Distributed State Sharing and Predicate Detection over RDMA

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ABSTRACT

We present SST (Shared State Table), a framework for nodes in a single rack connected by RDMA to share local states and detect system events. An SST over a group of nodes is a table consisting of a row for each member of the group and columns representing state variables. We provide a mechanism for defining system events (called predicates) and callbacks (triggers) over the entries of the state table. The triggers are executed when the predicates are detected to be true. SST focuses on minimizing the time to detect predicates with the secondary concern of judicious use of RDMA resources. SST optimizes for RDMA operations and abstracts them from the programmer, thus providing a convenient interface to code applications to run over RDMA networks. We carefully examine the characteristics of one-sided RDMA reads and writes to find an optimal design for the SST, and provide new insights into system design using RDMA for peer-to-peer architectures. SST adds minimal overhead over raw RDMA primitives and scales linearly with the number of nodes. Our experimental study measures delay for detecting different categories of predicates, and illustrates the use of SST in a scenario based on OSPF routing.

1. INTRODUCTION

A fundamental component of any distributed system is the mechanism employed for sharing state between its components. Replicas of a service running in a rack of a data center might share information about load, computation progress, parameters, and those servers might use the evolving state information to adaptively modify their behaviors. Closely-coupled distributed systems share application state and user-defined data relevant to their distributed functionality. System monitoring and management tools have a strong dependence upon state sharing and tracking. For example, load balancers, replica managers, and other fault-tolerance tools, frequently exchange short messages, approximating a shared global view of the system and using this to coordinate decentralized control actions.

Although there has been prior work on tracking or data-mining state to monitor global system status, for example in the Astrolabe [13] system, most existing systems were designed to run over the TCP/IP network stack, which introduces substantial delays due to the need to process packets in the OS kernel. Such systems have often been deployed at genuinely massive scale, and hence are typically designed to tolerate relatively high latencies and low data sharing rates. Our premise is that these latencies are far higher than necessary. For example, state sharing systems that run at rack scale often exchange just a few parameters: load, queue length, etc. The control programs that coordinate network routers or switches at the top of the datacenter routing hierarchy similarly require relatively small amounts of shared state, with which they optimize route selection and avoid congesting links or the routers themselves. Were a solution available that could support this functionality at sharply lower latency, the door would be opened to adaptive behaviors well beyond what classical management infrastructures currently achieve.

With this objective, we focus upon RDMA networking technology. RDMA eliminates the need for CPU processing at the end host by providing direct memory access through an RDMA-capable NIC. RDMA is dramatically faster than kernel-mediated TCP/IP and is finding widespread adoption in modern datacenters and HPC clusters, to the extent that the technology is quickly becoming a de-facto standard.

Given an RDMA infrastructure, it would of course be possible to revisit classical distributed monitoring and management tools, recording them to replace their TCP message-passing layers replaced by equivalent RDMA messaging. However, such an approach would be unlikely to achieve the highest possible performance because the entire architecture of existing tools is ill-fitted to a zero-copy data sharing model. Far better would be to design new solutions from the bottom up, using architectures that fully leverage RDMA. Such an approach can yield dramatic performance gains, as seen in recent work on key-value stores [6, 10]. Here we do something similar for state sharing. Note that our target use case is poorly matched to the key-value model, and hence that these recent results do not solve our problem.

In this paper, we present **SST** (Shared State Table), a framework to share local states and detect system events for servers in a single rack connected by RDMA. SST consists of two main components, the **State Table** and the **Predicate Detection** subsystem. The state table consists of rows for each node with columns of the table denoting state variables, and the predicate detection system allows applications to register (predicate, trigger) pairs to react to system events. A predicate defines a set of conditions on the state variables, and triggers define actions that need to be taken when their corresponding predicate is true. The application manages the set of rows in the SST: our API permits rows to be added or removed. If a node crashes, our implementation will freeze the corresponding row (we also do an upcall to the application if we actually detect a problem, but because a node might crash and yet its NIC could remain healthy, this is not something the application can count upon).

As an example of how SST might be used, consider an application running on a group of nodes that involves sending messages from a master node to all the other nodes with the condition that the new message be sent only when the previous one has been delivered to all the nodes. Suppose the nodes have identifiers $\{0, 1, ..., n\}$ with 0 being the ID of the master node. Let the messages have integer identifiers in an increasing sequence. If `statetable` is an instance of the SST state table, we can define `statetable[i].msg_num` to be the ID of the most recent message received by node i. The condition that node 0 should send message k if all nodes have received message $k-1$ can be expressed as `statetable[i].msg_num`$= k-1$ for all $i \in \{1, 2, ..., n\}$. In our terminology, this condition is the *predicate,* and sending the next message is the *trigger.*

SST maintains an updated copy of the state table in the local memory of every node by posting RDMA operations (reads and writes), and it continuously evaluates predicates on the local copy. It focuses on minimizing the time to detect predicates and is targeted at low-level network applications where performance is critical. SST makes optimal use of RDMA operations and abstracts them from the programmer, thus providing a convenient interface for programming distributed applications to run on RDMA networks.

We have implemented and compared two versions of SST, **SST-reads** and **SST-writes**, based on one-sided RDMA reads and RDMA writes, respectively. Our paper makes the following contributions:

1. We propose a predicate-driven event model and show that it represents a useful abstraction for important classes of computations in distributed systems.

2. We present a high-performance implementation of this new model, and we evaluate the solution in a variety of RDMA settings.

3. We explore various implementation choices, notably SST-reads (based on on-sided RDMA reads) and SST-writes (based on one-sided RDMA writes). We show that in most cases, SST-writes represents a better choice.

4. We offer insights into the achievable RDMA performance for tightly coupled groups of nodes in a datacenter network design.

We have evaluated the system on the Susitna cluster of Emulab, which is connected with 40 Gbps Infiniband, and in the Texas Stampede cluster, which has a 56-Gbps Infiniband system that includes routing over one or two levels of top-of rack switches: the former lets us explore a rack-scale computing case, while the latter is more similar to what might be seen in a datacenter routing infrastructure. We show that SST adds minimal overhead over raw RDMA primitives, scales linearly with the number of nodes, and is tolerant of RDMA routing delays. We discuss and evaluate different types of predicates varying in complexity and structure and demonstrate a use case of OSPF routing.

