Seriema: RDMA-based Remote Invocation with a Case-Study on Monte-Carlo Tree Search

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Abstract

We introduce Seriema, a middleware that integrates RDMA-based remote invocation, asynchronous data transfer, NUMA-aware automatic management of registered memory, and message aggregation in idiomatic C++1x. Seriema supports the notion that remote invocation and asynchronous data transfer are complementary services that, when tightly-integrated, allow distributed data structures, overlay networks, and Cloud & datacenter service applications to be expressed effectively and naturally, resembling sequential code. In order to evaluate the usability of Seriema, we implement a Monte-Carlo Tree Search (MCTS) application framework, which runs distributed simulations given only a sequential problem specification. Micro-benchmarks show that Seriema provides remote invocations with low overhead, and that our MCTS application framework scales well up to the number of non-hyperthreaded CPU cores while simulating plays of the board game Hex.

1 Introduction

InfiniBand (IB) is a low-latency, high-throughput communication standard that allows applications to bypass the OS and perform Remote Direct Memory Access (RDMA) to remote machines in the network. Recent standard revisions by Mellanox feature communication latency on the order of 1 µs in their latest iterations[9].

RDMA data transfer requires addressing several details related to memory management, such as mapping (registering) physical memory into the IB device’s hardware, manually managing lifetime & recycling for send/receive buffers of registered memory, and possibly even application re-engineering in order to accommodate critical polling operations directly associated with latency and throughput. While libraries exist to abstract some of these concerns [3], this
work supports the notion that RDMA data transfer alone is not a service comprehensive enough to fully support a large class of distributed applications, such as distributed data structures, overlay networks, Cloud services, and datacenter services such as scheduling or consensus. Many of these applications transmit small, latency-sensitive messages that eventually trigger large-scale, throughput-sensitive data transfers. We see asynchronous remote invocation performed over RDMA, in the form of RPCs (remote procedure calls) or their object-oriented counterpart RMI (remote method invocation), as complementary to one-sided RDMA-based data transfer, where remote memory is written to directly without any awareness of a destination process.

We present a system called Seriema that provides RDMA-based remote invocation, NUMA-aware automatic management of registered memory, asynchronous data transfer, and message aggregation in idiomatic C++1x. Remote invocation and asynchronous data transfer are tightly-integrated in Seriema. Some of our remote invocation primitives condition execution to completing previous, associated data transfers holding the function’s data. In addition, remote invocation and asynchronous data transfer share a common notification infrastructure (Sec. 3.1) and have identical configuration options related to (NUMA-aware) memory-management. Our design approach targets unobtrusiveness, which we define as allowing developers to simultaneously access multiple levels of abstraction in Seriema, choosing the interface that best suits the application as it currently is. Hence, an application can use routines ranging among (a) a simple RDMA library that abstracts some performance-enabling programming techniques; (b) a more comprehensive RDMA solution, that also provides automatic memory management (allocation & recycling) and automatic selective signaling (Sec. 4.1); (c) a distributed system fabric, which in addition allows processes and threads to be placed and named, and also provides basic remote invocation; up to (d) a complete solution to asynchronous remote invocation using one-sided RDMA (see Sec. 2), with optional local aggregation of remote calls. A single application could access Seriema concurrently in any of these levels.

As a usability experiment, we implemented a distributed Monte-Carlo Tree Search (MCTS) application framework, a choice based on the wide applicability of MCTS and its challenges for parallelization (Sec. 2). Our MCTS framework, a higher-level middleware itself, accepts MCTS problem specifications to be run in a distributed fashion, without any user-provided communication or MCTS logic code. Micro-benchmarks show that Seriema has low overhead remote invocations, and our proof-of-concept MCTS framework scales well up to the number of non-hyperthreaded CPU cores in our distributed testing environment while simulating plays of the board game Hex.

The main challenges addressed by Seriema are not only those related with the mechanics of RDMA (abstracting memory registration & management, thread synchronization for selective signaling, etc) but also those related to usability aspects of asynchronous remote invocation, particularly when complemented with one-sided RDMA. For example, challenges in the usability domain include (i) managing flow control when using remote buffers in a flexible manner, giving a
variety of options to applications, including local buffering that honors RDMA’s “no-copy” principle, by carefully managing registered memory; (ii) allowing notification of remote invocation to be setup in different ways, including a notification when either the send buffer could be reused, or when the remote thread consumed the function; (iii) designing serialization protocols that allow internal components of Seriema to identify partial writes in serialized functions (or data associated with functions), and abstract those from the applications; (iv) requiring no communication setup between short-lived threads, and only simple, one-shot setup routines for long-lived threads that communicate with one-sided RDMA; (v) providing message aggregation for remote invocations, honoring the “no-copy” principle of RDMA; (vi) implementing NUMA awareness, which is critical for RDMA performance [20], but not only making NUMA abstracted from applications (in buffer memory registration & management, for example), but also optionally exposed to applications, in cases where performance depends critically on precise thread/buffer placement; (vii) providing options to handle incoming remote invocations, so calls could be handled by application threads directly, or by process level consumers; (viii) allowing calls to block, use hardware transactional memory (HTM), or employ fine remote-memory synchronization operations, so that the application can implement a highly-diverse set of synchronization patterns (e.g. delegation [1], combining [11], among others). Items (i), (iv), and (v) are particularly aimed at irregular applications, namely those with communication patterns highly sensitive to the problem’s input. With a combination of RDMA-based asynchronous remote invocation and RDMA data transfers, we expect to handle a wide variety of distributed applications.

Our MCTS framework would require considerable coding effort without Seriema. RDMA memory management (registration, recycling, buffer management & flow control for remote invocation, NUMA awareness, etc), wait-free synchronization for RDMA selective signaling, protocol design for function serialization and completion notifications, queue-pair sharing & configuration, among others. MCTS-related code represents less than 10% of the total codebase necessary to compile our MCTS application framework, the rest coming from high-level, high-performance routines abstracted by Seriema. After background and related work in Sec. 2, architecture overview in Sec. 3, and implementation details in Sec. 4, Sec. 5 we evaluate both usability and performance aspects of Seriema with the lens of our MCTS framework.

