Transparent Checkpoint-Restart over InfiniBand

Jiajun Cao,* Gregory Kerr,* Kapil Arya,* Gene Cooperman*

College of Computer and Information Science

Northeastern University

Boston, MA 02115 / USA

Email: jiajun@ccs.neu.edu, kerrgi@gmail.com, {kapil,gene}@ccs.neu.edu

Abstract

InfiniBand is widely used for low-latency, high-throughput cluster computing. Saving the state of the InfiniBand network as part of distributed checkpointing has been a long-standing challenge for researchers. Because of a lack of a solution, typical MPI implementations have included custom checkpoint-restart services that "tear down" the network, checkpoint each node as if the node were a standalone computer, and then re-connect the network again. We present the first example of transparent, system-initiated checkpoint-restart that directly supports InfiniBand. The new approach is independent of any particular Linux kernel, thus simplifying the current practice of using a kernel-based module, such as BLCR. This direct approach results in checkpoints that are found to be faster than with the use of a checkpoint-restart service. The generality of this approach is shown not only by checkpointing an MPI computation, but also a native UPC computation (Berkeley Unified Parallel C), which does not use MPI. Scalability is shown by checkpointing 2,048 MPI processes across 128 nodes (with 16 cores per node). In addition, a cost-effective debugging approach is also enabled, in which a checkpoint image from an InfiniBand-based production cluster is copied to a local Ethernet-based cluster, where it can be restarted and an interactive debugger can be attached to it. This work is based on a plugin that extends the DMTCP (Distributed MultiThreaded CheckPointing) checkpoint-restart package.

1 Introduction

InfiniBand is the preferred network for most of high performance computing and for certain Cloud applications, due to its low latency. We present a new approach to checkpointing over InfiniBand. This is the first efficient and transparent solution for *direct* checkpoint-restart over the InfiniBand network (without the intermediary of an MPI implementation-specific checkpoint-restart service). This also extends to other language implementations over InfiniBand, such as Unified Parallel C (UPC). This work contains several subtleties, such as whether to drain the "in-flight data" in an InfiniBand network prior to checkpoint, or whether to force a re-send of data after resume and restart. A particularly efficient solution was found, which combines the two approaches. The InfiniBand completion queue is drained and refilled on resume or restart, and yet data is never re-sent, *except* in the case of restart.

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Historically, transparent (system-initiated) checkpoint-restart has typically been the first technology that one examines in order to provide fault tolerance during long-running computations. For example, transparency implies that a checkpointing scheme works independently of the programming language being used (e.g., Fortran, C, or C++). In the case of distributed computations over Ethernet, several distributed checkpointing approaches have been proposed [7, 16, 21, 20, 26]. Unfortunately, those solutions do not extend to supporting the InfiniBand network. Other solutions for distributed checkpointing are specific to a particular MPI implementation [4, 11, 14, 15, 19, 22, 24, 25]. These MPI-based checkpoint-restart services "tear down" the InfiniBand connection, after which a single-process checkpoint-restart package can be applied.

Finally, checkpoint-restart is the process of saving to stable storage (such as disk or SSD) the state of the processes in a running computation, and later re-starting from stable storage. *Checkpoint* refers to saving the state, *resume* refers to the original process resuming computation, and *restart* refers to launching a new process that will restart from stable storage. The checkpoint-restart is *transparent* if no modification of the application is required. This is sometimes called *system-initiated* checkpointing.

Prior schemes specific to each MPI implementation had: (i) blocked the sending of new messages and waited until pending messages have been received; (ii) "torn down" the network connection; (iii) checkpointed each process in isolation (without the network), typically using the BLCR package [9, 13] based on a kernel module; (iv) and then re-builds the network connection. Those methods have three drawbacks:

- 1. Checkpoint-resume can be slower due to the need to tear down and re-connect the network.
- 2. PGAS languages such as UPC [10] must be re-factored to run over MPI instead of directly over InfiniBand in order to gain support for transparent checkpoint-restart. This can produce additional overhead.
- 3. The use of a BLCR kernel module implied that the restart cluster must use the same Linux kernel as the checkpoint cluster.

The current work is implemented as a plugin on top of DMTCP (Distributed MultiThreaded CheckPointing) [1]. The experimental evaluation demonstrates DMTCP-based checkpointing of Open MPI for the NAS LU benchmark and others. For 512 processes, checkpointing to a local disk drive, occurs in 232 seconds, whereas it requires 36 seconds when checkpointing to back-end Lustre-based storage. Checkpointing of up to 2,048 MPI processes (128 nodes with 16 cores per node) is shown to have a run-time overhead between 0.8% and 1.7%. This overhead is shown to be a little less than the overhead when using the checkpoint-restart of Open MPI using BLCR. Tests were also carried out on Berkeley UPC [5] over GASNet's ibv conduit [3], with similar results for checkpoint times and run-time overhead.

The new approach can also be extended to provide capabilities similar to the existing interconnectionagnostic use of the Open MPI checkpoint-restart service [14]. Specifically, we demonstrate an additional IB2TCP plugin that supports cost-effective use of a symbolic debugger (e.g., GDB) on a large production computation. The IB2TCP plugin enables checkpointing over InfiniBand and restarting over Ethernet. Thus, when a computation fails after on a production cluster (perhaps after hours or days), the checkpoint image can be copied to an inexpensive, smaller, Ethernet-based cluster for interactive debugging. An important contribution of the IB2TCP plugin, is that unlike the BLCR kernel-based approach, the DMTCP/IB2TCP approach supports using an Ethernet-based cluster that uses a different Linux kernel, something that occurs frequently in practice. Finally, the approach of using DMTCP plugins provides is easily maintainable, as measured by lines of code. The primary plugin, supporting checkpointing over InfiniBand, consists of 2,700 lines of code. The additional IB2TCP plugin consists of 1,000 lines of code.

Organization of Paper. The rest of this paper includes the background of DMTCP (Section 2. and the algorithm for checkpointing over InfiniBand (Section 3). Limitations of this approach are discussed in Section 4. An experimental evaluation is presented in Section 6. Section 6.4 is of particular note, in reporting on the IB2TCP plugin for migrating a computation from a production cluster to a debug cluster. Finally, the related work (Section 5) and conclusions (Section 8) are presented.

