An Introduction to Remote Direct Memory Access

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Outline

Traditional Networks

TCP

- Reliable, connected
- Byte stream-oriented protocol
- Buffered in kernel-space on both sides
- Flow control via window size
- Synchronous: data transfer operations block until they complete

IP/Ethernet

- Each switch and router completely independent, autonomous
- Datagram-oriented
- Lossy—relies on upper layers to retransmit lost packets

RDMA

- Message-oriented protocol
- “Zero-copy”: direct application virtual memory to application virtual memory transfers
- Kernel bypass: userspace application talks directly with the hardware to do data transfers
- Flow control via credits at link layer—no loss due to congestion
- Asynchronous: data transfer operations placed onto queue
- Message latencies on the order of microseconds

RDMA Technologies

InfiniBand [InfiniBand 2007]

- Most popular RDMA implementation
- Defines entire network stack from top to bottom
- Speeds: SDR (10 Gbps), DDR (20 Gbps), QDR (40 Gbps), FDR (56 Gbps)

iWARP (Internet Wide-Area RDMA Protocol) [RFC 5040, RFC 5041, RFC 5044]

- Implements RDMA on top of TCP with 3 layers
- Defined by IETF

RoCE (RDMA over Converged Ethernet) [InfiniBand 2010]

- Implements upper layers of InfiniBand on top of Ethernet
- Defined by InfiniBand Trade Association

Terminology

- A local-area RDMA network is usually referred to as a **fabric**
- A **channel adapter** is the hardware component that connects a system to the fabric
  - iWARP refers to it as an RNIC (RDMA Network Interface Card)

OpenFabrics Alliance

InfiniBand Verbs

InfiniBand defines a set of "verbs" to communicate with RDMA hardware, but not an API

- Semantic details but no specific function calls, data structures, ...

OFA Verbs

The OpenFabrics Alliance (OFA) created a vendor-independent C API to access the InfiniBand verbs

- Very low-level API, involving direct manipulation of data structures
- Lots of code needed to write a very simple data transfer

OFED

The OFA periodically releases OFED (OpenFabrics Enterprise Distribution) which contains drivers and userspace libraries/tools for RDMA

Outline

Memory Registration

Current RDMA hardware has specific requirements for memory used in data transfers:

- Memory must not be modified by application during data transfer
- Memory cannot be paged out by operating system—physical to virtual mapping must be fixed

Registration

To deal with the second requirement, applications must **register** memory to be used in data transfers

- Returns a local and remote key pointing to memory area
- Registration keys are supplied as part of data transfer request

Queues

Queue Pairs

- A **queue pair** is associated with each side of an RDMA transfer
- Assigned an integer identifier that is sent to the other communication endpoint(s)
- A queue pair consists of a send and a receive request queue
- Post Send Request and Post Recv Request verbs used to add **work requests** to the queue

Completion Queues

- A send and receive **completion queue** is associated with a queue pair (at creation time)
- May be same queue for both, or two separate queues
- Poll Completion Queue verb used to remove completion events from the queue

Data Transfer Operations

SEND/RECV

- Analogous to socket send/recv, but using direct transfers
- RECV **must** be ready prior to arrival of SEND
- Both sides of transfer receive notification of completion

RDMA_WRITE

- Push of local data to remote memory area
- Sender must supply virtual address and remote key of destination memory area
- Sender initiates and receives notification; receiver is completely **passive** and receives no notification

Data Transfer Operations (continued)

RDMA_READ

- Pull of remote memory area to local memory area
- Receiver must supply virtual address and remote key of destination memory area
- Receiver initiates and receives notification; sender is completely **passive** and receives no notification
- Inefficient since request moves in opposite direction from data

RDMA_WRITE_WITH_IMM

- Like RDMA_WRITE, but receiver receives notification as well
- Request includes four bytes of out-of-band **immediate data**
- Immediate data included in receive completion event
- Supported by InfiniBand and RoCE, but not current version of iWARP

Outline

Subnet Manager

- One master **subnet manager** (SM) is elected for the entire fabric
- Can have other SMs, but for failover only
- Controls switching tables for entire fabric
- Switching tables must be recomputed every time a node added/removed to/from fabric

