TardiS: Migrating Containers with RDMA Networks

Maksym Planeta
TU Dresden

Jan Bierbaum
TU Dresden

Leo Sahaya Daphne Antony
AMOLF

Torsten Hoefler
ETH Zürich

Hermann Härting
TU Dresden

Abstract

Major data centre providers are introducing RDMA-based networks for their tenants, as well as for operating their underlying infrastructure. In comparison to traditional socket-based network stacks, RDMA-based networks offer higher throughput, lower latency, and reduced CPU overhead. However, RDMA networks make transparent checkpoint and migration operations much more difficult. The difficulties arise because RDMA network architectures remove the OS from the critical path of communication. As a result, the OS loses control over active RDMA network connections, required for live migration of RDMA-applications. This paper presents TardiS, an OS-level architecture for transparent live migration of RDMA-applications. TardiS offers changes at the OS software level and small changes to the RDMA communication protocol. As a proof of concept, we integrate the proposed changes into SoftRoCE, an open-source kernel-level implementation of an RDMA communication protocol. We designed these changes to introduce no runtime overhead, apart from the actual migration costs. TardiS allows seamless live migration of applications in data centre settings. It also allows HPC clusters to explore new scheduling strategies, which currently do not consider migration as an option to reallocate the resources.

1. Introduction

Cloud computing is undergoing a phase of rapidly increasing network performance. This trend implies higher requirements on the data and packet processing rate and results in the adoption of high-performance network stacks. RDMA network architectures address this demand by offloading packet processing onto specialised circuitry of the network interface controllers (RDMA NICs). These RDMA NICs process packets much faster than CPUs. User applications communicate directly with the NICs to send and receive messages using specialised RDMA-APIs, like IB verbs. This direct access minimises network latency, which made RDMA networks ubiquitous in HPC and increasingly more accustomed in the data centre context. As a result, major data centre providers already offer RDMA connectivity for the end-users.

Similarly, containers have also become ubiquitous for lightweight virtualisation in data centre settings. Containerised applications do not depend on the software stack of the host, thus greatly simplifying distributed application deployment and administration. However, RDMA networks and containerisation come at odds, when employed together: The former try to bring applications and underlying hardware “closer” to each other, whereas the latter facilitates the opposite. This paper, in particular, addresses the issue of migratability of containerised RDMA-applications through OS-level techniques.

The ability to live-migrate applications has long been available for virtual machines (VMs) and is widely appreciated in cloud computing. We

1IB verbs is the most common low-level API for RDMA networks.
expect live migration to become even more popular with the growth of disaggregated [25, 52], serverless [22], and fog computing [60]. In contrast to VMs, containerised applications share the kernel, and thus their state, with the host system. In general, it is still possible to extract the relevant container state from the kernel and restore it on another host later on. This recoverable state includes open TCP connections, shell sessions, file locks [9, 41]. However, the state of RDMA communication channels is not recoverable by existing systems, and hence applications using RDMA cannot be checkpointed or migrated.

To outline the conceptual difficulties involved in saving the state of RDMA communication channels, we compare a traditional TCP/IP-based network stack and the IB verbs API (see Figure 1). First, with a traditional network stack, the kernel fully controls when the communication happens: applications need to perform system calls to send or receive a message. In IB verbs, because of direct communication between the NIC and the application, the OS has no communication interception points, except of tearing down the connection. Although the OS can stop a process from sending further messages, the NIC may still silently change the application state. Second, part of the connection state resides at the NIC and is inaccessible for the OS. Creating a consistent checkpoint is impossible in this situation.

In this paper, we propose TardiS, an architecture enabling transparent live migration of containerised RDMA-applications on the OS level. We identify the missing hardware capabilities of existing RDMA-enabled NICs required for transparent live migration. We augment the underlying RoCEv2 communication protocol to update the physical addresses of a migrated container transparently. We modify a software RoCEv2-implementation to show that the required protocol changes are small and do not affect the critical path of the communication. Finally, we demonstrate an end-to-end live migration flow of containerised RDMA-applications.

2 Background

This section gives a short introduction to containerisation and RDMA networking. We further outline live migration and how RDMA networking obstructs this process.

2.1 Containers

In Linux, processes and process trees can be logically separated from the rest of the system using namespace isolation. Using namespaces, allows process creation with an isolated view on the file system, network devices, users, etc. Container runtimes leverage namespaces and other low-level kernel mechanisms [3, 51] to create a complete system view without external dependencies. Considering their close relation, we use the terms container and process interchangeably in this paper. A distributed application may comprise multiple containers across a network: a Spark application, for example, can run the master and each worker in an isolated container and an MPI [28] application can containerise each rank.