2 Background: InfiniBand and DMTCP

Section 2.1 reviews some concepts of InfiniBand, necessary for understanding the checkpointing approach described in Section 3. Section 2.2 describes the use of plugins in DMTCP.

2.1 Review of InfiniBand ibverbs API



Figure 1: InfiniBand Concepts

In order to understand the algorithm, we review some concepts from the Verbs API of Infini-Band. While there are several references that describe InfiniBand, we recommend one of [18, 2] as a gentle introduction for a general audience. Recall that the InfiniBand network uses *RDMA* (remote DMA to the RAM of a remote computer). Each computer node must have a Host Channel Adapter (HCA) board with access to the system bus (memory bus). With only two computer nodes, the HCA adapter boards may be connected directly to each other. With three or more nodes, communication must go through an InfiniBand switch in the middle. Note also that the bytes of an InfiniBand message may be delivered out of order.

Figure 1 reviews the basic elements of an InfiniBand network. A hardware host channel adapter (HCA) and the software library and driver together maintain at least one *queue pair* and a *completion queue* on each node. The queue pair consists of a send queue on one node and a receive queue on a second node. In a bidirectional connection, each node will contain both a send queue and a receive queue. Sending a message across a queue pair causes an entry to be added to the completion queue on each node. However, it is possible to set a flag when posting a work request to the send queue, such that no entry is added to the completion queue on the "send" side of the connection.

Although not explicitly introduced as a standard, libibverbs (provided by the Linux OFED distribution) is the most commonly used InfiniBand interface library. We will describe the model in terms of the functions prefixed by ibv_ for the *verbs library* (libibverbs). Many programs also use OFED's convenience functions, prefixed by rdma_*. OFED also provides an optional library, librdmacm (RDMA connection manager) for ease of connection set-up and tear-down in conjunction with the verbs interface. Since this applies only to set-up and tear-down, this library does not affect the ability to perform transparent checkpoint-restart.

We assume the reliable connection model (end-to-end context), which is by far the most commonly used model for InfiniBand. There are two models for the communication:

- Send-receive model
- RDMA (remote DMA) model (often employed for efficiency, and serving as the inspiration for the one-sided communication of the MPI-2 standard)

Our InfiniBand plugin supports both models, and a typical MPI implementation can be configured to use either model.

2.1.1 Send-Receive model of InfiniBand communication

We first describe the steps in processing the send-receive model for InfiniBand connection. It may be useful to examine Figure 1 while reading the steps below.

- 1. Initialize a hardware context, which causes a buffer in RAM to be allocated. All further operations are with respect to this hardware context.
- 2. Create a protection domain that sets the permissions to determine which computers may connect to it.
- 3. Register a memory region, which causes the virtual memory to be pinned to a physical address (so that the operating system will not page that memory in or out).
- 4. A completion queue is created for each of the sender and the receiver. This completion queue will be used later.

- 5. Create a queue pair (a send queue and a receive queue) associated with the completion queue.
- 6. An end-to-end connection is created between two queue pairs, with each queue pair associated with a port on an HCA adapter. The sender and receiver queue pair information (several ids) is exchanged, typically either using either TCP (through a side channel that is not non-InfiniBand), or by using an rdmacm library whose API is transport-neutral.
- 7. The receiver creates a work request and posts it to the receive queue. (One can post multiple receive buffers in advance.)
- 8. The sender creates one or more work requests and posts them to the send queue.
- 9. *NOTE:* The application must ensure that a receive buffer has been posted before it posts a work request to the send queue. It is an application error if this is not the case.
- 10. The transfer of data now takes place between a posted buffer on the send queue and a posted buffer on the receive queue. The posted send and receive buffers have now been used up, and further posts are required for further messages.
- 11. Upon completion, work completions are generated by the hardware and appended to each of the completion queues, one queue on the sender's node and one queue on the receiver's node.
- 12. The sender and receiver each poll the completion queue until a work completion is encountered. (A blocking request for work completion also exists as an alternative. A blocking request must be acknowledged on success.)
- 13. Polling causes the work completion to be removed from the completion queue. Hence, further polling will eventually see further completion events. Both blocking and non-blocking versions of the polling calls exist.

We also remark that a work request (a WQE or Work Queue Entry) points to a list of scatter/gather elements, so that the data of the message need not be contiguous.

2.1.2 RDMA model of InfiniBand communication

The RDMA model is similar to the send-receive model. However, in this case, one does not post receive buffers. The data is received directly in a memory region. An efficient implementation of MPI's one-sided communication (MPI_Put, MPI_Get, MPI_Accumulate), when implemented over InfiniBand, will typically employ the RDMA model [17].

As a consequence, Step 9 of Section 2.1.1 does not appear in the RDMA model. Similarly, Steps 11 and 12 are modified in the RDMA model to refer to completion and polling solely for the send end of the end-to-end connection.

Other variations exist, which are supported in our work, but not explicitly discussed here. In one example, an InfiniBand application may choose to send several messages without requesting a work completion in the completion queue. In these cases, an application-specific algorithm will follow this sequence with a message that includes a work completion. In a second example, an RDMA-based work request may request an immediate mode, in which the work completion is placed only in the remote completion queue and not in the local completion queue.

2.2 DMTCP and Plugins

DMTCP is a transparent, checkpoint-restart package that supports third-party plugins. The current work on InfiniBand support was implemented as a DMTCP plugin [8]. The plugin is used here to virtualize the InfiniBand resources exposed to the end user, such as the queue pair struct (ibv_qp) (see Figure 1). This is needed since upon restart from a checkpoint image, the plugin will need to create a new queue pair for communication. As a result, the InfiniBand driver will create a new queue pair struct at a new address in user space, with new ids.