Node Addressing

Global Identifier (GID)

- Every InfiniBand node has an assigned **EUI-64 identifier**
  - 24 bit company identifier assigned by IEEE
  - 40 bit extension identifier assigned by manufacturer
- **Global Identifier** (GID) is a 128-bit identifier built from **EUI-64 identifier** and 64-bit **subnet prefix** assigned by SM
- Used for routing between subnets

Local Identifier (LID)

- Local ID (LID) is a 16-bit identifier dynamically assigned by SM
- Used for switching within a subnet
- may change during switching table recalculation

Transport Protocols

InfiniBand specifies four transport protocols:

- Reliable Connected (analogous to TCP)
- Reliable Datagram
- Unreliable Connected
- Unreliable Datagram (analogous to UDP)

InfiniBand Packet Format [InfiniBand 2007]

Local Route Header
Base Transport Header
Extended Transport Headers *(if needed)*
Packet Payload
Invariant CRC
Variant CRC

This is the packet format for packets using InfiniBand transport protocols

Local Route Header

<table>
<tr><td>0</td><td></td><td></td><td></td><td></td><td></td><td></td><td>7</td><td>8</td><td></td><td></td><td></td><td></td><td></td><td></td><td>15</td></tr>
<tr><td colspan="4">virtual lane</td><td colspan="4">version</td><td colspan="4">service level</td><td colspan="2">reserved</td><td colspan="2">LNH</td></tr>
<tr><td colspan="16">destination LID</td></tr>
<tr><td colspan="5">reserved</td><td colspan="11">packet length</td></tr>
<tr><td colspan="16">source LID</td></tr>
</table>

- Virtual Lane and Service Level fields used in QoS
- LNH is Link Next Header–1 bit global/local, 1 bit IB/raw
- Packet Length is in 4-byte words

Base Transport Header

0 7	8			15	16 23 24 31
opcode	SE	M	PadCnt	Version	Partition Key (P_KEY)
reserved	destination QPN				
A reserved	packet sequence number				

- SE (Solicited Event) bit indicates that CQ event handler should fire
- M is related to Automatic Path Migration
- PadCnt is number of bytes of padding in the Packet Length
- Partitions are analogous to VLANs on Ethernet
- Note that source Queue Pair Number is not part of this header

RDMA Extended Transport Header

<table>
<tr><th>0 … 31</th><th>32 … 63</th></tr>
<tr><td colspan="2">Virtual Address</td></tr>
<tr><td>Remote Key (R_KEY)</td><td>DMA Length</td></tr>
</table>

ACK Extended Transport Header

0 7	8 15 16 23 24 31
Syndrome	Message Sequence Number

Outline

Simultaneous Operations

Due to the asynchronous nature of RDMA, a key part of using RDMA effectively is having as many simultaneously outstanding transfer operations as possible.

The usual strategy is:

- Post as many RECV operations as possible
- Post a new RECV as soon as a RECV completion event fires
- Post send operations as soon as the data is ready to send

More simultaneous operations are needed over distance

Completion Event Detection Strategies

Event Notification

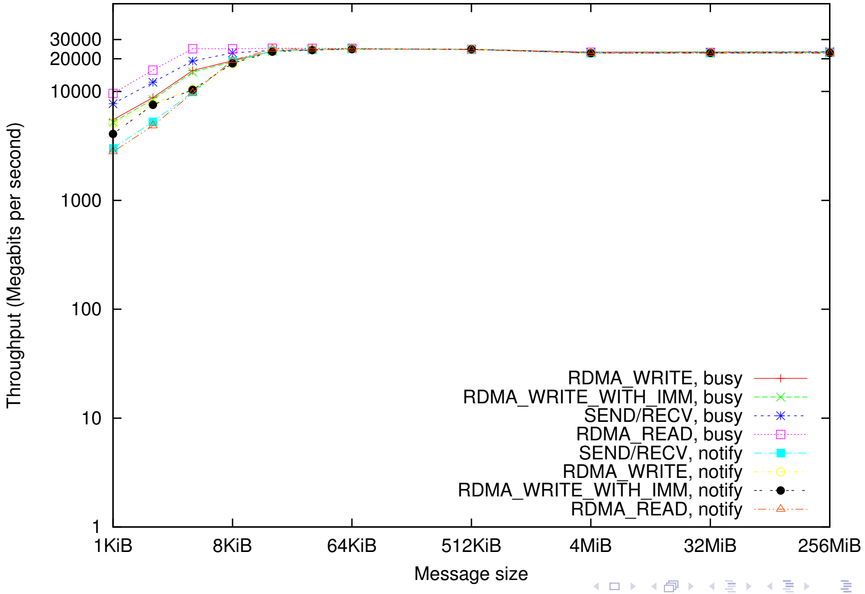
- User requests notification when a completion event arrives
- Requires kernel involvement to put thread/process to sleep and wake it up when event arrives
- Benefit: Very low CPU usage
- Cost: Lower throughput and higher latency