2 Background and Related Work

RDMA has been well-used in distributed applications, notably in the database domain [26, 4, 16, 18]. Yet, some aspects of system integration, particularly with NUMA, are still under evaluation [20] (our performance observations in Sec. 5.3 align with this work).

FaRM [10] provides a rich interface, with remote memory allocation, transactions, and a message-passing service with one-sided RDMA. We have different design and implementation perspectives: (i) we do not create a single shared
memory space across the system; (ii) our remote invocation service is richer, with automatic memory management (NUMA-aware) and message aggregation still being “zero-copy” (Sec. 4.4); (iii) besides one-sided RDMA remote invocation, we have send-based services for short-lived threads; (iv) all system-level synchronization for shared queue pairs, including those related to selective signaling and memory management, is done with a wait-free lightweight protocol, essential for latency-sensitive applications. We do not provide transaction services for remote memory like FaRM, Storm [21], or LITE [24], but rather tools to support transactions via asynchronous remote invocation: distributed lock managers, hardware transactional memory helpers, synchronization & atomic operation helpers, etc. As our invocations are by default handled directly by the receiving threads, in FIFO order, implementing process-local transactions largely reduces to shared-memory concurrent programming inside remote invocations. In addition, we think that different local and distributed data types might be subject to highly-diverse optimizations (delegation [6], combining [11], etc), better handled at the application-level not at the systems-level.

In [17], authors propose a higher-level abstraction for remote writes called RDMO (“O” for operation), each performing a series of non-blocking read/write/atomic operations on a remote data structure identified under a manager service. The authors note that this interface complements (and relies on) remote invocations, rather than substitutes them. In the other direction, our framework provides certain features that approach, but not quite implement their abstraction. As seen in Sec. 4.4 users can register functions to be executed by the receiving RDMAMessengers with runtime identifiers. Those functions can perform synchronized accesses to local data structures identified by an application-level table, as in [17].

Our biggest source of inspiration is Grappa [19]. Its interface is elegant, but the system imposes user-level threading to applications, forces remote objects to reside in a partitioned global address space (PGAS), does not allow explicit NUMA-aware remote memory allocation, and does not permit much RDMA performance tuning, as it relies on RDMA-based MPI for communication. We consider Grappa’s “global address” (representing a machine/address pair) and “RDMA aggregator” (which provides message aggregation) abstractions powerful and elegant. Our RDMA aggregation philosophy differs from Grappa, as we allow applications to establish optionally private channels between any $t_1$ and $t_2$, with its internal buffers allocated and controlled by the sender thread, avoiding any inter-thread data dependency that might introduce latency – the details are given in Sec. 4.4.

2.1 Monte-Carlo Tree Search

Monte-Carlo Tree Search (MCTS) is a state-space search algorithm with numerous applications in AI. Originally proposed for planning in Markov decision processes [1], MCTS has now many scientific and industrial applications.

We will describe the core algorithm for MCTS as applied to the board game Hex [14], but variations and extensions abound. Hex is played on a rhombus-
shaped board made of hexagonal cells. Players alternate coloring any empty cell, and a player wins if they connect their edges (p1: top–bottom; p2: left–right) with an unbroken path of their color.

MCTS explores possible moves in a game with a sequence of rollouts, which explore and expand a search tree incrementally, focusing effort on the most promising moves. Each rollout consists of four phases: selection, expansion, evaluation, and backpropagation. The selection phase traverses the MCTS tree from the root node representing the current game state down to some “frontier” node: one with unexplored moves. At each node $n$, a “move” $m$ is chosen among $n$’s children, according to a selection policy, which trades off exploration (trying new moves) with exploitation (gathering more information about the best moves). The standard policy, UCB, selects according to:

$$\text{argmax}_m \, \text{VAL}_m + C \sqrt{\frac{\ln (VIS_n)}{VIS_m}}$$

where $\text{VAL}_m$ is the value estimate for move $m$, $VIS_n$ is the number of visits to this node, $VIS_m$ is the number of times move $m$ has been tried here, and $C$ is a scaling constant. Note that this formula is increasing in $\text{VAL}_m$, promoting exploitation, and decreasing in $VIS_m$ promoting exploration. UCB derives from an optimal solution to this tradeoff in the multi-armed bandit setting [2], but numerous alternatives exist.

When selection reaches the frontier we move to the expansion phase, where an unexplored move is chosen (typically at random, as in our implementation) and added to the tree. Thus each rollout creates one new leaf node as a child of the frontier node. The evaluation phase determines a value estimate for the newly-expanded node. Most straightforwardly, this evaluation can be performed by simulating random moves to the end of the game, but hand-crafted or learned state-value functions can also be employed. Finally, the backpropagation phase updates the value estimates for nodes on the root-frontier path traversed during selection to incorporate the leaf-value obtained by evaluation. For a game like Hex, the value of a node corresponds to the win-rate for the player taking a turn there, and can be calculated as $\text{VAL}_m = \frac{WINS_m}{VIS_m}$.

A large amount of research and engineering effort has gone into parallelizing both the general MCTS algorithm and various domain-specific applications. Early efforts [7] sought ways to decompose the problem using either root parallelization, which runs several separate MCTS instances, or leaf parallelization, which runs one instance with multiple workers for the evaluation phase. A third approach, tree parallelization [8], where multiple threads traverse a shared tree structure, initially underperformed due to locking overhead, but with better implementations has become central to large-scale MCTS systems like AlphaGo [22].