Plugins provide three core features used here to support virtualization:

- 1. wrapper functions around functions of the InfiniBand library: these wrappers translate between virtual resources (see by the target application) and real resources (seen within the InfiniBand library, driver and hardware). The wrapper function also records changes to the queue pair and other resources for later replay during restart.
- 2. event hooks: these hooks are functions within the plugin that DMTCP will call at the time of checkpoint and restart. Hence, the plugin is notified at the time of checkpoint and restart, so as to update the virtual-to-real translations, to recreate the network connection upon restarting from a checkpoint image, and to replay some information from the logs.
- 3. a publish/subscribe facility: to exchange ids among plugins running on the different computer nodes whenever new device connections are created. Examples of such ids are local and remote queue pair numbers and remote keys of memory regions.

3 Algorithm

Figure 2 presents an overview of the virtualization of a queue pair. This is the most complex of the subsystems being checkpointed. In overview, observe that the DMTCP plugin library interposes between most calls from the target application to the InfiniBand ibverbs library. This allows the DMTCP InfiniBand plugin to intercept the creation of a queue pair by the InfiniBand kernel driver, and to create a shadow queue pair. The target application is passed a pointer only to the virtual queue pair created by the plugin. Thus, any further ibverbs calls to manipulate the queue pair will be intercepted by the plugin, and appropriate fields in the queue pair structure can be appropriately virtualized before the real ibverbs call.

Similarly, any ibverbs calls to post to the send or receive queue or to modify the queue pair are intercepted and saved in a log. This log is used for internal bookkeeping by the plugin, to appropriately model work requests as they evolve into the completion queue. In particular, note that a call to ibv_post_send may request that no work completion be entered on the completion queue.

3.1 The Checkpoint-Restart Algorithm

As the user base code makes calls to the verbs library, we will use DMTCP plugin wrapper functions around these library functions to interpose. Hence the user call goes first to our DMTCP plugin library. We then extract parameters describing how the resources were created, before passing on the call to the verbs library, and later passing back the return value. This allows us to recreate



Figure 2: Queue pair resources and their virtualization. (The plugin keeps a log of calls to post to or to modify the queue pair.)

semantically equivalent copies of those same resources on restart even if we restart on a new computer.

in particular, we record any calls to modify_qp and to modify_srq. On restart, those calls are replayed in order to place the corresponding data structures in a semantically equivalent state to pre-checkpoint.

While the description above appears simple, several subtleties arise, encapsulated in the following principles.

Principle 1: Never let the user see a pointer to the actual InfiniBand resource. A verbs call that creates a new InfiniBand resource will typically create a struct, and return a pointer to that struct. We will call this struct created by the verbs library a *real struct*. If the end user code create an InfiniBand resource, we interpose to copy that struct to a a new *shadow struct*, and then pass back to the end user the pointer to this shadow struct. Some examples of InfiniBand resources for which this is done are: a context, a protection domain, a memory region, and a queue pair.

The reason for this is that many implementations of InfiniBand libraries contain additional undocumented fields in these structs, in addition to those documented by the corresponding "man page". When we restart after checkpoint, we cannot pass the original pre-checkpoint struct to the verbs library. The undocumented (hidden) fields would not match the current state of the InfiniBand hardware on restart. (New device-dependent ids will be in use after restart.) So, on restart, we create an entirely new InfiniBand resource (using the same parameters as the original). This new struct should be semantically equivalent to the pre-checkpoint original, and the hidden fields will correspond to the post-restart state of the hardware.

One can think of this as a form of virtualization. The user is passed a pointer to a *virtual struct*, the shadow struct. The verbs library knows only about the *real struct*. So, we will guarantee that the verbs library only sees real structs, and that the end user code will only see virtual structs.

To do this, we interpose our DMTCP plugin library function if a verbs library function refers to one of these structs representing InfiniBand resources. If the end user calls a verbs library function that returns a pointer to a real struct, then our interposition will replace this and return a pointer to a corresponding virtual struct. If the user code passes an argument pointing to a virtual struct, we will replace it by a pointer to a real struct before calling the verbs library function.

Principle 2: Inline functions almost always operate through pointers to possibly devicedependent functions. Add wrappers around the pointers, and not the inline functions. The previous principle depends on wrapper functions that interpose in order to translate between real and virtual structs. But in the OFED ibverbs implementation, some of the apparent library calls to the verbs library are in fact inline functions. A DMTCP plugin cannot easily interpose on inline functions. Luckily, these inline functions are often associated with possibly device-dependent functions. So, the OFED software design expands the inline functions into calls to pointers to other functions. Those pointers can be found through the ops field of a struct ibv_context. The ops field is of type struct ibv_context_ops and contains the functions, which can then interpose and finally call the original function pointers created by the verbs library.

Principle 3: Carry out bookkeeping on posts of work queue entries to the send and receive queue. As work requests are entered onto a send queue or receive queue, the wrapper functions of the DMTCP plugin record those work requests (which have now become work queue entries). When the completion queue is polled, if a completion event corresponding to that work queue entry is found, then the DMTCP plugin records that the entry has been destroyed. At the time of checkpoint, there is a log of those work queue entries that have been posted and not yet destroyed. At the time of restart, the send and receive queues will initially be empty. So, those work queue entries are re-posted to their respective queues. (In the case of resume, the send and receive queues continue to hold their work queue entries, and so no special action is necessary.)

Principle 4: At the time of checkpoint, "drain" the completion queue of its completion events. At the time of checkpoint, and after all user threads have been quiesced, the checkpoint thread polls the completion queue for remaining completion events not yet seen by the end user code. A copy of each completion event seen is saved by the DMTCP plugin. Note that we must drain the completion queue for each of the sender and the receiver. Recall also that the verbs library function for polling the completion queue will also remove the polled completion event from the completion queue as it passes that event to the caller.

Principle 5: At the time of restart or resume, "refill" a virtual completion queue. At the time of restart or resume and before any user threads have been re-activated, we must somehow refill the completion queue, since the end user has not yet seen the completion events from the previous principle. To do this, the DMTCP plugin stores the completion events of the previous principle in its own private queue. The DMTCP plugin library then interposes between any end user calls to a completion queue and the corresponding verbs library function. If the end user polls the completion queue, the DMTCP wrapper function passes back to the end user the plugin's private copy of the completion events, and the verbs library function for polling is never called. Only after the private completion queue becomes empty are further polling calls passed on to the verbs library function. Hence, the plugin's private queue becomes part of a *virtual completion queue*.