2.2 Infiniband verbs

The IB verbs API is today’s de-facto standard for high-performance RDMA communication. It enables applications to achieve high throughput and low latency by accessing the NIC directly (OS-bypass), avoiding unnecessary memory movement (zero-copy), and delegating packet processing to the NIC (offloading).

Figure 2 shows the following IB verbs objects involved in communication. Memory regions (MRs) represent pinned memory shared between the application and the NIC. Queue pairs (QPs), comprising a send queue (SQ) and a receive (RQ) queue, represent connections. To reduce memory footprint, multiple QPs can replace multiple individual RQs with use a single shared receive queue (SRQ). Completion queues (CQs) inform the application about completed communication requests. A protection domain (PD) groups all these IB verbs objects together and represents the process address space to the NIC.

To establish a connection, an application needs to exchange the following addressing information: Memory protection keys to enable access to remote MRs, the global vendor-assigned address (GUID), the routable address (GID), the non-routable address (LID), and the node-specific QP number (QPN). This exchange happens over another network, like TCP/IP. During the
connection setup, each QP is configured for a specific type of service. We implement TardiS for Reliable Connections (RC) type of service, which provides reliable in-order message delivery between two communication partners.

The application sends or receives messages by posting send requests (SR) or receive requests (RR) to a QP. These requests describe the message structure and refer to the memory buffers within previously created MRs. The application checks for the completion of outstanding work requests by polling the CQ for work completions (WC).

There are various implementations of the IB verbs API for different hardware, including Infiniband [11], iWarp [30], and RoCE [7, 8]. InfiniBand is generally the fastest among these but requires specialised NICs and switches. RoCE and iWarp provide RDMA capabilities in Ethernet networks. They still require hardware support in the NIC, however, do not depend on specialised switches and thus make it easier to incorporate RDMA into an existing infrastructure. This work focuses on RoCEv2, a version of RoCE protocol.

To enable RDMA-application migration, it is important to consider the following challenges:

1. User applications have to use physical network addresses (QPN, LID, GID, GUID), and the IB verbs API does not specify a way for virtualising these.
2. The NIC can write to any memory it shares with the application without the OS noticing.
3. The OS cannot instruct the NIC to pause the communication, except abruptly terminating it.
4. The user applications are not prepared for a connection changing destination address and going into an erroneous state. As a result, the applications will terminate abruptly.
5. Although the OS is aware of all IB verbs objects created by the application, it does not control the whole state of these objects, as the state partially resides on the NIC.

We address all of these challenges in Section 3.

2.3 CRIU

CRIU is a software framework for transparently checkpointing and restoring the state of Linux processes [9]. It enables live migration, snapshots, or remote debugging of processes, process trees, and containers. To extract the user-space application state, CRIU uses conventional debugging mechanisms [5, 6]. However, to extract state of process-specific kernel objects, CRIU depends on special Linux kernel interfaces.

To restore a process, CRIU creates a new process that initially runs the CRIU executable which reads the image of the target process and recreates all OS objects on its behalf. This approach allows CRIU to utilise the available OS mechanisms to run most of the recovery without the need for significant kernel modifications. Finally, CRIU removes any traces of itself from the process.

CRIU is also capable of restoring the state of TCP connections. This feature is crucial for the live migration of distributed applications [41]. The Linux kernel introduced a new TCP connection state, TCP_REPAIR, for that purpose. In this state a user-level process can change the state of send and receive message queues, get and set message sequence numbers and timestamps, or open and close connection without notifying the other side.

As of now, if CRIU attempts to checkpoint an RDMA-application, it will detect IB verbs objects and will refuse to proceed. Discarding IB verbs objects in the naive hope that the application will be able to recover is failure-prone: once an application runs into an erroneous IB verbs object, in most cases, the application will hang or crash. Thus, we provide explicit support for IB verbs objects in CRIU (see Section 3).

3 Design

TardiS is based on modern container runtimes and reuses much of the existing infrastructure with minimal changes. Most importantly, we require no modification of the software running inside the container (see Section 3.1).

Existing container runtimes rely on CRIU for checkpoint/restore functionality [3, 14, 15, 51]. Therefore, it is sufficient to extend CRIU with IB verbs support to checkpoint and restore containerised RDMA-applications. Section 3.2 describes our modifications to the IB verbs API and how CRIU uses them.