Tree-parallel MCTS requires not only that threads avoid data races, but also that threads avoid duplicating work. Despite its name, MCTS generally makes deterministic choices during the selection phase, meaning that multiple threads traversing the search tree simultaneously will follow the same root-frontier path,
which in the worst case causes tree-parallel MCTS to approximate leaf-parallel with extra overhead. The standard technique for avoiding this duplication is known as a *virtual loss*, where threads pessimistically update the value of moves they choose during selection and then fix those updates during backpropagation. In the case of a game with only win/lose outcomes, this can be achieved by incrementing $VIS_m$ during selection and $WINS_m$ during backpropagation so that other threads visiting the same node will see a lower win rate for move $m$ in the interim.

Scaling parallel MCTS beyond shared memory systems requires partitioning the search tree. A common approach to partitioning is to compute a Zobrist hash—a deterministic function of the board state—that can be used to distribute search tree nodes uniformly across compute nodes [25]. This approach is demanding on the communication system, as each step in the traversal can require a remote invocation. Recent work proposes topology-aware mapping heuristics [13], and hybrid approaches that incorporate aspects of root-parallelization [23] in order to reduce the number of remote calls. Our experiments show that with Seriema (using additional local-memory concurrency optimizations, such as [6, 11]), even a tree parallelization approach can scale, with micro-benchmarks showing a very low remote invocation overhead.

### 3 Architecture Overview

Seriema has three subsystem abstractions, all directly accessible by applications, as seen in Fig. 1. In the lowest level, we have an RDMA Data Transfer Subsystem called DTutils. It provides queue-pair state control, abstracts important performance-related techniques for RDMA, such as selective signaling and queue-pair sharing, and provides an efficient, automatic NUMA-aware memory management for RDMA (including fast memory registration and recycling).

In the intermediate level, we have a Distributed System Fabric, called DSfabric, which initializes machines (e.g., creates and connects queue pairs according to users’ specifications), initializes processes and long-lived application threads among machines, provides machine/process/thread identification, and provides basic remote invocation methods (at this level, only send-based).

In the highest level, we have a Remote Invocation Subsystem, called RIutils. This module provides efficient asynchronous remote invocation with one-sided RDMA, with optional buffering and aggregation for remote calls (of course, both still honor RDMA’s “no-copy” general principle).

We assume an application with a set of long-lived operating system processes, running on a set of machines connected via InfiniBand. Each machine contains a set of multiple NUMA zones, and multiple InfiniBand endpoints (a combination of device and port).

While we envision one process per (zone × endpoint) inside each machine, users have total control on process placement. Each process executes a set of worker threads, consisting of user code, and a (possibly empty) set of service threads, consisting of system support code. Worker threads can be short-lived...
or long-lived, and they might choose to perform service-thread roles if dedicated service threads are not used.

After establishing queue pairs (QPs) between machines, relying on exchanging network interface “local IDs” (LID) and intra-device “port” numbers via an out-of-band channel, applications can use RDMA either with a send/recv interface – which we call send-based – or with a read/write interface, called one-sided. Send-based RDMA relies on the “target” machine registering receive buffers with the network interface, and on the “source” machine never exceeding the receive buffer sizes. Further, it also requires the “target” machine to consult whether receive buffers were consumed, typically via polling. One-sided RDMA performs reads/writes to memory at the “target” machine without awareness of the “target” application.
3.1 Remote Invocation

The remote invocation primitives available both in send-based and one-sided RDMA are summarized in Table 1. All primitives accept a function reference func, which is serialized into registered memory and executed remotely in the destination thread dest. C++ lambda captures allows users to include additional variables to the remote invocation context. All primitives accept a Synchronizer object called sync, which are semaphores that get decreased when either (i) the function has been transmitted in the sender thread; or (ii) the function has been invoked in the receiving thread. The actual behavior of sync is specified via template parameters to the remote calls. When the semaphore resides in registered memory, and we operate under behaviour (ii), the (remote) semaphore notification is done using RDMA write.

The call_buffer variants, besides including context variables via lambda captures, pass a buffer of unspecified type to the function executed remotely. The first variant of call_buffer writes orig_buffer (using RDMA write) into dest_buffer, and only then calls func on the destination thread, passing a pointer to the fully-written dest_buffer as an additional parameter. The second variant of call_buffer calls a helper function on the destination thread that (a) copies orig_buffer (using RDMA read) from the source thread into dest_buffer, and only then calls func on the (local) destination thread, with the fully-written dest_buffer as an additional parameter. Users can perform these steps either synchronously or in an asynchronous thread (controlled by a template parameter called Async in Tbl. 1). For one-sided remote invocation (via RDMMessengers and RDMAAggregators, described in Sec. 4.4), we can pass the function and buffer of call_buffer side-by-side in a single operation. The primitive call_return accepts a pointer to a remote object that will be populated with the return of the invocation of func in the destination thread; and finally the broadcast and broadcast_buffer primitives are respectively similar to call and call_buffer but employ a broadcast tree in order to affect all threads.

3.2 Data Transfer

Data transfer implies and necessitates memory allocation, so this responsibility is part of our lowest-level DTutils. We allow applications to allocate memory locally or remotely. All allocations perform memory registration, which is mapping its physical location into the IB interface’s translation hardware. Registration is required by RDMA for most memory, except segments small enough to fit inside hardware interface buffers. DTutils internally implements techniques for fast memory registration [12, 8], and provides a variety of memory allocators with different semantics (linear, circular, best-fit, etc). Details are discussed on Sec. 4.2.

We also expose to applications functions for remote memory allocation, and allow users to constrain remote memory residence to a specific NUMA zone, named directly or indirectly by a (long-lived) application thread’s name.
Primitive | Effect |
---|---|
`call(dest, func, sync)` | Thread `dest` calls `func()`. |
`call_buffer(dest, func, buffer, sync)` | Thread `dest` calls `func(buffer)`; buffer transmitted with the call. |
`call_buffer(dest, func, orig_buffer, dest_buffer, sync)` | Thread `dest` calls `func(dest_buffer)`; `orig_buffer` copied to `dest_buffer` via RDMA write. |
`call_buffer(dest, func, orig_buffer, sync)` | Thread `dest` calls `func(buffer)`; `orig_buffer` copied to `buffer` via RDMA read. |
`call_return(dest, func, orig, sync)` | Thread `dest` calls `func()`; return value copied back into `orig` via RDMA write. |
`broadcast(func, sync)` | Call on all threads using a broadcast tree. |
`broadcast_buffer(dest, func, orig_buffer, dest_buffer, sync)` | `call_buffer` (1st variation) on all threads using a broadcast tree. |
`broadcast_buffer(dest, func, orig_buffer, sync)` | `call_buffer` (2nd variation) on all threads using a broadcast tree. |

Table 1: Remote invocation primitives provided by DSComm (send-based) and RDMAMessenger/RDMAAggregator (one-sided). The `sync` parameter controls send/recv notification. Template parameters are discussed in the text.