Principle 6: Any InfiniBand messages still "in flight" can be ignored. If data from an InfiniBand message is still in flight (has not yet arrived in the receive buffer), then InfiniBand will not generate a completion event. Note that the InfiniBand hardware may continue to transport the data of a message, and even generate a completion event *after all user threads have been quiesced for checkpoint*. Nevertheless, a simple rule operates.

If our checkpoint thread has not seen a completion event that arrived late, then we will not have polled for that completion event. Therefore, our bookkeeping in Principle 3 will not have removed the send or receive post from our log. Further, this implies that the memory buffers will continue to have the complete data, since it was saved on checkpoint and restored on restart. Therefore, upon restart (which implies a fresh, empty completion queue), the checkpoint thread will issue another send or receive post (again following the logic of Principle 3).

Remark. Blocking requests for a completion event (ibv_get_cq_event) and for shared receive queues create further issues. While those details add some complication, their solution is straightforward and is not covered here.

3.2 Virtualization of InfiniBand Ids on Restart

A number of InfiniBand objects and associated ids will change on restart. All of these must be virtualized. Among these objects and ids are ibv contexts, protection domains, memory regions (the local and remote keys (lkey/rkey) of the memory regions), completion queues, queue pairs (the queue pair number, qp_num), and the local id of the HCA port being used (lid). Note that the lid of an HCA port will not change if restarting on the same host, but it may change needed when restarting on a new host, which may have been configured to use a different port.

In all of the above cases, the plugin assigns a virtual id and maintains a translation table between virtual and real id. The application sees only the virtual id. Any InfiniBand calls are processed through the plugin, where virtual ids are translated back to real ids.

On restart, the InfiniBand hardware may assign new real ids for a given InfiniBand object. In this case, the real ids are updated within the translation tables maintained by the plugin.

3.2.1 Virtualization of remote ids: rkey, qp_num and lid

However, a more difficult issue occurs in the case of remote memory keys (rkey), queue pair numbers (qp_num) and local ids (lid). In all three cases, an InfiniBand application must pass these ids to a remote node for communication with the local node. The remote need will need the qp_num and lid when calling ibv_modify_qp to initialize a queue pair that connects to the local node. The remote node will need the rkey when calling ibv_post_send to send a message to the local node.

Since the plugin allows the application to see only virtual ids, the application will employ a virtual id when calling ibv_modify_qp and ibv_post_send. The plugin will first replace the virtual id by the real id, which is known to the InfiniBand hardware. To do this, the plugin within each remote node must contain a virtualization table to translate all virtual ids by real ids.

Next, we recall how a remote node received a virtual id in the first place. The InfiniBand specification solves this bootstrapping problem by requiring the application to pass these three ids to the remote node through some out-of-band mechanism. When the application employs this out-of-band mechanism, the remote node will "see" the virtual ids that the plugin passed back to the application upon completion of an InfiniBand call.

The solution chosen for the InfiniBand plugin is that assigns a virtual id, which is the same as the real id at the time of the initial creation of the InfiniBand object. After restart, the InfiniBand hardware may change the real id. At the time of restart, the plugin uses the DMTCP coordinator and the publish-subscribe feature to exchange the new real ids, associated with a given virtual id. Since the application continues to see only the virtual ids, the plugin can continue to translate between virtual and real ids through any wrapper by which the application communicates to the InfiniBand hardware (see Figure 2. (A subtle issue can arise if a queue pair or memory region is created after restart. This is a rare case. Although we have not seen this in the current work, Section 4 discusses two possible solutions.)

3.2.2 Virtualization of rkeys

Next, the case of rkeys (remote memory region keys) poses a particular problem that does not occur for queue pair numbers or local ids. This is because an rkey is guaranteed unique by InfiniBand only with respect to the protection domain within which it was created. Thus, if a single InfiniBand node has received rkeys from many remote nodes, then the rkeys for two different remote nodes may conflict.

Normally, InfiniBand can resolve this conflict because a queue pair must be specified in order to send or receive a message. The local queue pair number determines a unique queue pair number on the remote node. The remote queue pair number then uniquely determines an associated protection domain pd. With the remote pd, all rkeys are unique. Hence, the InfiniBand driver on the remote node uses the (pd, rkey) pair, to determine a unique memory address on the remote node.

In the case of the InfiniBand plugin, the vrkey and rkey are identical if no restart has taken place. (It is only after restart that the rkey may change, for a given vrkey). Hence, prior to the first checkpoint, translation from vrkey to rkey is trivial.

After a restart, the InfiniBand plugin must employ a strategy motivated by that of the Infini-Band driver. In a call to ibv_post_send , the target application will provide both a virtual queue pair number and a virtual rkey (vrkey). Unlike InfiniBand, the plugin must translate the vrkey into the real rkey on the local node. However, during a restart, each node has published its locally generated rkey, the corresponding pd (as a globally unique id; see above), and the corresponding vrkey. Similarly, each node has published the virtual queue pair number and corresponding pd for any queue pair generated on that node. Each node has also subscribed to the above information published by all other nodes.

Hence, the local node is aware of the following through publish-subscribe during restart:

(qp_num, pd) (vkey, pd, rkey) The call to ibv_post_send provided the local virtual qp_num, and the vrkey. This allows us to translate into the remote virtual qp_num, and hence the remote real qp_num. This allows us to derive the globally unique pd from the tuples above. The pd and vkey together then allow us to use the second tuple to derive the necessary rkey, to be used when calling the InfiniBand hardware.

4 Limitations

Recall that DMTCP copies and restores all of user-space memory. In reviewing Figure 2, one notes that the user-space memory includes a low-level device-dependent driver in user space. If, for example, one checkpoints on a cluster partition using Intel/QLogic, and if one restarts on a Mellanox partition, then the Mellanox low-level driver will be missing. This presents a restriction for heterogeneous computing centers in the current implementation.