We also add two new QP states to enable CRIU to create consistent checkpoints (see Section 3.3). Finally, Section 3.4 describes minimal changes to the packet-level RoCEv2 protocol to ensure that each QP maintains correct information about the location of its partner QP.

3.1 Software Stack

Typically, access to the RDMA network is hidden deep inside the software stack. Figure 3 gives an example of a containerised RDMA-application. The container image comes with all library dependencies, like the libc, but not the kernel-level drivers. The application uses a stack of communication libraries, comprising Open MPI [28], Open UCX [64] (not shown), and IB verbs. Normally,
to migrate, container runtime would require the application inside the container to terminate and later recover all IB verbs objects. This removes transparency from live migration.

TardiS runs alongside the container comprising of a container runtime (e.g., docker[51]), CRIU, and IB verbs library. We modified CRIU to make it aware of IB verbs, so that it can successfully save IB verbs objects when CRIU traverses the kernel objects belonging to the container. We extend the IB verbs library (m-ibv-user and ibv-kern) to enable serialisation and deserialisation of the IB verbs objects. Importantly, the API extension is backwards compatible with the IB verbs library running inside the container. Thus, both m-ibv-user and ibv-user use the same kernel version of IB verbs. TardiS requires no modifications of any software inside the container.

3.2 Checkpoint/Restore API

To enable checkpoint/restore for processes and containers, we extend the IB verbs API with two new calls (see [Listing 1], ibv_dump_context and ibv_restore_object). The dump call returns dump of all IB verbs objects within a specific IB verbs context. The dumping runs almost entirely inside the kernel for two reasons. First, some links between the objects are only visible at the kernel level. Second, to get a consistent checkpoint it is crucial to ensure an atomic dump.

Of course, the existing IB verbs API allows to create new objects. However, the existing IB verbs API is not expressive enough for restoring objects. For example, when restoring a completion queue (CQ), the current API does not allow to specify the address of the shared memory region for this queue. Also it is not possible to recreate a queue pair (QP) directly in the Ready-to-Send (RTS) state. Instead, the QP has to traverse all intermediate states before reaching RTS.

We introduce a fine-grained ibv_restore_object call to restore IB verbs objects one by one, for situations when the existing API is not sufficient. In turn, modified TardiS, uses the extended IB verbs API to save and restore the IB verbs state of applications. During recovery, TardiS reads the object dump and applies a specific recovery procedure for each object type. For example, to recover a QP, TardiS calls ibv_restore_object with the command CREATE and progresses the QP through the Init, RTR, and RTS states using ibv_modify_qp. The contents of memory regions or QP buffers are recovered using the standard file and memory operations. Finally, TardiS brings the queue to the original state using the REFILL command of the restore call.

3.3 Queue Pair States

Before communication can commence, an application

```c
int ibv_dump_context(
    struct ibv_context *ctx,
    int *count, void *dump,
    size_t length);

int ibv_restore_object(
    struct ibv_context *ctx,
    void **object,
    int object_type, int cmd,
    void *args, size_t length);
```

Listing 1: Checkpoint/Restart extension for the IB verbs API. ibv_dump_context creates an image of the IB verbs context ctx with count objects and stores it in the caller-provided memory region dump of size length. ibv_restore_object executes the restore command cmd for an individual object (QP, CQ, etc.) of type object_type. The call expects a list of arguments specific to the object type and recovery command. args is an opaque pointer to the argument buffer of size length. A pointer to the restored object is returned via object.
establishes a connection bringing a QP through a sequence of states (depicted in Figure 4). Each newly-created QP is in the Reset (R) state. To send and receive messages, a QP must reach its final Ready-to-Send (RTS) state. Before reaching RTS, the QP traverses the Init and Ready-to-Receive (RTR) states. In case of an error, the QP goes into one of the error states: Error (E), or Send Queue Error (SQE). In the Send Queue Drain (SQD) state, a QP does not accept new send requests. Apart from that, SQD is equivalent to the RTS state.

In addition to the existing states, we add two new states invisible to the user application (see Figure 4): Stopped (S) and Paused (P). When the kernel executes ibv_dump_context, all QPs of the specified context go into a Stopped state. A stopped QP does not send or receive any messages. The QPs remain stopped until they are destroyed together with the checkpointed process. A QP becomes Paused when learning its destination QP has become Stopped (see Section 3.4). A paused QP does not send messages, but also has no other QP to receive messages from. A QP remains paused, until the migrated destination QP restores at a new location and sends a message with the new location address. The paused QP retains the new location of the destination QP and returns to RTS state. After that, the communication can continue.