Remotely-allocated memory is identified by a handle class called `RemoteMemoryLocator`.

## 4 Implementation

Given an overview of Seriema, we now describe some implementation details that merit more careful presentation.

### 4.1 Selective Signaling & Memory Management

By default, work requests submitted to IB are *signaled*, meaning that they will generate an RDMA completion queue entries upon finishing. Most commonly, however, we are not interested in completion events for every operation, and can thus reduce the overhead of generation and polling of completion events by making most operations *unsigned*. Each IB device has a maximum number of outstanding unsigned transfers before they overflow (call it $u_{max}$), but when signaled operations complete, we are sure that all unsigned operations that preceded it have also been completed. Hence, for all $k \mod u_{max} = 0$, we
can make only the $k$-th operations signaled, avoiding overflow and minimizing overhead.

With multiple threads, it is not enough to define an atomic counter $k$ for each operation within an RDMA QP, and poll its completion queue only when $k = 0 \mod u_{\text{max}}$. In the time between the one where $k$ becomes $0 \mod u_{\text{max}}$ and the one in which we flush the completion queue, other threads may perform operations and overflow the device. The solution is to define an additional atomic counter $k'$, indicating the number of times the queue pair’s completion queue was flushed, called the flush number. As long as $\lfloor k/u_{\text{max}} \rfloor > k'$, all threads perform signaled operations, flush the QP’s completion queue, and update $k'$ to the right flush number. The key feature, however, is that the flush number $k'$ not only avoids overflowing the device with unsignaled operations, but also helps recycle registered memory every $u_{\text{max}}$ operations.

We tag all RDMAMemory handles used with an IBTransmitter with its associated QP’s identifier and current flush number just after an operation is performed. When the IBTransmitter’s flush number increases, we know that all unsignaled operations tagged with smaller flush numbers are completed, and thus multiple memory regions are instantly freed with a single atomic update on memory. Higher abstractions for memory management automatically circulate buffers according to such tags (Sec. 4.2). Our selective signaling / memory recycling protocol is wait-free [15], meaning that threads never block another thread’s progress when they have to update flush numbers. We consider this property essential for any low-latency system or service, particularly in latency-sensitive applications where the input might introduce high load imbalance and long data dependencies between threads.

### 4.2 NUMA-Awareness and Memory Registration

DTutils provides a variety of memory allocators to its users. In the most fundamental level, a set of concurrent RDMAAllocators, one per NUMA zone, is responsible for retrieving NUMA-local memory in chunks of 1 GB superpages, registering the whole segment at allocation time. Registering superpages reduces the overhead of mapping physical memory into the device’s memory management hardware multiple times [12, 5]. RDMAAllocators are still accessible directly by the application, from inside their respective machine, or even remotely. RDMAAllocators also allow users to consume smaller chunks of 2MB superpages within each 1GB superpage.

In addition to RDMAAllocator, users have access to circular allocators, linear-circular allocators, and general allocators.

A circular allocator subdivides 2MB chunks from RDMAAllocator into a circular buffer of RDMAMemory units. We move across units as long as they are free in the QPs in which they were last used, according to the protocol described in Sec. 4.1. In a circular buffer, note that we would be unable to move to a unit $a$ (free in a QP $q_a$) if we have some previous unit $b$ not free in a QP $q_b$. In order to avoid introducing latency because some QPs move slower than others, we allow latency-critical applications to create one circular allocator per IBTransmitter
per thread—an application-controlled tradeoff between latency and memory consumption. In circular allocators, the unit size is user-configured, and the total buffer size grows linearly or exponentially, up to a maximum limit, all user-configured.

The linear-circular allocator operates exactly like the circular allocators, but allows users to obtain segments inside units, avoiding internal fragmentation. Finally, our general allocator obtains 1GB or 2MB chunks from RDMAAllocator and uses a traditional best-fit/first-fit strategies to allocate memory for applications. Chunks larger than 1GB are of course supported, but the superpage optimization described previously cannot be guaranteed for such large allocations.

4.3 Send-Based RDMA
Recall that all of our invocation primitives are available in send-based or one-sided RDMA. In principle, send-based invocation seems inadequate, because (i) send-based invocations are limited by the size of the memory units posted by the service thread running on the receiver machine; and (ii) send-based RDMA has lower throughput than one-sided RDMA, because each call generates completion events on the service thread running on the receiver machine; and (iii) the handles for the buffers containing remote calls need to be further distributed to worker threads on the receiver machine.

Despite the shortcomings of send-based RDMA, particularly the overhead of generating and polling completion events, send-based calls do not require any a priori negotiation of receive buffers between sender and receiver threads, a property that we call no-setup. This is very convenient to implement higher-level services—for example, our one-sided invocation services (RDMAMessenger and RDMAAggregator) themselves use no-setup calls to allocate remote memory buffers across the system, and once this setup is performed, these buffers are used for one-sided RDMA operations. Given that flexibility, we allow applications to launch service threads, which handle send-based remote invocation, and calls directed to and handled by service threads are denoted service calls. We also allow service threads to receive send-based remote invocation directed at worker threads (not to the service thread itself), populating receive queues each associated with worker threads.