In future work, we will consider one of two alternative implementations. First, it is possible to implement a generic "stub" driver library, which can then dispatch to the appropriate devicedependent library. Second, it is possible to force the InfiniBand library to re-initialize itself by restoring the pre-initialization version of the InfiniBand library data segment, instead of the data segment as it existed just prior to checkpoint. This will cause the InfiniBand library to appear to be uninitialized, and it will re-load the appropriate device-dependent library.

Another issue is that the InfiniBand hardware may post completions to the sender and receiver at slightly different times. Thus, after draining the completion queue, the plugin waits for a fraction of a second, and then drains the completion queue one more time. This is repeated until no completions are seen in the latest period. Thus, correctness is affected only if the InfiniBand hardware posts corresponding completions relatively far apart in time, which is highly unlikely. (Note that this situation occurs in two cases: InfiniBand send-receive mode; and InfiniBand RDMA mode for the special case of ibv_post_send while setting the immediate data flag.)

In a related issue, when using the immediate data flag or the inline flag in the RDMA model, a completion is posted only on the receiving node. These flags are intended primarily for applications that send small messages. Hence, the current implementation sleeps for a small amount of time to ensure that such messages complete. A future implementation will use the DMTCP coordinator to complete the bookkeeping concerning messages sent and received, and will continue to wait if needed.

Next, the current implementation does not support unreliable connections (the analog of UDP for TCP/IP). Most target applications do not use this mode, and so this is not considered a priority.

A small memory leak on the order of hundreds of bytes per restart can occur because the memory for the queue pair struct and other data structures generated by by InfiniBand driver are not recovered. While techniques exist to correct this issue, it is not considered important, given the small amount of memory. (Note that this is not an issue for registered or pinned memory, since on restart, a fresh process does not have any pinned memory.)

5 Related Work

The implementation described here can be viewed as interposing a shadow device driver between the end user's code and the true device driver. This provides an opportunity to virtualize the fields of the queue pair struct seen by the end user code. Thus, the InfiniBand driver is modelled without the need to understand its internals. This is analogous the idea of using a shadow kernel device by Swift et al. [27, 28]. In that work, after a catastrophic failure by the kernel device driver, the shadow device driver was able to take over and place the true device driver back in a sane state. In a similar manner, restarting on a new host with a new HCA Adapter can be viewed as a catastrophic failure of the InfiniBand user-space library. Our virtual queue pair along with the log of pending posts and modifications to the queue pair serves as a type of shadow device driver. This allows us to place back into a sane state the HCA hardware, the kernel driver and the device-dependent user-space driver.

This work is based on DMTCP (Distributed MultiThreaded CheckPointing) [1]. The DMTCP project began in 2004 [6, 7]. With the development of DMTCP versions 2.x, it has emphasized the use of plugins [8] for more modular maintainable code.

Currently, BLCR [13] is widely used as one component of an MPI dialect-specific checkpointrestart service. This design is fundamentally different, since an MPI-specific checkpoint-restart service calls BLCR, whereas DMTCP transparently invokes an arbitrary MPI implementation. Since BLCR is kernel-based, it provides direct support only on one computer node. Most MPI dialects overcome this in their checkpoint-restart service by disconnecting any network connections, delegating to BLCR the task of a single-node checkpoint, and then reconnect the network connection. Among the MPI implementations using BLCR are Open MPI [15] (CRCP coordination protocol), LAM/MPI [24], MPICH-V [4], and MVAPICH2 [11]. Other MPI implementations provide their own analogs [11, 22, 24, 25]. In some cases, an MPI implementation may support an *application-initiated* protocol in combination with BLCR (such as SELF [15, 24]). For applicationinitiated checkpointing, the application writer guarantees that there are no active messages at the time of calling for a checkpoint.

Some recommended technical reports for further reading on the design of InfiniBand are [2, 18], along with the earlier introduction to the C API [29]. The report [18] was a direct result of the original search for a clean design in checkpointing over InfiniBand, and [19] represents a talk on interim progress.

In addition to DMTCP, there have been several packages for transparent, distributed checkpointrestart of applications running over TCP sockets [16, 20, 21, 26]. The first two packages ([16] and [21, 20]) are based on the Zap package [23].

The Berkeley language Unified Parallel C (UPC) [10] is an example of a PGAS language (Partitioned Global Address Space). It runs over GASNet [3] and evolved from experience with earlier languages for DSM (Distributed Shared Memory).

6 Experimental Evaluation

The experiments are divided into four parts: scalability with more nodes in the case of Open MPI (Section 6.1); comparison between BLCR and DMTCP for MPI-based computations (Section 6.2); tests on Unified Parallel C (UPC) (Section 6.3); and demonstration of migration from InfiniBand to TCP (Section 6.4).

The LU benchmark from the NAS parallel benchmarks was used except for tests on UPC, for which there was no available port of the NAS LU benchmark.

Note that the default behavior of DMTCP is to compress checkpoint images using gzip. All of the experiments used the default gzip invocation, unless otherwise noted. As shown in Section 6.1, gzip produced almost no additional compression, but it is also true that the additional CPU time in running gzip was less than 5% of the checkpoint and restart times. For DMTCP, all checkpoints are to a local disk (local to the given computer node), except as noted. Open MPI/BLCR checkpointing invokes an additional step to copy all checkpoint images to a single, central node.

Experimental Configuration. Two clusters were employed for the experiments described here. Sections 6.2 and 6.3 refer to a cluster at the Center for Computational Research at the University of Buffalo. It uses SLURM as its resource manager, and a common NFS-mounted filesystem. Each node is equipped with either a Mellanox or QLogic (now Intel) HCA, although a given partition under which an experiment was run was always homogeneous (either all Mellanox or all QLogic). The operating system is RedHat Enterprise Linux 6.1 with Linux kernel version 2.6.32.

Experiments were run using one core per computer. Hence, the MPI rank was equal to the number of computers, and so MPI processes were on separate computer nodes. Since the memory per node was not fixed, we set the memory limit per CPU to 3 GB. Each CPU has a clock rate ranging from 2.13 GHz to 2.40 GHz, and the specific CPUs can vary.