3.4 Connection Migration

There are two considerations, when migrating a connection. First, during the migration, the communication partner of the migrating container must not confuse migration with a network failure. Second, once the migration is complete, all partners of the communication node need to learn its new address.

We address the first issue by extending RoCEv2 with a connection migration protocol. The connection migration protocol is active during and after migration (see Figure 5). This protocol is part of the low-level packet transmission protocol and is typically implemented entirely within the NIC. Also, we add a new negative acknowledgement type NAK_STOPPED. If a stopped QP receives a packet, it replies with NAK_STOPPED and drops the packet. When the partner QP receives this negative acknowledgement, it transitions to the Paused (P) state and refrains from sending further packets until receiving a resume message.

After migration completes, the new host of the migrated process restores all QPs to their original state. Once a QP reaches the RTS state, the new host executes the REFILL command. This command restores the driver-specific internal QP state and sends a newly introduced resume message to the partner QP. Resume messages are sent unconditionally, even if the partner QP was not paused before. This way, we also address the second issue: The recipient of the resume message updates its internal address information to point to the new location of the migrated QP; the source address of the resume message.

Each pause and resume message carry source and destination information. Thus, if multiple QPs migrate at the same time, there can be no confusion which QPs must be paused or resumed. If at any point the migration process fails, the paused QPs will remain stuck and will not resume communication. This scenario is completely analogous to a failure during a TCP-connection migration. In both cases, TardiS will be responsible for cleaning up the resources.

4 Implementation

To provide transparent live migration, TardiS incorporates changes to CRIU, IB verbs library, RDMA-device driver (SoftRoCE), and packet-level RoCEv2-protocol. To migrate an application, the container runtime invokes CRIU which checkpoints the target container. CRIU stops active RDMA-connections and saves the state of IB verbs objects (see Section 4.1). SoftRoCE then pauses communication using our extensions to the packet-level protocol. After transferring the checkpoint to the destination node, the container runtime at that node invokes CRIU to recover the IB verbs objects and restores the application. SoftRoCE then resumes all paused communication to complete the migration process.

SoftRoCE is a Linux kernel-level software implementation (not an emulation [47]) of the RoCEv2 protocol [8]. RoCEv2 runs RDMA communication by tunnelling Infiniband packets through a well-known UDP port. In contrast to other RDMA-device drivers, SoftRoCE allows the OS to inspect, modify, and control the
state of IB verbs objects completely.

As a performance-critical component of RDMA communication, RoCEv2 usually runs in NIC hardware. So changes to the protocol require hardware changes. We implement TardiS with the focus on minimising these protocol changes. The key part of TardiS is the addition of connection migration capabilities to the existing RoCEv2 protocol (see Section 4.2).

### 4.1 State Extraction and Recovery

State extraction begins when CRIU discovers that its target process opened an IB verbs device. We modified CRIU to use the API presented in Section 3.2 to extract the state of all available IB verbs objects. CRIU stores this state together with other process data in an image. Later, CRIU recovers the image on another node using the new API.

When CRIU recovers MRs and QPs of the migrated application, the recovered objects must maintain their original unique identifiers. These identifiers are system-global and assigned by the NIC (in our case the SoftRoCE driver) in a sequential manner. We augmented the SoftRoCE driver to expose the IDs of the last assigned MR and QP to TardiS in userspace. These IDs are memory region number (MRN) and queue pair number correspondingly. Before recreating an MR or QP, CRIU configures the last ID appropriately. If no other MR or QP occupies this ID, the newly created object will maintain the original ID. This approach is analogous to the way CRIU maintains the process ID of a restored process using ns_last_pid mechanism in Linux, which exposes the last process ID assigned by the kernel.

It is possible for some other process to occupy MRN or QPN, which CRIU wants to restore. Two processes cannot use the same MRN or QPN on the same node, resulting in a conflict. In the current scheme, we avoid these conflicts by partitioning QP and MR addresses globally among all nodes in the system before the application startup. CRIU faces the very same problem with process ID collisions. This problem has only been solved with the introduction of process ID namespaces. To remedy the collision problem for IB verbs objects, a similar namespace-based mechanism, would be required. We leave this issue for future work.

Additionally, recovered MRs, have to maintain their original memory protection keys. The protection keys are pseudo-random numbers provided by the NIC and are used by a remote communication partner when sending a packet. An RDMA operation succeeds only if the provided key matches the expected key of a given MR. Other than that, the key’s value does not carry any additional semantics. Thus, no collision problems exist for protection keys.