Both send-based and one-sided remote invocation require identification of the function to be executed remotely, which could be as simple as the function address—when address-space layout randomization (ASLR) is disabled for processes1. While we support this mechanism, we also allow users to (i) register their functions with application-level identifiers; or (ii) generate identifiers at compile time, because every lambda function $F$ invoked remotely has a helper class FunctionWrapper$<F>$, and its type ID can serve as function identifier.

1Generating non-position-independent executables also forces disabling ASLR.
4.4 The Remote Invocation Subsystem

Our highest-level subsystem RIutils provides one-sided remote invocation and message aggregation. Our core abstraction for one-sided remote invocation is the RDMAMessenger class. It is created on a “sender” thread $s$ with a “destination” thread $d$ as a constructor parameter. Two RDMAMessengers with symmetrical sender/destination IDs are themselves called symmetrical, and synchronize with each other, forming two channels for bidirectional communication. Each channel has its own set of memory buffers. For the sake of presentation, we will consider a single direction, calling one side sending and the other side receiving.

4.4.1 Sender-Controlled Buffer Management

Upon the first invocation (or a call to setup()) in the sending RDMAMessenger, the sending thread performs a no-setup service call on the destination machine in order to obtain $k$ handles of registered memory. These handles point to memory resident in the NUMA zone of the receiving thread, and are represented by RemoteMemoryLocator objects. We call the remote memory buffer, which will subsequently receive serialized calls, a chunk. As chunk allocations are done with no-setup service calls, there is no involvement of the receiving thread, reducing latency and avoiding deadlocks that would be possible otherwise. The sending RDMAMessenger stores handles for remote memory, and the receiving RDMAMessenger is notified of chunks operated remotely by the sending thread.

Users configure a parameter $c$, the number of handles obtained (or chunks allocated) per service call transaction, and a parameter $c_{\text{max}}$, the maximum number of obtained chunks (or allocated chunks). Our default settings have $c = 2$ and $c_{\text{max}} = 16$. Each handle points to a contiguous section of eight 2MB superpages in the receiving machine by default (the size user-configurable).

The no-setup service calls performing chunk allocation will: (i) allocate memory in the NUMA zone of the receiving thread; (ii) write the sending thread information on a header located inside the first allocated chunk; (iii) insert a handle for each allocated chunk into a concurrent, wait-free map “owned” by the receiving thread, where the key is the sending thread ID (the map is called incoming memory map); and finally (iv) returns the chunk handle for the sending thread. Once the sending thread has obtained chunks, it may start serializing calls into them via RDMA write; once the receiving thread polls for messages in its receiving RDMAMessenger, it will note a new chunk associated with the sender thread in its incoming memory map, which will be extracted and incorporated into a circular buffer maintained by the receiving RDMAMessenger. The sending RDMAMessenger maintains a circular buffer of remote handles, and the receiving RDMAMessenger maintains a circular buffer of chunks. These symmetric circular buffers have to be kept “symmetric” even when new chunks are allocated (and new handles are obtained). We explain how this is done below.

Each chunk contains a Header, with two sub-structures called Producer and Consumer. The header is physically located in the receiving thread, and the Consumer section is modified only with local operations by the receiving
thread; the **Producer** section is modified only with remote operations by the sending thread. The **Producer** header contains a monotonic, global offset of the first and last serialized calls within the chunk, updated by the sending thread when requested by users, or when a chunk is filled.

The destination thread updates the consumed offset in the chunk header via a local operation. At this point, the sending thread could technically obtain, in **pulling** fashion, the last consumed offset by performing an RDMA read operation in the chunk header. This however introduces unnecessary waiting on the sender thread, so we implement a pushing mechanism as well. When the **first** chunk is allocated on the receiving thread, information about the sending thread – particularly, the memory location of the sending thread’s **RDMAMessenger** – is passed within the chunk header. Hence, the receiving thread notifies its last consumed offset in a **pushing** fashion through an RDMA write operation to a variable inside the sending thread’s **RDMAMessenger**, but only does that infrequently: this write happens only when a chunk is completely consumed. So now the sending thread can decide whether it can move forward within its circular buffer as the buffer gets fully consumed, without polling the receiver thread continuously.

If the sending thread cannot move forward within its circular buffer, it can allocate more chunks in the receiving machine up to $c_{\text{max}}$, obtain the handles, and grow the handle circular buffer in the sending **RDMAMessenger**. The receiving thread will eventually notice the newly allocated chunks, and also incorporate them into the chunk circular buffer in the receiving **RDMAMessenger**. To ensure the the circular buffers remain perfectly symmetrical, whenever the sending thread finishes filling a chunk, it writes a special bit inside the **Producer** header of the associated chunk indicating the position where newly allocated chunks should be added in the receiving **RDMAMessenger**. This hints to the receiving thread to look into its incoming memory map in order to obtain new chunks, which have been allocated by the sending thread in order to expand the circular buffer.

Aside from this, note that the **only** actual information about chunk consumption needed by the sending thread to decide whether it can rotate among its circular buffer of handles is a value written by the receiving thread in a pushing fashion. Hence, no remote invocations (and incurred latency) are needed at these particularly critical moments in the sending thread. If more chunks are needed, the protocol described in the previous paragraph allocates more memory without any involvement of the receiving thread (and incurred latency). If the sending thread reaches the limit of chunk allocations, remote invocations in the sending thread fail (that is, return false), until consumption picks up.

For convenience, we make available a higher-level class, called **RDMAMessengerGlobal**, that creates on demand the appropriate **RDMAMessengers** at the sending thread upon the first communication attempt with any given destination thread.
4.4.2 Aggregation & Zero-Copy

An **RDMAAggregator** is a class that operates on top of **RDMAMessengers** and batches multiple remote calls into a single remote data transfer. We support two modes of operation: (i) a “traditional” approach, where remote invocations are batched locally, and flushed via **RDMAMessenger** to the destination thread at 4K intervals (size is user-configurable); or (ii) an “overflow” approach, where we perform local aggregation only when an underlying **RDMAMessenger** cannot make progress by its own. This occurs, for instance, when the sending thread is waiting for the destination thread to consume serialized calls and the number of allocated chunks has already reached \( c_{\text{max}} \). In the overflow approach, we denote the invocations batched locally in the sending thread as **exceeding**. Users can specify memory consumption limits for exceeding invocations before invocations fail at the application level. Note that we honor RDMA’s “zero-copy” principle by having exceeding invocations be serialized in registered memory, later transferred remotely – noting lambda serialization into registered memory would need to happen regardless of aggregation.