In terms of software, we used Open MPI 1.6, DMTCP 2.1 (or a pre-release version in some cases), Berkeley UPC 2.16.2, and BLCR 0.8.3, respectively. Open MPI was run in its default mode, which typically used the RDMA model for InfiniBand, rather than the send-receive model. Although, DMTCP version 2.1 was used, the plugin included some additional bug fixes appearing after that DMTCP release. For the applications, we used Berkeley UPC (Unified Parallel C) version 2.18.0. The NAS Parallel Benchmark was version 3.1.

Tests of BLCR under Open MPI were run by using the Open MPI checkpoint-restart service [14]. Tests of DMTCP for Open MPI did not use the checkpoint-restart service. Under both DMTCP and BLCR, each node produced a checkpoint image file in a local, per-node scratch partition. However, the time reported for BLCR includes the time to copy all checkpoint images to a single node, preventing a direct comparison.

In the case of BLCR, the current Open MPI checkpoint-restart service copies each local checkpointimage to a central coordinator process. Unfortunately, this serializes part of the parallel checkpoint. Hence, checkpoint times for BLCR are not directly comparable to those for DMTCP.

In the case of DMTCP, all tests were run using the DMTCP default parameters, which include dynamic gzip compression. Gzip compression results in little compression for numerical data, and increases the checkpoint time several fold. Further, DMTCP is checkpointing to a local "tmp" directory on each node. BLCR checkpoints to a local "tmp" directory, and then the Open MPI service copies them to a central node that saves them in a different "tmp" directory.

6.1 Scalability of InfiniBand Plugin

Scalability tests for the DMTCP plugin are presented, using Open MPI as the vehicle for these tests. All tests in this section were run at the Massachusetts Green High-Performance Computing Center (MGHPCC). Intel Xeon E5-2650 CPUs running at 2 GHz. Each node is dual-CPU, for a total of 16 cores per node. It employs Mellanox HCA adapters. In addition to the front-end InfiniBand network, there is a Lustre back-end network. All checkpoints are written to a local disk, except for a comparison with Lustre, described later in Table 4.

Table 1 presents a study of scalability for the InfiniBand plugin. The NAS MPI test for LU is mmployed. For a given number of processes, each of classes C, D, and E are tested provided that the running time for the test is of reasonable length. The overhead when using DMTCP is analyzed further in Table 2.

NAS	Num. of	Runtime (s)	Runtime (s)
benchmark	processes	(natively)	(w/DMTCP)
LU.C	64	18.5	21.7
LU.C	128	11.5	16.1
LU.C	256	7.7	12.8
LU.C	512	6.6	11.9
LU.C	1024	6.2	13.0
LU.D	64	292.6	298.0
LU.D	128	154.9	161.6
LU.D	256	89.0	94.8
LU.D	512	53.2	61.3
LU.D	1024	30.5	39.6
LU.D	2048	26.9	40.3
LU.E	512	677.2	691.6
LU.E	1024	351.6	364.9
LU.E	2048	239.3	256.4

Table 1: Demonstration of scalability: running times without DMTCP (natively) and with DMTCP

In Table 2, the overhead derived from Table 1 is decomposed into two components: startup overhead and runtime overhead. Given a NAS parallel benchmark, the total overhead is the difference of the runtime with DMTCP and the the native runtime (without DMTCP). Consider a fixed number of processes on which two different classes of the same benchmark are run. For example, given the native runtimes for two different classes of the LU benchmark (e.g., t_1 for LU.C and t_2 for LU.D), and the total overhead in each case (o_1 and o_2), one can derive an assumed startup overhead s in seconds and runtime overhead ratio r, based on the formulas:

$$o_1 = s + rn_1$$
$$o_2 = s + rn_2$$

# processes	NAS	Startup	Slope (runtime
(running LU)	classes	overhead (s)	overhead in $\%$)
64	C, D	3.1	0.8
128	C, D	4.4	1.5
256	C, D	5.0	0.9
512	D, E	7.6	1.0
1024	D, E	8.7	1.3
2048	D, E	12.9	1.7

Table 2: Analysis of Table 1 showing derived breakdown of DMTCP overhead into startup overhead and runtime overhead. (See analysis in text.)

Table 2 reports the derived startup overhead and runtime overhead using the formula above. In cases where three classes of the NAS LU benchmark were run for the same number of nodes, the largest two classes were chosen for analysis. This decision was made to ensure that any timing perturbations in the experiment would be a small percentage of the native runtimes.

The runtime overhead shown in Table 2 remains in a narrow range of 0.8% to 1.7%. The startup overhead grows as the cube root of the number of MPI processes.

Table 3 below shows the effects on checkpoint time and checkpoint image size under several configurations. Note that the first three tests hold constant the number of MPI processes at 512. In this situation, the checkpoint size remains constant (to within the natural variability of repeated runs). Further, in all cases, the checkpoint time is roughly proportional to the total size of the checkpoint images on a single node. A checkpoint time of between 20 MB/s and 27 MB/s was achieved in writing to local disk, with the faster times occurring for 16 processes per node (on 16 core nodes).

NAS	Number of	Ckpt	Ckpt
benchmark	processes	time (s)	size (MB)
LU.E	128×4	70.8	350
LU.E	64×8	136.6	356
LU.E	32×16	222.6	355
LU.E	128×16	70.2	117

Table 3: Checkpoint times and image sizes for the same NAS benchmark, under different configurations. The checkpoint image size is for a single MPI process.

Next, a test was run to compare checkpoint times when using the Lustre back-end storage versus the default checkpoint to a local disk. As expected, Lustre was faster. Specifically, Table 4 shows that checkpoint times were 6.5 times faster with Lustre, although restart times were essentially unchanged. Small differences in checkpoint image sizes and checkpoint times are part of normal variation between runs, and was always limited to less than 5%.

Disk type	Ckpt	Ckpt	Restart	
	size (MB)	time (s)	time (MB)	
local disk	356	232.3	11.1	
Lustre	365	35.7	10.9	

Table 4: Comparison with checkpoints to local disk or Lustre back-end. Each case was run for NAS LU (class E), and 512 processes (32 nodes \times 16 cores per node). Each node was writing approximately $16 \times 360 = 5.76$ GB of checkpoint images.