CRIU sets all protection keys to their original values before communication restarts by making an ibv_restore_object call with the IBV_RESTORE_MR_KEYS command.

### 4.2 Resuming Connections

The connection migration protocol ensures that connections are terminated gracefully and recovered to a consistent state. The implementation of this protocol is device- and driver-specific. In this work, we modify the SoftRoCE driver to make it compliant with the connection migration protocol (Section 3.4) by providing an implementation of the checkpoint/restore API (Section 3.2).

Figure 6 outlines the basic operation of the SoftRoCE driver. The driver creates three kernel tasks for each QP: requester, responder, and completer. When an application posts send (SR) and receive (RR) work requests to a QP, they are processed by requester and responder correspondingly. A work request may be split into multiple packets, depending on the MTU size. When the whole work request is complete, requester or completer notify the application by posting a work completion to the completion queue.

The kernel tasks process all requests packet by packet. Each task maintains the packet sequence number (PSN) of the next packet. A packet sent by a requester is processed by the responder of the partner QP. The responder replies with an acknowledgement that is processed by the completer. The completer generates a work completion (WC) after receiving acknowledgement for the last packet in an SR. Similarly, the responder generates a WC after receiving all packets of an RR.

After migration, when the recovered QP_a is ready to communicate again, it sends a resume message to QP_b with the new address. This way, QP_b learns the new location of QP_a. Receiving this resume message, the responder of QP_b replies with an acknowledgement of the
last successfully received packet. If some packets were lost during the migration, the next PSN at the responder of QP\(_b\) is smaller than the next PSN at the requester of QP\(_a\). The difference corresponds to the lost packets, which must be retransmitted. Simultaneously, the requester of QP\(_b\) can already start sending messages. At this point, the connection between QP\(_a\) and QP\(_b\) is fully recovered.

The presented protocol ensures that both QPs recover the connection without losing packets irrecoverably. If packets were lost during migration, the QPs can determine which packets were lost and retransmit them. This retransmission is part of the normal RoCEv2 protocol. The whole connection migration protocol runs transparently for the user applications.

5 Evaluation

We evaluate TardiS from three main aspects. First, we analyse the implementation effort, with a specific focus on changes to the RoCEv2 protocol. Second, we study the overhead of adding migration capability, outside of the migration phase. Third, we estimate the fine-grained cost of migration for individual IB verbs objects, as well as the full latency of migration in realistic RDMA-applications.

For most experiments, we use a system with two machines: Each machine is equipped with an Intel i7-4790 CPU, 16 GiB RAM, an on-board Intel 1 Gb Ethernet adapter, a Mellanox ConnectX-3 VPI adapter, and a Mellanox Connect-IB 56 Gb adapter. The Mellanox VPI adapters are set to 40 Gb Ethernet mode and connected to a Cisco C93128TX 40 Gb Ethernet switch. The SoftRoCE driver communicates over this adapter. The machines run Debian 11 with a custom Linux 5.7-based kernel. We refer to this setup as local.

We conduct further measurements on a cluster comprising two-socket Intel E5-2680 v3 CPUs nodes with Connect-IB 56 Gb NICs deployed by Bull. We refer to this setup as cluster. Two nodes similar to those in the cluster were used in a local setup and equipped with Mellanox ConnectX-3 VPI NICs configured to 56 Gb InfiniBand mode.

5.1 Magnitude of Changes

TardiS requires few changes to the low-level RoCEv2 protocol, as shown in Table 1. We count newly added or modified source lines of code in different components of the software stack. Only around 10% of all the changes apply to the kernel-level SoftRoCE driver. These changes mostly focus on saving and restoring the state of IB verbs objects. We counted separately changes to the requester, responder, and completer QP

| Level  | Component | Original | ∆   |
|-------|-----------|----------|-----|
| Kernel | IB verbs  | 30565    | 719 |
| SoftRoCE | 9 446    | 872      |
| QP tasks | 1 112    | 249      |
| User   | IB verbs  | 12 431   | 339 |
| SoftRoCE | 1 004    | 332      |
| CRIU   | 61 616    | 1 845    |
| Total  | 4 137     |          |

Table 1: Development effort in SLOC. We specifically show magnitude of changes done to QP tasks (see Figure 6).

| Object  | Features required | State (b) |
|---------|-------------------|-----------|
| PD      | None              | 12        |
| MR      | Set MR keys and MRN | 48        |
| CQ      | Set ring buffer state | 64        |
| SRQ     | Set ring buffer state | 68        |
| QP      | + QP tasks state | 271       |
| QP w/ SRQ | + Current WQE state | 823       |

Table 2: Additional features implemented in the kernel-level SoftRoCE driver to enable recovery of IB verbs objects. We provide the size each object occupies in the dump.