5 Experiments

We now describe our evaluation of: (i) the **DTutils** subsystem, via microbenchmarks (Sec. 5.1); (ii) the **DSfabric** and **RIutils** subsystems, by assessing the cost of send-based and one-sided remote method invocation, as compared to the basic data transmission from **DTutils** (Sec. 5.2); and (iii) the MCTS distributed framework implemented using our system (Sec. 5.3). We have 4 machines, each with one dual-port QSFP Mellanox ConnectX-3 Pro VPI FDR InfiniBand switch, connected with the host by x8 PCI express 3.0. Each port on each device is connected to a Mellanox SX6012 X-2 FDR InfiniBand switch. The MTU of our interfaces is set to 4096. Each machine is a dual-socket Intel Xeon E5-2620v4, with 8 cores each running at 2.1GHz (varies between 2.0 and 2.5 with TurboBoosting), and 128GB of memory. Each core can run two hyperthreads (HT), giving a total of 16 cores (non-HT) or 32 cores (HT) per machine. The tool **numactl --hardware** reports relative intra-node distances of 10 and inter-node distances of 21 (no units). We use Open MPI 2.1.1 and compile with **gcc -O3 -std=c++17**.

5.1 Microbenchmarks on DTutils

We first evaluate the **DTutils** subsystem, recalling it is also a **detachable library**: applications can use it directly and separately from the other abstractions of Seriema. On Fig. 2, **infinity (⋆ss)** refers to the IB library from [4], measured here for the sake of comparison. We implement selective signaling manually with that library. **DTutils (⋆ss)** refers to our own **DTutils**, accessing it through **IBQueuePair** directly, thus we also implement selective signaling manually in this case. Finally, **DTutils (auto)** refers to using our own **DTutils**, accessing
it through IBTransmitter, thus selective signaling and circular buffer memory management are automatic, following the protocol of Sec. 4.1.

Figure 2 (p. 15) shows, for each setting, the number of messages per second with varying message sizes, representing an average of three tests, with each test performing 128K transmissions in total. We provide the equivalent MB/s for some data points, as they will be useful in further analyses ahead. The graph suggests that we have lower per-message overhead, which affects mostly small-sized messages. It also suggests that our automatic features introduce little overhead, as we compare DTutils (+ss) with DTutils (auto). Note that our automatic selective signaling also eliminates around 5 lines of C/C++ per remote invocation in the user code related to selective signaling, and also takes care of memory management for the transmission circular buffer. A single line of code is enough to provide remote invocation with both features enabled automatically when using IBTransmitters.

![Message sizes in B vs. throughput in msg/s. Equivalent MB/s annotated under the x axis.](image)

**5.2 Remote Invocation Performance**

Table 2 shows the throughput of call under: (i) send-based RDMA, provided by DSfabric (labeled send); one-sided RDMA, provided by RDMAMessengers in RIutils (labeled write); (iii) overflow aggregation with one-sided RDMA (labeled ovfl); (iv) traditional aggregation, flushing at every 4K buffer marks (labeled trad); and (v) for the sake of analysis, max-raw reports the throughput using send-based RDMA in DTutils, excluding any copying costs. The send, write, trad, and ovfl metrics, include the copying costs. Importantly, max-raw in send-based RDMA at the largest buffer sizes (say, 4K) tends to the theoretical maximum using one-sided RDMA, because the impact of polling becomes increasingly smaller at larger transfers. We test three different sizes of remote invocations (small/8B, medium/64B and large/256B). We expect that most applications will perform remote invocations with context and parameters in that size magnitude. Each reported number is an average of three experiments, with each transmitting 65 million messages.

As write/ovfl (one-sided RDMA) closely follow max-raw (send-based RDMA) at their equivalent buffer sizes, we can visualize how one-sided RDMA is much
Table 2: call throughput (MB/s): send-based (send), one-sided (write), one-sided + local aggregation (trad), one-sided + overflow aggregation (ovfl). Control is send-based without serialization (max-raw).

| size (B) | send   | write | trad   | ovfl   | max-raw |
|----------|--------|-------|--------|--------|---------|
| 8        | 12.07  | 38.39 | 2116.78| 36.52  | 35.84   |
| 64       | 112.95 | 301.47| 4256.14| 283.15 | 291.93  |
| 256      | 367.08 | 1129.82| 5318.89| 1061.37| 1135.74 |

better-performing than send-based RDMA: write and ovfl include the cost of function serialization (with sizes between 8B-256B), but max-raw does not. All metrics for remote invocation (all but max-raw) also include the invocation overhead of an empty function (not elided by the compiler), although we measured no impact in the overall transfer throughput, which is expected. So, with one-sided RDMA, we have low overhead both in function serialization done at the sender, and function invocation done at the receiver. In fact, “margins are tight”: even the very thin code layer of RDMAAggregator in ovfl mode, which directly forwards calls to an underlying RDMAMessenger as long as no local buffering is performed, imposes a 9% performance slowdown in throughput.

As discussed in Sec. 4.3, our one-sided services (RDMAAggregator and RDMAMessenger) use send-based RDMA in their initial setup. RDMAAggregator in ovfl mode is at most 6.2% under max-raw up to 256B (1065 MB/s vs 1135 MB/s), including function serialization and invocation overhead. The biggest performance gain comes with RDMAAggregator in trad mode (flushing at every 4KB data mark): as function sizes increase, its throughput quickly converges to at most 2.5% under our theoretical maximum, namely max-raw for 4KB (5318 MB/s in 256B calls in trad vs 5464 MB/s for 4KB transfers in DTutils). The throughput variation of RDMAAggregator in trad mode at different function sizes is indicative of the function serialization overhead, although this overhead is sublinear in relation to decreasing function sizes.