The paper is organized as follows: In section 2 we provide some background on RDMA. In section 3 we discuss our high-level system model, and in section 4 we describe the design of SST in detail. Section 5 describes our experimental evaluations and results. Finally, section 6 discusses related work on state management systems and RDMA based systems, and we conclude with a discussion of future work.

2. BACKGROUND ON RDMA

For reasons of brevity, we assume that the reader is familiar with RDMA. We only provide a short summary here with a focus on setting some of the notations right and stating the technologies we use.

SST runs on the Verbs API which exposes RDMA functionality available on Infiniband hardware, but should also be compatible with RoCE (Ethernet). RDMA is a connection-based protocol, hence there is a connection establishment step, which occurs before our experiments run. The protocol supports two modes of operations : a) synchronous, consisting of **send** and **receive**, which require the cooperation of both the sender and the receiver and b) asynchronous (also known as *one-sided*) operations, consisting of **read** and **write** in which a process P, respectively, reads from or writes to memory region of process Q. Q grants permission for one-sided access during initialization, but the actual reads and writes require no action by Q: the memory module on Q handles these operations just as it handles reads and writes from any local core, and provides the same cache-line atomicity guarantees. Our experiments ran

on Mellanox hardware but we use no Mellanox-specific features, hence our code should run on any hardware compliant with the relevant standards.

SST does not use the RDMA connection mode, hence the remainder of our discussion will focus purely on one-sided RDMA operations. These require *posting* the read/write request to the NIC and busy *polling* for completion notification of the operation at the initiator node.

3. SYSTEM MODEL

3.1 State Table

A row is a user defined struct containing some number of entries. By an entry, we refer to a cell of the table i.e. a state variable of some node. Each entry is a boolean, integer, floating point value, or any other "plain old data" type that will fit within a single cache line. Every node has a single local row. Taken together, the rows from all nodes in the group form a State Table. All rows in the table are readable by any host, but only the local row may be modified. After such an update is done, SST makes sure that the modifications quickly become visible in all copies of the state table.

3.2 Predicate Model

Predicates are boolean-valued pure functions that operate on a state table. Users may register any number of predicates to detect specific events, along with lists of triggers to be run when each predicate first evaluates to true. Triggers are void-valued functions that can change the local row as well as add additional predicates and triggers. All operations involving predicates occur locally on the host where they are registered. We use a single thread for predicate evaluation and trigger execution, hence no local locking is needed; if the application needs to ensure that that updates won't occur while predicate evaluation is underway, or while a trigger is running, a simple snapshot feature of SST freezes a copy, at the cost of allocating memory and performing the needed copying.

It is very convenient to program in this model. As an example, a k-step synchronous algorithm can be implemented by registering predicates for each step that check whether the entries in a step_num column indicate that all nodes have reached that step. The associated trigger could actually perform the work for the step and then increment the local step_num entry.

4. DESIGN

4.1 State table

The row format is provided by a template parameter at initialization of SST and must be a struct in C++. An example is given in Listing 1 in which every row contains a step number, an array of timestamps and percentage CPU load. A row represents the local state of its owner node, and only the owner of a row has write access to it. A node can read the local states of other rows and therefore, has read access to all the rows. SST maintains an in-memory instance of the entire table at every node.

For RDMA operations to succeed, it is very important that the memory layout of the rows be predictable. We require that the struct specifying the format of the row be a POD (plain old datatype), and that it not contain pointers to the actual state members. The memory layout of member variables of non-POD structures can be in non-contiguous regions and similarly, the actual data pointed to by a member pointer can be somewhere else in memory. An example of a non-POD struct is given in Listing 2. All its members are either non-POD types or pointers. For instance, a vector's size is not fixed at compile time, so the vector object stores a pointer to the actual member array. There are two major issues associated with such structures. First, it is not clear how to determine the actual addresses of the state variables from a general struct template provided by the user. Second, since the state variables are stored in non-contiguous addresses, we have to pin all the different memory regions to the NIC and exchange all addresses at SST creation time, which complicates the initialization process. Worse, reading a row of a remote node or writing the local row to a remote node would entail issuing multiple RDMA operations, one for each contiguous memory region of the struct, leading to a severe degradation in performance. In this context, it is important to recall that RDMA offers very basic primitives; in particular, there is no pointer indirection in remote memory. By avoiding these complex scenarios and allowing only POD structs without pointers, we are guaranteed that all the state variables are stored in one contiguous memory region. This makes it simple to pin memory and exchange addresses during initialization, and reading/writing a remote row takes only one RDMA operation.

We fix the structure of the table (number of rows and their owner nodes as well as the row format) at SST creation because any changes to row structure or membership would require reallocating the table at each node, leading to repinning of memory with the NIC. Since this is such a costly operation, it would effectively take no less time than destroying the SST object and creating a new one, so when the application adds or removes rows, our implementation tears down the existing SST object and creates a new one. This also allows the application to dynamically change the structure of the table, if desired, provided that the new structure is also a POD.

4.2 Operations on the table

Our goal is to support lock-free, fully asynchronous state reads and updates, i.e. a node should be able to update its local row and read other rows without being delayed by other nodes, or depending upon any form of cooperation by other nodes. Subject to this constraint, SST should guarantee atomicity at the level of updates

```
struct Row {
  int step_num;
  struct timespec timestamps[2];
  double cpu_load;
};
```

Listing 1: An example of an SST row structure

```
struct Row {
  vector <struct timespec> timestamps;
  list <int> costs;
  map <int, string> ip_addrs;
  double *cpu_load;
  int *step_num;
};
```

Listing 2: non-POD structs are not allowed

and reads to objects that reside fully within a single cache line and are written or read by some single instruction, analogous to lock-free updates and reads to volatile variables in C++. Since our users are expected to be skilled C++ programmers, they would normally be familiar with concurrency and lock-free data management. We chose not to offer distributed locking of any kind to avoid unpredictable synchronization delays. Thus two basic design choices remain, one based on RDMA one-sided reads and the other based on RDMA one-sided writes. We describe both of these options.