Finally, a test was run in which DMTCP was configured not to use its default gzip compression. Table 5, below, shows that this makes little difference both for the checkpoint image size and the checkpoint time. The checkpoint time is about 5% faster when gzip is not invoked.

6.2 Comparison between DMTCP and BLCR

Table 6, below, shows the overall performance of DMTCP and BLCR. We chose Open MPI and the NAS Parallel Benchmarks for a test of performance across a broad test suite. For the sake of comparability with previous tests on the checkpoint-restart service of Open MPI [14], we include

Program and	Ckpt	Ckpt	Restart
processes	size (MB)	time (s)	time (MB)
with gzip	117	70.2	23.5
w/o gzip	116	67.3	23.2

Table 5: Comparison of checkpointing with and without the use of gzip for on-the-fly compression by DMTCP.

the previously used NAS tests: LU C, EP D, BT C and SP C. An analysis of the performance must consider both runtime overhead and times for checkpoint and restart.

Runtime overhead. The runtime overhead is the overhead for running a program under a checkpoint-restart package as compared to running natively. No checkpoints are taken when measuring runtime overhead. Table 6 shows that neither DMTCP nor BLCR has significant runtime overhead. For longer running program the runtime overhead is in the range of 1% to 2%. A typical runtime overhead is in the range of 1 to 5 seconds, with 3 seconds being common. Since these overhead times do not correlate with the length of time during which the program was run, we posit that they reflect a constant overhead that is incurred primarily at the time of for program startup.

Checkpoint/Restart times. Table 6 also shows checkpoint and restart times. These times are as reported by a central DMTCP coordinator, or an Open MPI coordinator in the case of BLCR.

Note that the restart time for DMTCP was typically under 4 seconds, even for larger computations using 64 computer nodes. The BLCR package did not report restart times.

Checkpoint times are particularly important for issues of fault tolerance, since checkpoints are by far the more common operation. Surprisingly, the checkpoint time for DMTCP falls with an

NAS	Number of	Runtime (s)	Runtime (s)	Runtime (s)	DMTCP	BLCR	DMTCP
benchmark	processes	natively	with DMTCP	with BLCR	Ckpt (s)	Ckpt (s)	Restart (s)
	8	224.7	229.0	240.9	7.6	16.8	2.3
LU C	16	116.0	117.5	118.7	5.2	16.8	2.3
	32	61.0	64.2	64.8	3.8	16.2	2.1
	64	32.3	35.4	34.0	2.6	20.6	2.1
	8	885.3	886.2	887.9	1.2	3.1	0.8
EP D	16	442.3	447.2	448.3	1.3	3.4	1.2
	32	223.2	225.4	227.6	1.4	4.7	3.3
	64	115.9	118.2	122.0	1.6	8.2	1.8
	9	224.3	227.9	227.4	13.3	26.9	3.9
	16	137.8	138.4	137.8	9.1	24.2	4.0
BT C	25	79.3	79.7	81.2	6.4	25.5	3.6
	36	57.3	58.7	59.1	5.4	29.2	2.2
	64	31.3	32.3	33.6	3.9	33.8	2.3
	9	234.5	238.3	238.0	10.3	23.6	4.0
	16	132.5	133.1	133.3	6.8	21.1	3.7
SP C	25	77.8	80.1	79.0	5.8	22.4	1.9
	36	55.7	57.3	58.7	4.8	25.8	2.0
	64	33.4	33.7	31.1	3.1	34.1	2.2

Table 6: Comparison of running natively or with DMTCP or BLCR. Runtime overheads and checkpoint-restart times are shown. (However, BLCR does not report statistics for restart times.) Note that for the BT and SP tests, they require a number of nodes that is a square of an integer.

increasing number of nodes (except in the case of EP: *Embarrassingly Parallel*), while the checkpoint time for BLCR increases slowly with an increasing number of nodes.

For DMTCP, checkpoint times are smaller with an increasing number of nodes because the NAS benchmarks leave fixed the total amount of work. Thus, twice as many nodes implies half as much work. In the case of most of the NAS benchmarks, the reduced work per node seems to imply a reduced checkpoint image size (except for EP: *Embarrassingly Parallel*). This accounts for the faster checkpoint times as the number of nodes increases.

In contrast, the checkpoint-restart service of Open MPI, the times for checkpointing with Open MPI/BLCR are often roughly constant. We estimate this time is dominated by the last phase, in which Open MPI copies the local checkpoint images to a single, central node.

6.3 Checkpointing under UPC: a non-MPI Case Study

In our study of Berkeley UPC, is based on a port of the NAS parallel benchmarks at George Washington University [12]. Since that did not include a port of the LU benchmark, we switch to considering FT in this example.

We compiled the Berkeley UPC package to run natively over InfiniBand, so that it did not use MPI. We chose to test on the FT B NAS benchmark, as ported to run on UPC. The FT benchmark was used because that port does not support the more communication-intensive LU benchmark. Table 7 shows that the native runtimes for FT B under UPC are compared to the time for MPI in Table 6. DMTCP total run-time overhead ranges from 4% down to less than 1%. We posit that the higher overhead of 4% is due to the extremely short running time in the case of 16 processes, and is explained by significant startup overhead, consistent with Table 2.

Note that BLCR could not be tested in this regime, since BLCR depends on the Open MPI checkpoint-restart service for its use in distributed computations.

Number of	Runtime	Runtime w/	Ckpt	Restart
processes	natively (s)	DMTCP (s)	(s)	(s)
4	123.5	124.2	27.6	9.7
8	64.2	65.1	21.9	8.9
16	34.2	35.5	16.3	7.0

Table 7: Runtime overhead and Checkpoint-restart times for UPC FT B running under DMTCP

6.4 Migrating from InfiniBand to TCP sockets

Some traditional checkpoint-restart services, such as that for Open MPI [14], offer the ability to checkpoint over one network, and restart on a second network. This is especially useful for interactive debugging. A set of checkpoint images from an InfiniBand-based production cluster can be copied to an Ethernet/TCP-based debug cluster. Thus, if a bug is encountered after running for hours on the production cluster, the most recent checkpoints can be used to restart on the debug cluster under a symbolic debugger, such as GDB. The approach of this paper offers the added feature that the Linux kernel on the debug cluster does not have to be the same as on the production cluster.