5.3 Usability and Distributed MCTS

We evaluate the usability of Seriema by implementing an MCTS distributed framework, a higher-level middleware itself that performs the MCTS computation in a distributed fashion given a user-provided MCTS application specification. The following section discusses the reasons why MCTS is considered as appropriate for that goal. The parallelization approach for our MCTS framework is the tree-parallel approach [8], discussed in Sec. 2. We test our MCTS framework (and hence the performance and usability aspects of Seriema) with the board game Hex.

Seriema consists of around 10050 non-empty C++14-conformant LoC, while the MCTS framework (considered as “application” relative to Seriema) contains three components: (a) a class representing tree nodes (475 non-empty, C++14-
conformant LoC); (b) the worker thread functions that start rollouts over distributed tree nodes (210 non-empty, C++14-conformant LoC); and (c) the main function, which specifies configuration, and launches/places threads within the system (30 non-empty, C++14 conformant LoC). Finally, the Hex specification (considered as “application” now relative to the MCTS distributed framework) contains about 200 non-empty LoC. So, the MCTS distributed framework (MCTS logic) + the MCTS application specification (game logic) consist together only around 8% of our implemented codebase.

5.3.1 Rationale for System Validation

Apart from applicability considerations of MCTS (discussed in Sec. 2), a distributed MCTS framework is appropriate to evaluate Seriema since: (i) it relies on a distributed data structure, as we choose to employ the tree-parallel distribution strategy of [8]; (ii) it is a memory-bound problem, which suggests that it could highly benefit from the NUMA-awareness in Seriema not-only in the remote invocations themselves, but also in the application-level, as we expose to applications our “internal” tools for NUMA-aware, automatic memory management; (iii) depending on the application, MCTS can behave rather irregularly, as the best choices in the MCTS computation at each node might be consistently biased toward certain children. The combination of factors (i) and (iii) is particularly challenging, because while distributing MCTS nodes uniformly at random across machines is applicable to irregularity, it completely destroys the communication locality. In theory, low-overhead, aggregate communication would mitigate these problems substantially, and we certainly intend to evaluate this aspect of Seriema as it reflects in a real-world relevant application.

5.3.2 Setup and Usability Considerations

An MCTS tree node is represented by class MCTS_Node. Each MCTS_Node is “owned” by a particular thread. A global variable root initially points to the unique MCTS_Node in the tree, owned by thread 0. We denote the number of threads as \( n \), the number of processes as \( n_p \), and the number of machines \( n_m \).

In our experiment, the computation is divided into phases. In each phase, all threads residing in the same process as the root owner start rollouts, up to a maximum of \( 4K \cdot n \) rollouts. When an expansion needs to be performed in a node \( N_p \), owned by thread \( T_p \), a thread is selected uniformly at random to become the owner \( T_e \) of a child node \( N_e \). A (possibly remote) call_buffer is done for \( T_e \), which will create the new MCTS_Node \( N_e \), later notifying the parent of the new node location, by means of a call. We create children nodes using call_buffer as we have to pass a buffer representing the game state associated with \( N_p \). When a selection needs to be performed in the (possibly remote) node \( N_e \), a call is performed on the appropriate child in order to continue moving down the tree. We can easily set the MCTS framework to only perform remote calls, so even when \( T_p \neq T_e \), if they both share a process, \( T_p \) will create the child on behalf of \( T_e \). We did not see any statistically-significant change
in performance under this setting, indicative of low-overhead in remote call serialization.

Note that since all threads in the same process as the root node operate concurrently on it, there might be a gap between (a) when a call is made for $T_c$ in order to create $N_c$, and (b) when $T_c$ actually finishes notifying the parent of $N_c$’s location. We have a mechanism called deferred selection, which essentially accumulates selection requests in the parent, and relies on the child notification to, in addition to notifying the parent $N_p$ of the child $N_c$’s address, resume deferred selections at the parent, directing them to the child.

When the selection process reaches a leaf node, a simulation request is distributed uniformly at random among the threads that reside locally on such a leaf node, using wait-free concurrent queues. Upon consuming from those queues, worker threads perform random simulations (16 by default), and perform backpropagation upwards, using again distributed call and call_buffer. The selection updates visit counters on the nodes as it moves down the tree, and the backpropagation updates win counters moving upwards. Each node has such counters associated with each of its children, in order to implement selection.

Notably, most code in the MCTS framework layer is related to message synchronization (e.g. deferred selections), or to shared-memory synchronization (e.g wait-free concurrent data structures to store children pointers, relaxed-memory atomic operations to update visit/win counters in the virtual loss technique, etc). In the MCTS framework, the only aspects related to inter-thread communication are (a) the creation of RDMAAggregators, a one-time operation per worker thread when it launches; (b) performing remote calls using call and call_buffer invocations inside MCTS_Node; and (c) shutting down the RDMAAggregators, which sends a unidirectional shutdown signal to the symmetrical RDMAAggregators, also a one-time operation per worker thread. While Seriema allows users to obtain chunks of remote memory, and copy data directly over them, being able to perform remote invocations over remote machines proved incredibly convenient, from an implementer’s perspective, for the completion of the MCTS framework.

5.3.3 Performance Considerations

We tested many configurations for process/thread placement, and show results in Fig. 3. In our experiments, threads communicate using RDMAAggregators, in trad or ovf1 mode, as discussed in Sec. 4.4. In the figure, a configuration is shown in the form $m \times p \times t$, where $m$ is the number of machines, $p$ is the number of processes per machine, and $t$ is the number of threads per process. Prefixes 1× or 1×1× are omitted.

