors (inner)
- Both Put and Target counter exhibit the load imbalance for stencil
- PE0 has a high target counter value because of collective and synchronize operations

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## Different ISx Implementations

<table>
<thead>
<tr>
<th>ISx Implementation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>Default implementation with blocking Put and AMO</td>
</tr>
<tr>
<td>NB-Put</td>
<td>Implementation with non-blocking Put</td>
</tr>
<tr>
<td>NB-Put-AMO</td>
<td>Implementation with non-blocking Put and AMO in two distributed loops using <code>shmem_quiet</code> in between</td>
</tr>
<tr>
<td>NB-Put-AMO-W</td>
<td>Implementation with non-blocking Put and AMO in two distributed loops using <code>shmem_wait_until</code></td>
</tr>
<tr>
<td>NB-Put-OMP2</td>
<td>Implementation with non-blocking Put and 2 OpenMP threads</td>
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<td>Implementation with non-blocking Put and 4 OpenMP threads</td>
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<tr>
<td>NB-Put-AMO-W-OMP2</td>
<td>Implementation with non-blocking Put and AMO in two distributed loops using <code>shmem_wait_until</code> and 2 OMP threads</td>
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<td>NB-Put-AMO-W-OMP4</td>
<td>Implementation with non-blocking Put and AMO in two distributed loops using <code>shmem_wait_until</code> and 4 OMP threads</td>
</tr>
</tbody>
</table>
Weak Scale Analysis

• Comparison of non-threaded implementations in 2 to 14 nodes (16 PEs/node)
  • NB-Put achieves 16.5% benefit compared to the Default; NB-Put-AMO-W out-performs NB-Put-AMO by 8.3%

• Comparison of threaded implementations in 2 to 14 nodes (16 PEs/node) with 2, 4 threads
  • NB-Put-OMP2 achieves 10% benefit compared to the single-threaded NB-Put-AMO-W; Additional threads degrade performance

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Collector Overhead

- Analysis on three different implementations based on different optimization choices
- Observe 20-100 ms overhead in average all-to-all time per PE for NB-Put-AMO-W
- Additional overheads for threaded implementation, NB-Put-OMP2
- Can collect reasonable number of samples with a sleep duration of 0.1 ms

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Conclusion and Future Work

• Proposed a performance counter API extension to OpenSHMEM specification
• Implemented the APIs in Sandia OpenSHMEM library
• Designed and implemented a low-overhead collector to use these APIs
• Analyzed applications with the performance counters to
  – Reveal and fix implementation bug in communication scheduling
  – Characterize load balance
  – Identify opportunities to improve pipelining and overlapping deficiencies
• Proposed approaches improve the average all-to-all time for ISx by 30%

• Investigation on automated methods for analyzing the collected data
• Use performance counter APIs to aid developers of recent and proposed API extensions
• Identify system-level performance optimization opportunities
Questions?