4.2.1 SST-reads

In SST-reads, every pair of nodes exchange the address of their local row with each other at initialization. A local state update is implemented by a DMA write to the local row, whereas reading other rows is achieved by posting RDMA reads to their owners and storing the result in the local table.

Our first design decision is to determine how a node should use RDMA read operations to keep its local in-memory table updated. We first measure the latency of RDMA reads for two nodes. Figure 1(a) plots the time it takes one of the nodes from posting the operation to successful completion for varying data sizes. We break up the time in two parts : a) time to post the request to the NIC and b) remaining time until the end of successful polling. The time to post the read is constant (since it only involves notifying the NIC of the request), whereas time to poll completion increasing linearly with data size as the data transfer time increases. As is clear from the graph, the majority of the time is spent busy polling for completion of the RDMA read.

To better utilize this idle time, we post all the requests to all the rows first and only then wait for them to complete. The pseudo-code is given in Listing 3. This allows for the operations to be carried out in parallel, and reduces the overall latency by a significant amount

```
for every other node k:
  post read of local row of node k

for num_rows-1 times:
  poll completion of one entry
```

Listing 3: Table refresh in SST-reads

```
for every other node k:
  post write of local row to node k

for num_rows-1 times:
  poll completion of one entry
```

Listing 4: Local row update in SST-writes

as the time for polling completion is amortized over all the operations. We verify this experimentally by varying the number of rows and measuring the average time taken for the parallel reads to finish. The graph is plotted for different data sizes in Figure 3(a). From 1 to 7 parallel operations the total time increases by a factor of less than 2 for all data sizes, which is much less than 7. A schematic of the RDMA operations performed by a node in SST-reads is given in Figure 2(a).

4.2.2 SST-writes

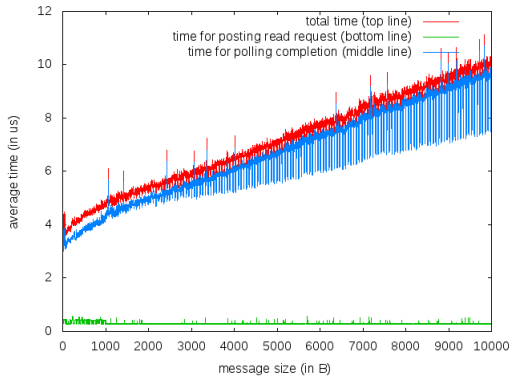
In SST-writes, every pair of nodes runs a protocol at initialization, with each sending its counterpart the address of the counterpart's row in its local memory. Thus, node P will know where P's row resides in Q's memory, and vice versa. A local state update involves posting RDMA writes to all the other nodes. Reading other rows is trivial: the local node simply reads from local memory. Cache-line atomicity is guaranteed by the hardware, but notice that updates involving multiple writes would not be atomic.

RDMA write operations have similar behavior to RDMA reads as shown in Figure 1(b). Therefore, by posting write requests in parallel, we can improve performance compared to posting each write sequentially (Figure 3(b)). The pseudo-code for the parallel writes is given in 4. Figure 2(b) shows the pattern of RDMA operations performed by a node in SST writes.

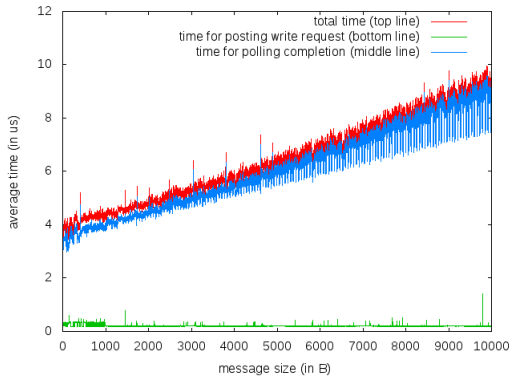
4.3 Predicates and Triggers

Predicates are C++ functions that take the SST object as a parameter and return a bool and are local to every node. Each predicate has a list of triggers associated with it that are executed in order, when the evaluation of the predicate returns true. Triggers are simply C++ functions that take the SST object as an argument, and return void.

We consider three types of predicates : a) Predicates that always remain in the system and fire their associated triggers each time they are evaluated to be true, b) Predicates that remain in the system until the first



(a) Reads



(b) Writes

Figure 1: Latency of RDMA read and write operations as message size increases

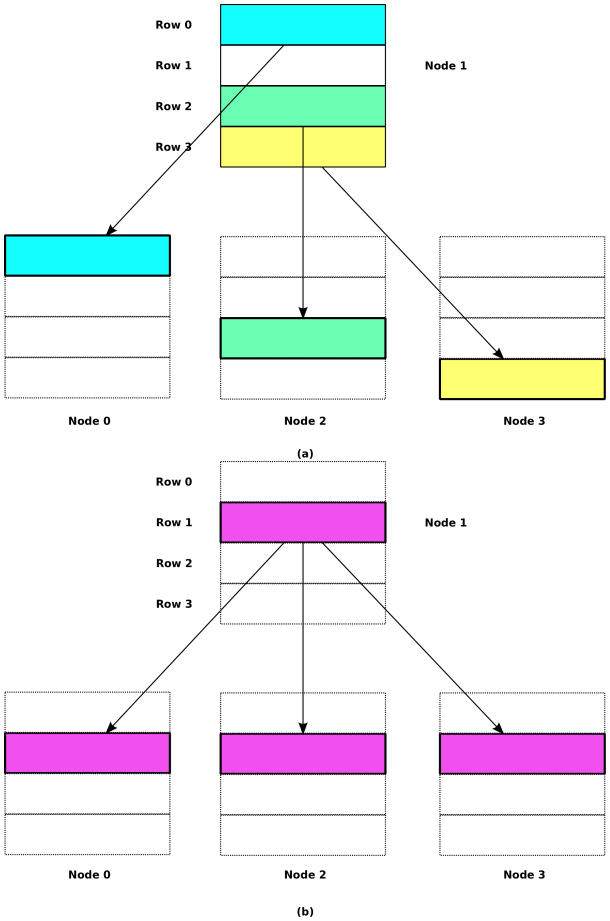


Figure 2: Illustration of SST-reads vs SST-writes. Node i owns row i of the table for i = 0,1,2,3. In (a), Node 1 reads the rows 0,2,3 from their respective owners. In (b), Node 1 writes its local row at all the nodes.

time they are true, and therefore, fire only once and c) Predicates that fire only when their evaluation changes from false to true. This provides additional choice to the user who can use an appropriate type based on the use case.