We recall that each machine has 2 NUMA zones, each with 8 cores and 16 hyperthreads. Within one machine, single-process configurations 1, 2, 4, and 8 pin threads to cores within a single NUMA zone. Configuration 16 has 8 threads in each NUMA zone, avoiding hyperthreading, and configuration 32 has 16 threads in each NUMA zone, relying on hyperthreading. Within one
machine, two-process configurations 2x4, 2x8, and 2x16 each have one process in its own NUMA zone, without hyperthreading for 2x4 and 2x8, and with hyperthreading for 2x16.

In Fig. 3 we note scalability within a single NUMA zone up to 4 processes, at which point the 2x4-configuration outperforms the 8-configuration. Despite a bigger cost with inter-process remote calls in the 2x4-configuration (rather than only intra-process calls in the 8-configuration), we have less memory pressure on the cache-coherence protocol, because at most 4 threads (rather than 8 threads) concurrently operate on a single memory operation in order to update visits/wins counters as to implement the virtual loss technique. The 2x8- and 2x16-configurations benefit similarly compared to the 16- and 32-configurations, but in \texttt{trad} mode the 2x8-configuration (resp. 2x16-configuration) scales at slope 0.75 compared to the 2x4-configuration (resp. 2x8-configuration), where the ideal would be 1.0. Application profiling seems to indicate that this is due to (i) increased memory pressure on the atomic operations for visits/wins counters; and (ii) the impact of hyperthreading, as relative costs of functions are similar among the configurations. In \texttt{ovfl} mode, there is an additional penalty with high thread counts compared to 16 threads. We measured the maximum number of buffered chunks in \texttt{ovfl} mode, which happens whenever threads generate remote calls faster than receivers consume them. This number was bigger than 1 in only 0.016\% of symmetrical \texttt{RDMAMessengers}, so threads almost always had chunk space in order to perform remote writes, without waiting for remote allocations. The reason for the overhead in \texttt{ovfl} mode is simply the 20x to 60x worse performance compared to \texttt{trad} mode with remote invocations in the order of 8-64 B in size, as seen in Tbl. 2 in the previous section. With larger thread counts, traditional aggregation pays off. The 2x2x8, 3x2x8, and 4x2x8 represent optimal NUMA placement with less memory pressure as we have two processes per machine, as discussed before, and they represent our best-scaling configuration as we double the number of threads up to 64 physical cores among the machines.
6 Conclusion

We present Seriema, a middleware that provides integrated RDMA-based remote invocation, NUMA-aware remote memory allocation, asynchronous data transfer, and message aggregation in idiomatic C++1x. As Seriema aims to support distributed data structures and applications sensitive to latency or subject to irregular communication, we evaluate the usability of our system by implementing a higher-level Monte-Carlo Tree Search framework. Our MCTS framework executes a user-provided MCTS problem specification in a distributed fashion, and the MCTS problem specifications do not require users to implement any code related to RDMA communication, memory management for RDMA (handled by Seriema), or MCTS logic (handled by the MCTS framework). We show that our remote invocations have low overhead with a comparative microbenchmark, and our MCTS application framework, while simulating plays of the board game Hex, scales well up to the number of non-hyperthreaded CPU cores in our testing environment.

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Listing 1: **Real** C++ code demo. Please refer to additional discussion in the text.

```cpp
void demonstration_thread(int offset) {
    seriema::init_thread(offset);
    RDMAMessengerGlobal messenger;

    for(uint64_t i = 0; i < number_operations; i++) {
        RDMAMemory *registered_data = seriema::thread_information->circular_allocator->allocator();
        int filled_size = fill_data(registered_data->get_buffer()); // User function
        bool result = messenger.buffer<RetryAsync>(destination_thread, [source_thread = i](void *buffer, uint64_t size) {
            // Remote function body:
            // - can use "source_thread", "buffer", "size"
            // - "buffer" has all "size" bytes filled in the source thread
            // - requires synchronization only if it accesses concurrent objects
        }, source, 0, filled_size, synchronizer);
        // Processing remote messages can also be delegated to helper threads
        if(i % 128 == 0) { messenger.process_calls_all(); } }
    }

    Synchronizer remote_synchronizer;
    seriema::call<RemoteNotify>(0, [source_thread = i] { // Remote function body:
        // "source_thread" notified it is done
    }, remote_synchronizer);
    remote_synchronizer.spin_nonzero_operations_left();
    messenger.shutdown_all();
    seriema::finalize_thread();
}
```

### A Real Code Example

We provide a real C++11 example of Seriema’s features on Lst. 1 below. Line 1 initializes the thread-local allocators discussed Sec. 4.2), and by default we allocate one per thread. Line 2 initializes one RDMAMessengerGlobal per destination thread (see Sec. 4.4) as we instantiate one RDMAMessengerGlobal. Line 6 allocates registered memory in the thread-local circular buffer, on which we produce data in line 7. Line 8 performs a remote call_buffer on the RDMAMessenger associated with the destination thread, using one-sided RDMA. Note the similarity with line 21, where we perform an invocation using send-based RDMA. In line 17, the thread handles messages received from others, noting that handling remote invocations could be delegated to separate helper threads. Naturally, in this case, the application is expected to make sure that remote calls use proper synchronization to avoid data races with respect to the destination thread and to other helper threads while accessing shared objects.

Lines 18 and 21 also demonstrate how lambda captures on the source thread are serialized and become available for the destination threads in a natural way. Finally, every call or call_buffer invocation, when using one-sided RDMA,
can specify what to do in case the remote buffer where we write serialized calls becomes full. If **Retry** is specified, the invocation blocks until remote buffers become available, and if **RetryAsync** is specified, the serialized invocation is pushed to a buffer where helper threads asynchronously try to finish the operation, guaranteeing a per-thread FIFO order. On line 21, the **RemoteNotify** specifies that once the receiver consumed the call, it will notify the **Synchronizer** in the source, in this case with send-based RDMA. If the **Synchronizer** passed to the remote invocation was wrapped inside a **RemoteObject** class, the notification for the sender would be done by one-sided RDMA. The sender blocks until the notification is received in line 25.