We used gprof to record the coverage of connection migration support code outside of migration phase. Out of all changes done to the QP tasks, only 28 lines were touched, while the application communication was active. Among them, 3 lines are variable assignments, one is an unconditional jump, the rest are newly introduced if-else-conditions that occur at most once per packet sent or received. The rest of the code changes to the QP task run only during the connection migration phase.

Besides additional logic to the QP tasks, saving and restoring IB verbs objects requires manipulation of implementation-specific attributes. Some of these attributes cannot be set through original IB verbs API. For example, recovery of an MR requires an additional ability to restore the original values of memory keys and
3. an MRN. Some other attributes are not visible in original IB verbs API at all. The queues (CQ, SRQ, QP) implemented in SoftRoCE require an ability to save and restore metadata of ring buffers backing up the queues. If a QP uses a shared receive queue (SRQ), the dump of the QP additionally includes the full state of the current work queue entry (WQE). We identified all required attributes for SoftRoCE, calculated their memory footprint (see Table 2), and implemented features required by these attributes.

We show the analysis of the required changes to RoCEv2 implemented by SoftRoCE. We claim that similar changes are required to other low-level implementations of RoCEv2 protocol residing in RDMA-capable NICs. We demonstrate the changes to the communication path are minimal, outside of the migration phase. We reasonably expect that once mapped to the hardware the proposed changes will remain minimal.

5.2 Overhead of Migratability

Just adding the capability for transparent container migration already may incur overhead even when the migration does not occur. For example, DMTCP (see Section 6) intercepts all IB verbs library calls and rewrites both work requests and completions before forwarding them to the NIC. The interception happens persistently, even when the process running under DMTCP never migrates. In contrast to this, TardiS does not intercept communication operations at the critical path, thereby introducing no measurable overhead. This subsection explores the overhead added for normal communication operations without migrations.

First, we reaffirm that the proposed low-level protocol changes are minimal. For that, we need to compare performance of migratable and non-migratable versions of SoftRoCE driver. Unfortunately, the original version (vanilla kernel, without any modifications from our side) of the SoftRoCE driver turned out to be notoriously unstable. The original driver contained multitude of concurrency bugs and required significant restructuring.

Finally, we ended up with three versions of the driver: the original buggy version, a non-migratable fixed version, and a migratable fixed version (see Figure 7). The original version rendered to be faster, nevertheless for the scope of our paper correctness was of higher priority than the performance. Nevertheless, the performance of both fixed versions of the SoftRoCE driver is practically indistinguishable. Therefore, we conclude that TardiS introduces no runtime overhead outside of the migration phase.

Next, we show the overhead added by DMTCP, which intercepts all IB verbs calls. This way, we study the cost of adding migration capability at the user level. We use the latency and bandwidth benchmarks from the OSU 5.6.1 benchmark suite [4] running on top of Open MPI 4.0 [28]. We ran the experiment on the previously described cluster with ConnectIB NICs. As we have shown above, adding support for the migration does not add performance penalty. Thus, running without DMTCP is similar to having native migration support. To be able to extract the state of IB verbs objects, DMTCP maintains shadow objects, which act as prox-

2SIGINT to a user-level RDMA-application caused the kernel to panic.
Table 3: RDMA-capable NICs used for the evaluation.

| Short | Full name                  | Location |
|-------|----------------------------|----------|
| SR    | SoftRoCE                  | local    |
| CX3/40| ConnectX-3 40 Gb Ethernet | local    |
| CX3/56| ConnectX-3 56 Gb InfiniBand| cluster  |
| CIB   | ConnectIB                 | local    |
| BIB   | Bull Connect-IB           | cluster  |

Figure 9: Object creation time for different RDMA-devices. Before being able to send a message, a QP needs to be in the state RTS, which requires the traversal of three intermediate states (Reset, Init, RTR). We show the interval of the standard deviation around the mean.

Figure 10 shows the MR registration time, depending on the region’s size. MR registration costs are split between the OS and the NIC: The OS pins the memory and the NIC learns about the virtual memory mapping of the registered region. SoftRoCE does not incur the “NIC-part” of the cost, therefore MR registration with SoftRoCE is faster than for RDMA-enabled NICs. For this experiment, we do not consider the costs of transferring the contents of the MR during migration.