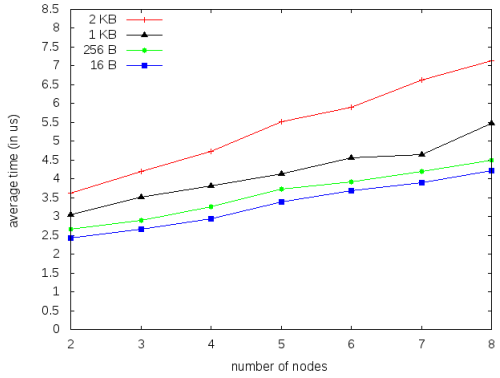
For SST-reads, if for every evaluation of predicates, we needed to read the remote rows, detection would be very slow. Accordingly, SST instead performs predicate detection and table refreshes (RDMA reads) in two separate threads. The predicate detection thread continuously evaluates the predicate on the local copy of table while it is simultaneously refreshed by the reader thread. Our belief is that SST use cases will require the highest possible performance, and that given this goal, dedicating a thread (indeed, a core) to play the role of refreshing the table is an acceptable level of overhead. The frequency of refreshes can be adjusted if necessary.

In the writes version, in contrast, the local node controls when to push the local state changes to other nodes, and no separate thread is needed. In most systems, the number of state updates are far less than the number of reads, and therefore, the writes version in most cases would involve fewer RDMA operations. Threads and their functions for both SST-reads and SST-writes is listed in Table 1.

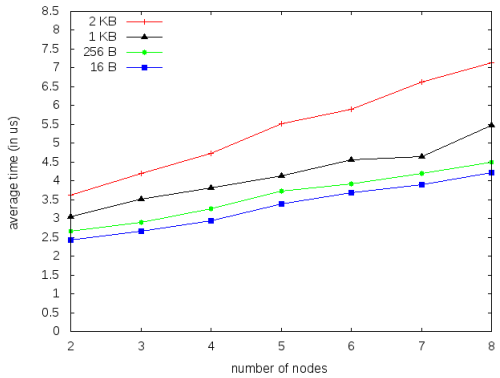
The predicates and triggers are provided the original SST object so that they can change the local row and add additional predicates. This means that the table entries can change while the predicate or trigger is being run. For cases where this possibility is not desired, SST provides a function get_snapshot that returns a constant copy of the table for evaluation. It is worth noting that since the triggers associated to a single predicate are executed in order, the final state of the SST depends on the order of execution as well as the order in which the predicates are evaluated and determined to be true.

4.4 Race Conditions

Read-write races arise in our design. In addition to race conditions caused by local threads, local reads/writes to the table can conflict with remote operations. There are two such cases, one in each version of the SST:



(a) Reads



(b) Writes

Figure 3: Latency of parallel RDMA reads and write as the number of nodes increases

1. In SST-Reads, a write to the local row can conflict with the RDMA read operation of the row by a remote node

2. In SST-Writes, an update of a local row at a remote node can conflict with the remote node's local read of it

In the context in which we expect SST to be used, introducing locks or other concurrency controls into the SST itself would create an undesirable latency overhead for the common, non-conflicting case. Instead, as noted earlier, we rely on a feature of the Intel processor architecture: DMA reads and writes of single cache lines are atomic [8]. Thus, if each state variable is of size less than the cache line size (64 B typically), RDMA reads and writes of such variables are atomic. This provides a basic guarantee of read/write atomicity for each state variable separately.

The FaRM key-value store makes this same atomicity assumption but then goes beyond it, implementing a transactional layer by adding a transaction identifier to every cache-line: if a multi-line read occurs in a transaction and the id's differ, the transaction is aborted and

Thread	Work performed
Reader	Refreshes local table in SST-reads
Detector	evaluates predicates and fires triggers
Main	establishes connections, creates SST object , updates local row

Table 1: Work performed by various threads in SST

restarted, looping until it sees a consistent state. We considered this, but worried that the space consumed by the ids could be substantial, and further, that looping in this manner would make evaluation times unpredictable. Since SST is oriented towards extremely high speed sharing of simpler forms of state, we concluded that transactions on the state should be viewed as an end-user abstraction. However the application itself could easily add a FaRM-like mechanism by using a struct that tracks transaction ids at cache-line granularity and checking these within the predicate.

5. EVALUATION

We report some microbenchmarks, discuss the performance of SST for different types of predicates and table rows, show how SST scales to larger numbers of nodes, then describe and evaluate a sample application of SST.

5.1 Experimental Setup

With one exception that we will note below, the experiments in this section were conducted on the the Emulab Susitna cluster, which has 35 nodes using 40 Gb/s Mellanox NICs. Each node has four 16-core Opteron 6272 Processors and 128 GB of DDR3 memory. The cluster is running Ubuntu 14.04.1 LTS.

5.2 Performance Metrics

5.2.1 Latency

SST is aimed at high-performance, latency-sensitive applications. The single most important property that affects application latency is the time SST takes to detect a predicate becoming true. A higher rate of predicate detection allows triggers to be fired more promptly and hence allows the application to respond quickly to state changes.

We define the time to detect a predicate as follows. When a predicate changes from false to true, this must correspond to an update of some local state variables by a node. Since writes of a state variable to memory are atomic, we can order the writes and identify the last write to some state variable by a node that caused the predicate to be true. So, we are interested in measuring the time from this last write to the time it is detected at the node where the predicate is registered. In SST-reads, this start time is when the state variable was updated in local memory, whereas in SST-writes, it is when the node initiated the remote write to all the nodes.