Busy Polling

- User polls in a tight loop for new completion events
- Get events as soon as they arrive with no kernel involvement
- Benefit: High throughput and low latency
- Cost: 100% CPU usage

[MacArthur and Russell 2012]

Completion Event Detection Strategies

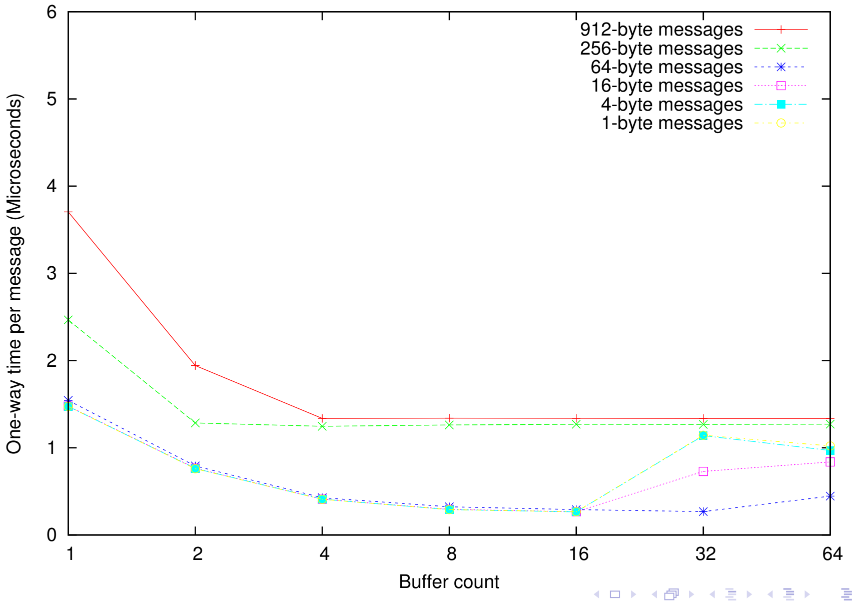


Inline Send Requests

- The **inline** feature causes an RDMA adapter to copy a small message into a buffer on the CA at the time that the work request is posted
- Subject to channel adapter limit
- Avoids need for memory registration on sending side
- Performance gain for very small messages, but hurts for larger messages

[MacArthur and Russell 2012]

One-way Time for Inline Send Requests



Outline

UNH EXS (Extended Sockets)

- Based on ES-API (Extended Sockets API) published by the Open Group [Interconnect 2005]
- Extensions to sockets API to provide asynchronous, zero-copy transfers
  - Memory registration (exs_mregister(), exs_mderegister())
  - Event queues for completion of asynchronous events (exs_qcreate(), exs_qdequeue(), exs_qdelete())
  - Asynchronous operations (exs_send(), exs_recv(), exs_accept(), exs_connect())
- UNH EXS supports SOCK_SEQPACKET (reliable message-oriented) and SOCK_STREAM (reliable stream-oriented) modes

Sample asynchronous send operation

```
exs_mhandle_t mh = exs_mregister(buf, bufsize, EXS_ACCESS_READ);
exs_qhandle_t qh = exs_qcreate(10);

if (exs_send(fd, buf, bufsize, 0, mh, 0, qh) < 0) {
        perror("Could not start send operation");
        /* bail out */
}

/* do work in parallel with data transfer */

exs_event_t ev;
if (exs_qdequeue(qh, &ev, 1, NULL) < 0) {
        perror("Could not get send completion event");
        /* bail out */
}
fprintf(stderr, "Send of %d bytes complete with errno=%d; actual byte count %d\n",
        bufsize, ev.exs_evt_errno,
        ev.exs_evt_union.exs_evt_xfer.exs_evt_length);
```