The number of QPs is the second variable influencing the migration time. Figure 11 shows the time for migrating a container running the \texttt{ib\_send\_bw} benchmark. The benchmark consists of two single-process containers running on two different nodes. Three seconds after the communication starts, the container runtime migrates one of the containers to another node. The migration time is measured as the maximum message latency as seen by the container that did not move. The checkpoint is transferred over the same network link used by the benchmarks for communication. With growing number of QPs, the benchmark consumes more memory, ranging from 8 MiB to 20 MiB. To put things into perspective, we estimated the migration time for real devices by calculating the time to recreate IB verbs objects with SoftRoCE from the measured migration time and added time to create IB verbs objects with RDMA-NICs (from Figure 9). We show our estimations with the dashed lines.

5.4 MPI Application Migration

For evaluating transparent live-migration of real-world applications we chose to migrate NPB 3.4.1 [17], an
Figure 10: MR registration time depending on the region size.

Figure 11: Migration speed with different numbers of QPs.

Figure 12: Migration speed comparison of Docker against CR-X (X).

Figure 13: MPI application migration.

MPI benchmark suite. The MPI applications run on top of Open MPI 4.0 [28], which in turn uses OpenUCX 1.6.1 [66] for point to point communication. We configured UCX to use IB verbs communication over reliable connection (RC).

This setup corresponds to Figure 3. We containerised the applications using self-developed runtime CR-X, based on libcontainer [15]. Unlike Docker, our container runtime facilitates faster live migration by sending the image directly to the destination node, instead of the local storage, during the checkpoint process. Moreover, our container runtime stores checkpoint in RAM, reducing migration latency even further. The remaining description of our container runtime is out of scope of this paper.

To measure the latency of application migration, we start each MPI application with four processes (ranks). We migrate one of the ranks to another node approximately in the middle of the application progress. Each benchmark has a size (A to F) parameter. We chose size such that different benchmarks run between 10 and 300 seconds. For this reason, we excluded dt benchmark, because it runs only around a second. Figure 13 shows container migration latency and standard deviation around the mean, averaged over 20 runs of each benchmark.

We break down the migration latency into three parts: checkpoint, transfer, and restore. TardiS stops the target container in the beginning of the checkpoint phase. Large part of the checkpoint arrives to the destination node already during the checkpoint phase. After, the transfer phase is over, TardiS recovers the container on the destination node. Overall, we observe the migration time to be proportional to the checkpoint size. The benchmarks experience runtime delay proportional to the migration latency.

To show interoperability with other container runtimes, we measured migration costs, when using Docker 19.03 (see Figure 12). We had to implement full end-to-end migration flow ourselves, because Docker supports only checkpoint and restore features. To our disappointment, Docker does not employ some important optimisations and takes line time to complete migration. Nevertheless, we prove our claim that TardiS is readily interoperable with other container runtimes.

6 Related Work

Checkpoint/Restart Techniques Transparent live migration of processes [18, 53, 68], containers [50, 54, 57], or virtual machines [24, 27, 37, 58, 62] has long been a topic of active research. The key challenge of this technique lies in the checkpoint/restart operation. For processes and containers, this operation can be implemented at three levels: application runtime, user-level system, or kernel-level system. Table 4 compares a selection of existing checkpoint/restart systems.

Runtime-based systems expect the user application to access all external resources through the API of the
Table 4: Selected checkpoint/restart systems handle either VMs, processes (P), containers (C), or application objects (O). Runtime-based systems naturally introduce no additional communication overhead for migration support.

| Runtime system       | RDMA | Nomad | PS MPI | DMTCP | MOSIX-4 | MOSIX-3 | TardiS |
|----------------------|------|-------|--------|-------|---------|---------|-------|
| Overhead             | Y    | Y     | Y      | X     | Y       | Y       | Y     |
| Users                | VM   | P     | P      | P     | P       | C       | Ours  |
| Reference            | [21] | [38]  | [64]   | [16]  | [19]    | [20]    | Ours  |

Almost all attempts to provide transparent live migration together with RDMA networks rely on modifications of the runtime system [16, 31, 38, 42, 64]. Some runtime systems operate on application-defined objects (tasks, agents, lightweight threads) for even more efficient state serialisation and deserialisation [21, 44, 73]. All runtime-based approaches bind the application to a particular runtime system. This restriction resolves two important issues with resource migratability: First, the runtime system controls exactly when the underlying resource is used and can easily stop the user application from doing so to serialise the state of the resource. Second, the runtime can maintain enough information about the state of the resource to facilitate resource serialisation and deserialisation. Such interception is cheap because it happens within the application’s address space.