If a predicate turns true as a result of multiple near simultaneous writes by different nodes, the start of time is difficult to measure. Accordingly, in our experiments a single node always performs the update that causes any given predicate to become true. A further problem is that the interesting use cases are ones in which the update and the detection happen at different nodes. At the extremely high speeds we are exploring, elapsed time can be difficult to measure across nodes: these latencies are of the order of microseconds and accurate measurements would require that time be synchronized to a resolution of tens or hundreds of nanoseconds. Therefore, the technique we employ is sort of a round trip of detection: Node A updates an entry of its row that fires predicate P at node B which in its trigger, sets some entry of its own row that fires the predicate Q at node A. Node A measures the whole round trip time and then, if the time to detect for P is already known, using the linearity of expectation (as we will see the time is probabilistic), we get an estimate (upper-bound) for time to detect Q.

5.2.2 *Throughput*

Another measure of performance is how many times can we evaluate a predicate and fire its associated trigger. To measure this, we make the conditions right for a predicate to evaluate (periodically or permanently) become true at high frequency, then count how many times the associated trigger actually fired.

When a predicate remains true for an extended period of time, throughput mostly depends on processor speed and not on any network characteristics. This is because predicate evaluation is performed in a separate thread. However, if a predicate becomes true periodically, then a number of factors combine to determine the likelihood that each new detection will occur in a timely manner. The next subsection discusses these and other "parameters" that ultimately determine SST performance.

5.3 Parameters

A number of parameters affect the core performance of SST.

5.3.1 *Predicate complexity*

If we increase the number of rows upon which a predicate depends, we increases the time of detection for two reasons :

a) It increases the evaluation time of the predicate and

b) Time to update the local copy of the table to reflect simultaneous changes to the rows goes up. Specially, in SST-reads, if half of the updated values are not detected in one table refresh, then they are not visible until the end of the next refresh cycle. This effect is somewhat less pronounced in SST-writes, because all the values are updated as soon as the write of the last update in local memory completes.

It is worth noting that the actual nature of the predicate is not a major factor (whether it finds the sum or the maximum of a column etc. is irrelevant), since the time is dependent on how fast can we refresh the table which is entirely determined by the RDMA operation (read or write), table size and the number of nodes.

5.3.2 *Table size*

Increase in the size of a row increases the time to refresh a table in SST-reads because data transfer time increases. In SST-writes, state variables can be selectively updated, so this is not much of a factor.

Increase in the number of rows increases the time to complete a table refresh in SST-reads and increases the time to update local row in SST-writes.

5.3.3 *Number of Nodes*

Increasing the number of nodes increases the number of rows, but additionally, it means that the rate of RDMA operations will be higher. However, the small row size of typical uses and highly-capable modern NICs ensure that this is not a major factor.

5.4 Number of predicates, and triggers

The application is permitted to register unlimited numbers of predicates and triggers. Because SST pins a core but then uses a single thread to perform detection and execute triggers, this implies that enthusiastic use of the SST will degrade its peak achievable performance. Further, aggressive use of the snapshot feature can impose substantial memory allocation and copying costs (on the processors we tested with, memcpy runs at 13.5Gbps: quite fast, but still a potentially significant cost at the speeds SST achieves).

5.5 Micro-benchmarks

5.5.1 *Latency of Simplest Predicate*

The simplest predicate is the one that depends on a single remote row in a 2 node system. The SST consists of the two rows and a single column **a** of type int, initially 0 for both rows. Node 0 at a random moment in time, sets its own entry to 1. We are interested in measuring the time to detect this change at node 1. To measure time, we do a round trip of detection. On detecting predicate at node 1, node 1 sets its own entry to 1 in the attached trigger, which is in turn detected by node 0. Node 0 measures the time taken from setting $SST[0].a = 1$ to detecting $SST[1].a = 1$ and divides it in half to get an upper bound for detecting the predicate. The predicates and the triggers are illustrated in Table 2 and the sequence of operations of the two nodes is given in Table 3. It is important to appreciate that the time taken depends on the actual order of local and remote operations on the memory and is thus probabilistic.

This sequence is illustrated in Figure 4 (a) and (b). In Figure 4 (a), S1, E1 and S2, E2 denote the two RDMA reads by the remote process. R1 and R2 are their respective reads of the local memory. If the local write shown as W1 takes place just before R1, the remote

process detects it at E1. If the local write instead takes place just after R1 (W2), the remote process misses it at E1 and detects it at E2. Time to detect in case 1 is length of W1E1, while it is length of W2E2 in case 2. Similarly, for the writes case in Figure 4 (b), S,E denote the write by the remote process with W denoting the time of DMA write to local memory and R1, R2 denote the points of local probe of memory. The time to detect is the length of SR2 which depends on the position of W between the interval [R1, R2]. Notice, that there is a definite order among the operations on memory because of the atomicity of the reads and writes of a state variable as observed in Section 4.

Due to the variation in the time of detection as well as in the RDMA operations themselves, we large numbers of tests and calculate the mean and standard deviation of the time. Notice that the standard deviation values will be higher for the reads version as compared to the writes version because local memory access takes less than one-fifth the time of an RDMA operation [9] (this can be seen in Figure 4, the length of the intervals for reads and writes is different). To give a sense of the performance overhead incurred by SST, we implement this predicate detection using directly the RDMA read and write operations i.e. without the formalism of a table and predicate detection subsystem. The results are provided in Table 4. As is clear from the data, the overhead incurred by SST is negligible.