UNH EXS Protocol

For SOCK_SEQPACKET:

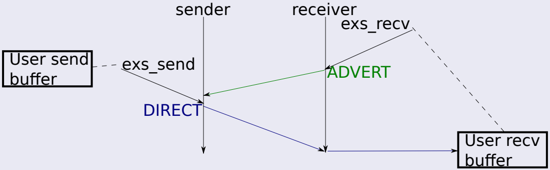
- Receiver sends ADVERT containing address, length, and remote key of receive buffer
- Sender uses RDMA_WRITE_WITH_IMM to write data directly into destination buffer

For SOCK_STREAM, same as above, except there is also an intermediate receive buffer that is used if no advertisements are available

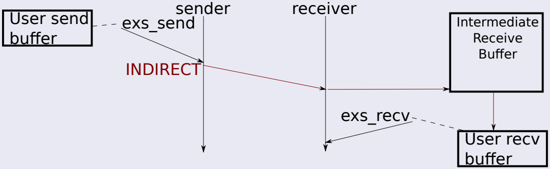
UNH EXS: Dynamic SOCK_STREAM Protocol

Key idea: allow sender to use direct or indirect transfer based on current conditions

Direct Transfer

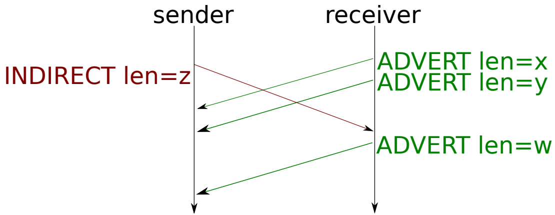


Indirect Transfer



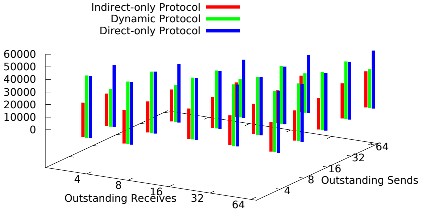
UNH EXS: Dynamic SOCK_STREAM Protocol

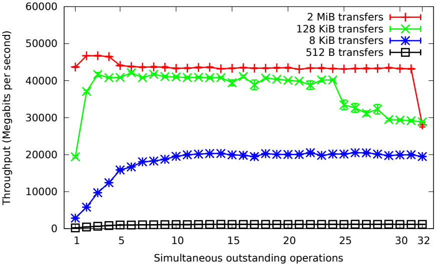
Key challenge: Advertisements may arrive late (i.e., after sender has already sent corresponding data), and sender must distinguish between "fresh" and "stale" advertisements

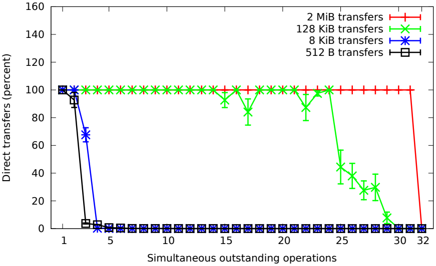


Here, the sender does not know how many exs_recv operations (corresponding to ADVERTs) were consumed by its INDIRECT send. The solution is to assign each advertisement a phase number and increment the phase number at the sender when an indirect transfer is sent.

UNH EXS Dynamic Stream Protocol Performance







Outline

Summary

- RDMA is used all over high-performance computing due to its high throughput and low latency
- Asynchronous, kernel bypass, and “zero-copy”
- Three standard protocol stacks: InfiniBand, iWARP, and RoCE

Open Issues

- OFED verbs library
  - Too complex for casual network programmers
  - Does not match semantics of consumers such as MPI
- Applications not written with RDMA in mind
  - Messages that are large for TCP/IP are **small** for RDMA
  - Applications often use only double buffering if they have any support at all for multiple outstanding transfers
- Subnet manager scalability
- Performance over distance
- Error handling

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