6.4.1 IB2TCP: Ping-pong

We tested the IB2TCP plugin with a communication intensive ping-pong example InfiniBand program from the OFED distribution. In this case, a smaller development cluster was used, with 6-core Xeon X5650 CPUs and a Mellanox HCA for InfiniBand. Gigabit Ethernet was used for the Ethernet portion. Parameters were set to run over 100,000 iterations.

Environment	Transfer	Transfer rate
	time (s)	(Gigabits/s)
IB (w/o DMTCP)	0.9	7.2
DMTCP/IB (w/o IB2TCP)	1.2	5.7
DMTCP/IB2TCP/IB	1.4	4.6
DMTCP/IB2TCP/Ethernet	65.7	0.1

Table 8: Transfer time variations when using two nodes on InfiniBand versus Gigabit Ethernet hardware, as affected by the DMTCP InfiniBand plugin and the IB2TCP plugin; 100,000 iterations of ping-pong, for a total transfer size of 819 MB

Table 8 presents the results. These results represent a worst case, since a typical MPI program is not as communication-intensive as the ping-ping test program. The times with IB2TCP were further degraded due to the current implementation's use of an in-memory copy. We hypothesize that the transfer rate under Gigabit Ethernet was also limited by the speed of the kernel implementation.

6.4.2 IB2TCP: NAS LU.A.2 Benchmark

Next, a preliminary test of IB2TCP for Open MPI, on only two nodes, is presented. This test was conducted on the the MGHPCC cluster, as described in Section 6.1.

Table 9 shows various times for NAS LU.A.2 benchmark for migrating from InfiniBand to Ethernet using the IB2TCP plugin. As can be seen, the InfiniBand and IB2TCP plugin do not add any considerable overhead to the run time of the application. However, when the process is migrated from InfiniBand to Ethernet, the runtime increases drastically. A runtime overhead of 67% is seen when the computation is restarted on two nodes. The runtime overhead further increases to 142% when the entire computation is restarted on a single node.

Environment	RunTime (s)
IB (w/o DMTCP)	26.61
DMTCP/IB (w/o IB2TCP)	27.81
DMTCP/IB2TCP/IB	27.38
DMTCP/IB2TCP/Ethernet	45.75
(restart on two nodes)	
DMTCP/IB2TCP/Ethernet	66.34
(restart on a single node)	

Table 9: Runtime variations for LU.A.2 benchmark when using two nodes on InfiniBand versus Gigabit Ethernet hardware, as affected by the DMTCP InfiniBand plugin and the IB2TCP plugin. The runtime does not involve the checkpoint and restart times.

7 Future Work

The current work supports only a homogeneous InfiniBand architecture. For example, one cannot checkpoint on a node using an Intel/Qlogic HCA and restart on a different node that uses a Mellanox HCA. This is because the checkpoint image already includes a low-level library to support a particular HCA. Future work will extend this implementation to support heterogeneous InfiniBand architectures by re-loading the low-level library, as described in Section 4.

Further, the experimental timings reported here did not employ any particular tuning techniques. There are opportunities to reduce the run-time overhead by reducing the copying of buffers.

Avoiding conflict of virtual ids after restart: In typical MPI implementations memory region keys (rkey), queue pair numbers (qp_num), and local ids (lid) are all exchanged out-of-band. Since virtualized ids are passed to the target application, it is the virtualized ids that are passed out-of-band. The remote plugin is then responsible for translating the virtual ids to the real ids known to the InfiniBand hardware, on succeeding InfiniBand calls.

The current implementation ensures that this is possible, and that there are no conflicts prior to the first checkpoint, as described in Section 3.2. In typical InfiniBand applications, queue pairs are created only during startup, and so all rkeys, qp_nums and lids will be assigned prior to the first checkpoint. However, it is theoretically possible for an application to create a new queue pair, memory region, or to query its local id after the first restart.

The current implementation assigns the virtual id to be the same as the real id at the time of the initial creation of the InfiniBand object. (After restart, the InfiniBand hardware may assign a different real id, but the virtual id for that object will remain the same.) If an object is created after restart, the real id assigned by InfiniBand may be the same as for an object created prior to checkpoint. This would create a conflict of the corresponding virtual ids.

Two solutions to this problem are possible. The simplest is to use DMTCP's publish-subscribe feature to generate globally unique virtual rkeys, and update a global table of virtual-to-real rkeys. In particular, one could use the existing implementation before the first checkpoint, and then switch to a publish-subscribe implementation after restart. A second solution is to choose the virtual rkeys in a globally unique manner, similarly to the globally unique protection domain ids of the current plugin.

8 Conclusion

A new approach to distributed transparent checkpoint-restart over InfiniBand has been demonstrated. This direct approach accommodates computations both for MPI and for UPC (Unified Parallel C). The approach uses a mechanism similar to that of a shadow device driver [27, 28]. In tests on the NAS LU parallel benchmark, a run-time overhead of between 0.7% and 1.9% is found on a computation with up to 2,048 MPI processes. Startup overhead is up to 13 seconds, and grows as the cube root of the number of MPI processes. Checkpoint times are roughly proportional to the total size of all checkpoint images on a single computer node. In one example, checkpoint times varied by a factor of 6.5 (from 232 seconds to 36 seconds), depending on whether checkpoint images were written to a local disk or to a faster, Lustre-based back-end. In each case, 16 MPI processes per node (512 processes in all) wrote a total of approximately 5.8 GB per node. Further, the new approach provides a viable checkpoint-restart mechanism for running UPC natively over InfiniBand — something that previously did not exist. finally, an IB2TCP plugin was demonstrated that allows users to checkpoint a computation on a production cluster under InfiniBand, and to restart on a smaller debug cluster under Ethernet — in a manner suitable for attaching an interactive debugger. This mode is analogous to the interconnection-agnostic feature of the Open MPI checkpoint restart service [14], but it has an added benefit in that the production cluster and the debug cluster do not have to have the same Linux kernel image.

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