P0 : SST[1].a = 1	P1 : SST[0].a = 1
T0 : end timer	T1 : set SST[1].a = 1

Table 2: P0 and P1 are the predicates for nodes 0 and 1 resp. and T0 and T1 are their associated triggers

Figure 4: Time of detection is different depending on the order between DMA writes and DMA reads by local and remote memory operations. (a) and (b) illustrate this for SST-reads and SST-writes respectively

Node 0	Node 1
create SST	create SST
set SST[0].a=0	set SST[1].a=0
register (P0, T0)	register (P1, T1)
wait for random time	
start timer	
set SST[0].a = 1	

Table 3: Sequence of operations for the two nodes

	SST Reads	RDMA Reads	SST Writes	RDMA Writes
mean	2.22	4.60	4.50	5.81
std. dev.	2.47	3.21	2.17	1.67

Table 4: Results for the simplest predicate detection

5.5.2 *Latency of Most Complex Predicate*

We now measure the time to detect a predicate that depends on the entire column of the state table. We consider the detection of the abstract predicate

$$SST[1].a \wedge SST[2].a \wedge ... \wedge SST[n-1].a$$

by node 0 for n=25 nodes. All predicates involving aggregates over a column like average, maximum, minimum etc. fall in this category. Since, we want all the nodes except 0 to set their state variable a to 1 at the same time, we make them wait till they detect $SST[0].a$ to 1. Node 0 starts the timer when it sets its entry to 1 and ends it when it detects that all the other entries are 1. To get an estimate of the time it takes to detect this predicate, we subtract the time to detect the simple predicate found in the previous experiment with n=25. This works because of the linearity of expectation. The averages time to detect the predicate is found to be 12.04 microseconds for SST-reads and 11.6 microseconds for SST-writes: less than a 6-fold increase.

5.5.3 *Throughput of a Basic Predicate and Trigger*

The predicate remains the same as the previous case, but it is registered only at node 0 and the **a** entries are already set to 1. So, as soon as the predicate is registered it starts firing. The trigger simply increments the counter. This captures the basic function call overheads of predicate detection. We find that there are 800K evaluations and trigger executions per second, confirming that the evaluation speed depends primarily on CPU speed.

5.6 Effects of Predicate and Row Complexity

5.6.1 *Latency with predicate complexity and the number of nodes*

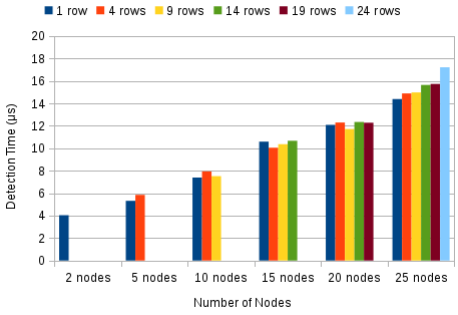
We vary the number of rows a node depends on, **r** and the number of nodes **n**. For a given $r < n$, the predicate at node 0 is

$$SST[1].a \wedge SST[2].a \wedge ... \wedge SST[r].a$$

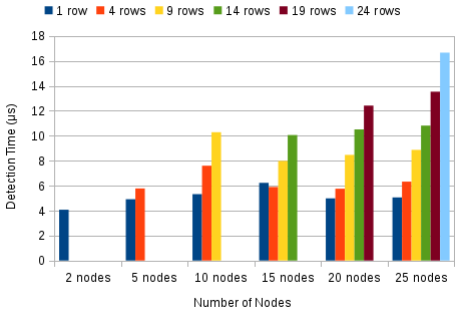
At initialization, we ensure that $SST[i].a$ is 1 for all nodes upto $r-1$, and then, node r sets it to 1 after a random wait. We again measure the time using a round trip of detection with r setting its entry after detecting $SST[0].a = 1$ and find the detection time by a similar technique as in Section 5.5.2. The results are shown in Figure 5(a) for SST-reads and 5(b) for SST-writes.

We see that the SST-reads and SST-writes have different characteristics overall. With SST-reads, we see

that for a given number of nodes, the latency of detection is very high even with the simple predicates, but remains roughly constant with the variation in predicate complexity. With SST-writes, we see that for a given number of nodes, the latency of detection is low for simple predicates and increases gradually with the predicate complexity converging to about the same value corresponding to the SST-reads data. This is because, SST-reads continuously updates the table by posting read operations to all the nodes, so if the updated value by node r that validates the predicate is missed by node 0 in a refresh cycle, it won't become available until the next cycle. However, in SST-writes node r simply writes the data to all the nodes and therefore, when it completes on node 0, node 0 detects the predicate. Hence, SST-writes has a better performance with predicates operating on fewer rows of the table for large number of table rows, while otherwise, the performance is comparable. As a corollary, for the same predicate complexity, time of detection increases with increasing number of nodes for SST-reads, while it remains roughly constant for SST-writes.



(a) SST-reads



(b) SST-writes

Figure 5: Latency of predicate detection with the complexity of predicates for different number of nodes

5.6.2 *Latency with row size and the number of nodes*

The row in this experiment consists of a single array **a** of integers, size of which is varied from 1 (4 Bytes) to 1024 (4 KB). The predicate depends on all the rows and all the columns and is as follows :

$$\forall_{0 \leq i < n} \forall_{0 \leq j < s} SST[i].a[j]$$

where, s is the size of the array. All the entries of all the rows are 1 except SST[n-1].a[s-1] which is set to 1 at a random time. We detect at node 0.

The results are shown for SST-reads in Figure 6. We find SST-reads and SST-writes to perform equivalently in this case, since, the size of the row increases the completion time of RDMA read and write operations identically. As is clear from the graph, the time for detection increases with the number of nodes as well as the data size.

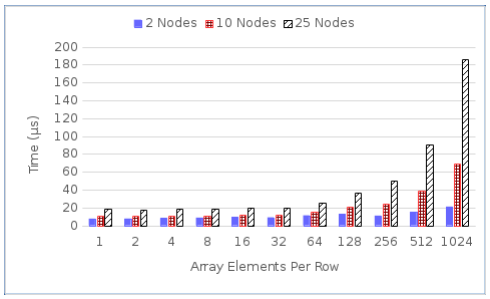


Figure 6: Latency of predicate detection with number of nodes for different number of row elements

5.6.3 *Throughput variation with predicate complexity*

To see how many a times can a predicate evaluate and fire the trigger continuously, we vary its complexity by varying r. The predicate remains the same as in Section 5.6.1 and the trigger increments the counter. The predicate is set to true before registering the predicate. The results are shown in Figure 7. The graph shows that the number of evaluations decreases slightly with the predicate complexity as the time to evaluate it increases. However, the throughput is good even for large rows: the number of evaluations for the predicate accessing 29 rows is still nearly 500K per second.