Almost all attempts to provide transparent live migration together with RDMA networks rely on modifications of the runtime system [16, 31, 38, 42, 64]. Some runtime systems operate on application-defined objects (tasks, agents, lightweight threads) for even more efficient state serialisation and deserialisation [21, 44, 73]. All runtime-based approaches bind the application to a particular runtime system.

**Network Virtualisation** TCP/IP network virtualisation is an essential tool for isolating distributed applications from the underlying physical network topology. Even though network virtualisation enables live migration, it introduces overhead due to additional encapsulation of network packets [59, 74]. Several new approaches try to address these performance problems [22, 59, 63, 74]. However, these approaches do not consider RDMA networks.

Other work focuses on virtualising RDMA networking. FreeFlow [45] intercepts communication via IB verbs in containers to implement connection control policies in software but does not support live container migration. Nomad [38] uses InfiniBand address virtualisation for VM migration but implements the connection migration protocol inside an application-level runtime. LITE [70] virtualises RDMA networks, but offers no migration support and requires application rewrite.

TardiS uses traditional network virtualisation for TCP/IP networks, which is not on the performance-critical path for RDMA-applications. However, TardiS avoids unnecessary interception of RDMA-communication. Instead, TardiS silently replaces addressing information during migration.

**RDMA Implementations** There are multiple open-source RDMA implementations. SoftRoCE [47] and SoftiWarp [69] are pure software implementations of RoCEv2 [8] and iWarp [30] respectively. Both provide no performance advantage over socket-based communication but are compatible with their hardware counterparts and facilitate the development and testing of RDMA-based applications. We chose to base our work on SoftRoCE because RoCEv2 found wider adoption than iWarp.

There are also open-source FPGA-based implementations of network stacks. NetFPGA [75] does not support RDMA communication. SiRoM [67] provides a proof-of-concept RoCEv2 implementation. However, we found it unfit to run real-world applications (for example, MPI) without further significant implementation efforts.
7 Discussion

Hardware Modifications and Software Implementation Propositions to modify hardware often meet criticism because they tend to be hard to validate in practice. We believe that limited hardware changes are worthy of consideration as the deployment of custom \cite{26, 46}, programmable \cite{46, 56}, or software-augmented NICs \cite{34} has already been proven feasible. IB verbs has routinely been extended with additional features \cite{39, 48} as well. Deploying TardiS to real data centres would require hardware changes. We believe this trade-off is justified because TardiS provides tangible performance benefits, in comparison to other approaches.

To find out whether our proposed changes have any effect on the critical path of the communication, we integrated them into a software implementation of RoCEv2. Our measurements show no performance difference after adding support for migration. Given the nature of these changes, we are confident this observation applies to hardware as well. Moreover, we provide our open-source software implementation to the research community for validating our findings and further study.

Compatibility with Existing Infrastructure TardiS ensures by design backwards compatibility at the IB verbs API and RoCEv2 protocol level. Moreover, TardiS allows to use container runtimes interchangeably. By enabling migratability through TardiS, a data centre provider does not have to make the hard choice of punishing applications that do not benefit from migration. We believe these features are crucial for successful integration into existing data centre management infrastructure.

Unreliable Datagram Communication TardiS provides live migration for reliable communication (RC), but omits unreliable datagram (UD) communication for two reasons: First, every message received over UD exposes the address of its sender. When this sender migrates, its address will change and currently TardiS cannot conceal this fact from the receiver. Second, a UD QP can receive messages from anywhere. This means that a UD QP does not know where to send resume messages after migration. We leave migration support for unreliable datagram for future work.

8 Conclusion

We introduce TardiS, an OS-level architecture enabling transparent live container migration. Our architecture design maintains full backwards-compatibility and interoperability with the existing RDMA network infrastructure at every level. We demonstrate end-to-end migration flow of MPI applications using different container runtimes and studied cost of migration. TardiS provides live migration without sacrificing RDMA network performance, yet at the cost of changes to the RDMA communication protocol.

To validate our solution, we integrated the proposed RDMA communication protocol changes into an open-source implementation of the RoCEv2 protocol, SoftRoCE. For real-world deployment, these protocol changes must be implemented in NIC hardware. Finally, we provide a detailed analysis of any changes we make to SoftRoCE to show their smallness.

We are convinced the architecture of TardiS can be useful for dynamic load balancing, efficient prepared fail-over, and live software updates in data centres or HPC clusters.

Availability

The anonymised version of the code is available here: dropbox.com/s/clych73kxmuwjrj

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