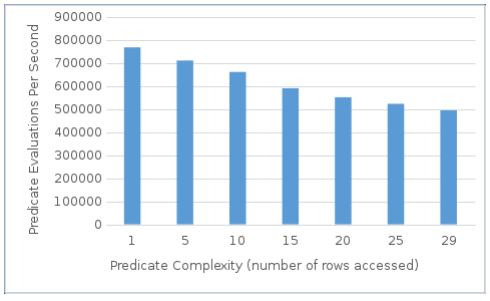


Figure 7: Variation of throughput with the predicate complexity

The number of times a predicate evaluates periodically depending on remote actions is explored in the next section along with scalability.

5.7 Scalability

For scalability, we implemented a form of distributed counting, where all nodes start counting from 0 in synchrony i.e. all nodes increment their counter, wait for everyone to increment it, then increment again and so on. The predicate corresponding to this is

$$\forall_i SST[i].count \geq SST[k].count$$

for a node k, and is registered at all the nodes. The trigger simply increments the counter. All nodes measure the time it takes to count up to a million and we take the average (the individual times are very close because this form of counting is synchronous). Figure 8 shows the plot of time with the number of nodes for read and write. Throughput in this experiment for SST-reads varies from about 400K evaluations per second for 3 nodes to 40K/s for 28 nodes. For SST-writes, it varies from 325K/s for 3 nodes to 48K/second for 28 nodes. From the graph, it is clear that SST scales well: the time varies linearly with the number of nodes. It is interesting to note that SST-writes scales better than SST-reads. The explanation is similar to the analysis discussed in 5.6.1. If a node in SST-reads does not see the updated counter values in an iteration, it will have to wait until the next cycle of table refresh, but a node in SST-writes will see the updated counter values of another node as soon as that node writes it into its memory. Thus, SST-writes scales better and performs better than SST-reads, even if the updates are fairly high.

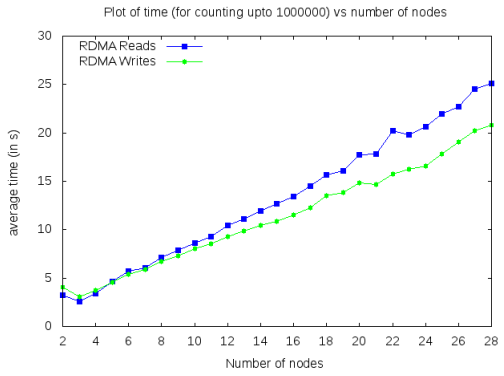


Figure 8: Time to count up to 1 million for different numbers of nodes

5.8 Routing Application

To demonstrate how SST could be used to support network applications that share state, we implemented a basic OSPF-like routing application using SST-writes. As in the OSPF protocol [11], each "router" node in the network forwards messages to other routers based on a forwarding table, which it constructs based on a link-state table that describes how each router is connected to other routers and networks and the cost associated with each link. However, instead of using gossip messages to exchange link state information, the link state table is stored in an SST instance. The SST has a column for each router (or other network endpoint) in the network, and the values in each column indicate the cost of the link to that router. Thus, `sst[src].link_state[dest]` is the cost (i.e. OSPF metric) of the link from `src` to `dest`, or a special value such as -1 if there is no link from `src` to `dest`. When a router gains or loses a link, or changes the cost of an existing link (e.g. due to a congestion control policy), it simply updates a value in its local row, and the SST ensures that this change in the link state table is propagated to all the other routers.

Instead of recomputing their routing table every time the link state changes, as in standard OSPF routing, our routers use a more sophisticated predicate to detect changes that could potentially cause a shortest path to change. After computing all shortest paths and creating its routing table, a router registers a predicate that evaluates to true if any of the links used in a shortest path increase their cost, or if any of the links left out of a shortest path decrease their cost. The trigger for this predicate is to recompute the routing table and construct a new predicate based on the new shortest paths. This demonstrates how SST's predicate system can be used to detect system events with more advanced logic.

To measure the performance of SST in this application, we measured the time it took for all the routers in a system to install new routing tables after a link state change. In order to ensure that a single link change would cause all routers to recompute their routing tables, the nodes in the test system were configured to use a virtual network topology in which one node was a central "hub" connecting to all other nodes with low-cost links, and all the other nodes were connected to each other in a ring of higher-cost links. Figure 9 shows the total time for all nodes to finish updating their routing tables, as well as the time it took for the first remote node (other than the node making the link change) to react. The gap between these times represents the variation in network latency between RDMA writes propagating the updated SST row to each remote node. Figure 9 also shows the amount of time a single node spent recomputing all shortest paths from the link state table, for each network size, in order to show the portion of the response time that did not depend on SST latency.

5.9 SST in other settings

5.9.1 *Nodes on different racks*

SST is built under the assumption that applications will generally run at rack-scale: our architecture matches best with settings in which all the nodes are connected

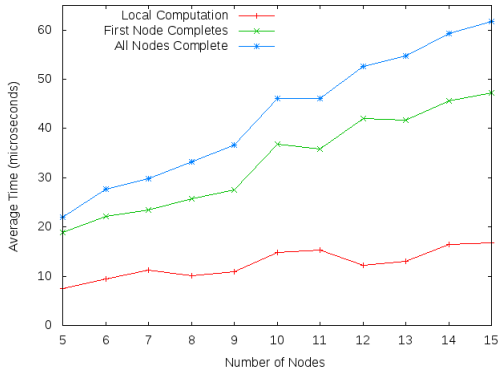


Figure 9: Time for nodes to install new routing tables after a link change

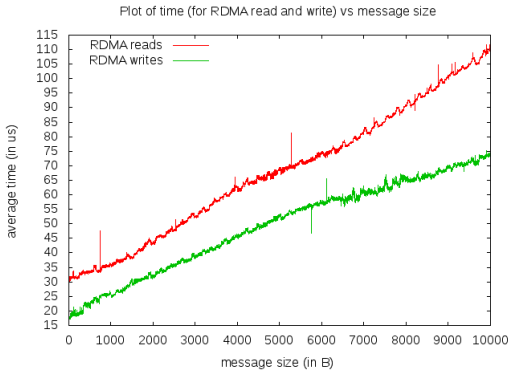


Figure 10: RDMA latencies on Marmot

to the same switch, so each pair of nodes has full bisection bandwidth and identical RDMA latencies. This is reflected in the design of refresh table in SST-reads and table update in SST-writes: We post all of the operations and then wait for them to complete. If the connection of a node A to some other node B is comparatively slow (because they are in different racks, for instance), the time it takes for a refresh or update to complete at A will increase, in which case it might make more sense to post reads/writes to node B less frequently than the other nodes and possibly in a separate thread.

We explored this issue in a real setting on the Texas Stampede cluster which has faster Infiniband switch than Susitna, 56 Gbps, but runs a scheduler that allocates jobs to nodes in what seems to be a highly randomized manner: we have no control over whether they are on the same rack, and by examination of node IP and MAC addresses, we find that each run seems to scatter our SST instances over a different set of nodes, often widely separated. Nodes on different racks on Stampede are connected via 3 different switches: the respective top of rack switches and the aggregator switch, which means that the RDMA operations latency between them is twice as high as compared to the latency for nodes on the same rack. Additionally, a rack has 2 IB switches connected to 20 nodes each and each leaf switch is oversubscribed to the core switch, so that the nodes on the same rack, but connected to different switches get only 80% of the bandwidth. Yet while such a setup is perhaps not typical for rack-scale scenarios, it could easily arise in routing applications or other data management use cases.

Accordingly, we wished to understand how SST might behave in such a case. We ran the distributed counting experiment on 8 and 16 nodes on a total of 3 racks. For comparison, we ran the same experiment on 2 nodes on the same rack and switch. The Table 5 shows the data, contrasting it with that for Susitna. As we can see, there is a significant improvement on Stampede for 2 nodes because of the higher bandwidth, but the numbers for the 8 and 16 nodes are comparable because of higher latency between nodes on different racks or same rack but different switches. We also observe that the throughput is still reasonably high, even though the variable latencies represent a significant departure from the intuition that drove our design.

Number of nodes	Stampede	Susitna
2	0.91	3.23
8	8.66	7.09
16	13.16	13.42

Table 5: Sequence of operations for the two nodes

5.9.2 *Old RDMA hardware*

We ran some of our experiments on Marmot, a cluster within Emulab that has a much slower 1 Gbps Infiniband. There are two major changes to note. Even though the RDMA operations' latency varies linearly, for reasons unclear to us, in this case we find that the latency of writes is much better than the reads. Figure 10 compares them. In this configuration, SST-reads scales very badly. The distributed counting experiment's result for Marmot are shown in Figure 11. In contrast, SST-writes still scales linearly.

5.10 Advantages of SST-writes

The design of SST-writes ensures that we have fewer RDMA operations in most use cases. The SST-writes allows a node to update a single state variable at remote nodes, leading to their faster detection. This is observed in the predicate complexity and scalability experiments. For many of our other experiments, SST-reads has comparable performance, but in some cases the performance difference is striking, and this was particularly evident in the "old hardware" experiment.

6. RELATED WORK

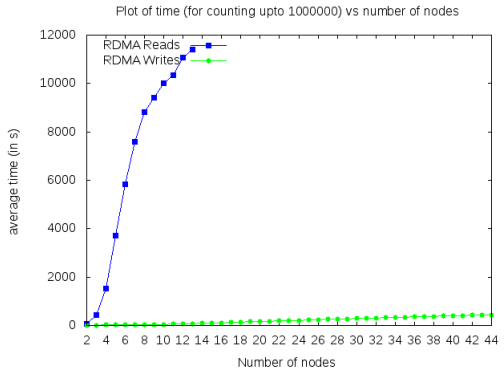


Figure 11: Distributed counting experiment on Marmot

The shared table model is a familiar paradigm and has been studied extensively in prior work, but at much lower data rates and much higher latencies. Work on distributed expression evaluation traces back to the META system [14], which evaluated expressions over sensors, modelling each sensor as a publish-subscribe group in which the sensor pushed updates to the interested receivers. This style of computation is common with pub-/sub systems, such as the Isis Toolkit [2], TIB/RendezVous [], Gryphon [12], and Siena [3]. In addition, there is a large body of research on event-structured database systems, including systems for running transactions both on streaming data and on stored data.

Important work on systems that focus on large scale systems include Astrolabe [13], BigTable [4] and Google's Spanner [5]. The Astrolabe system, designed for scalable data mining in very large data centers used a hierarchy of tables, and the BigTable platform used within Google brings table structured data to the file system. But none of these focus on low-latency scenarios.

Recently, there is a lot of work on systems using RDMA for scalable DHTs, such as Farm [6], Pilaf [10] and HERD [9]. These systems focus on the server-client model of computation, completely different than what we target with SST.

Thus, we believe that SST is unusual: by focusing on a pure sharing model, with the simplest possible lock-free sharing approach, and placing emphasis on raw speed and low latency, we create a genuinely new technology option. Indeed, the closest fit would probably be a technology like the MPI library [7], which supports barriers and shared memory backed by Infiniband. However, MPI is oriented towards HPC, and adopts a gang-scheduling model in which all the programs are replicas, with one designated as the leader and the others as workers, and is not able to adapt to add or drop new members.

7. CONCLUSIONS AND FUTURE WORK

Our paper introduces a simple shared state table implemented over RDMA, and demonstrates that the SST abstraction is a fast and convenient way to share system state on RDMA networks. We implement and compare two versions, one based on one-sided RDMA reads, the other on one-sided writes; the latter is found to scale better and involves fewer RDMA operations. Although designed for settings with uniform latency, experiments show that SST is very tolerant of routing delays.

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