Implementing TCP Sockets over RDMA

Patrick MacArthur <pio3@cs.unh.edu>
Robert D. Russell <rdr@cs.unh.edu>

Department of Computer Science
University of New Hampshire
Durham, NH 03824-3591, USA

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1 Background

2 RSockets

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Differences Between RDMA and TCP Sockets

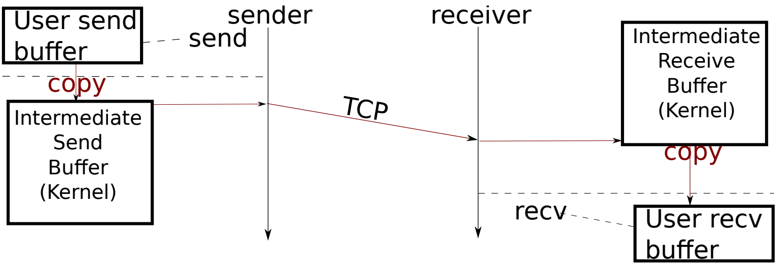
RDMA

- "Kernel bypass": data transfers with no OS involvement
- "Zero-copy": Direct virtual memory to virtual memory transfers
- Message-oriented
- Asynchronous programming interface

TCP Sockets

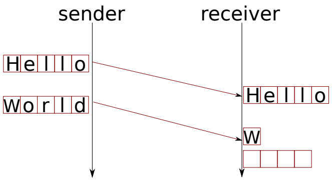
- Kernel involvement in all data transfers
- Buffered in kernel-space on both sides of connection
- Byte-stream oriented protocol
- Synchronous programming interface

TCP Sockets Data Transfer

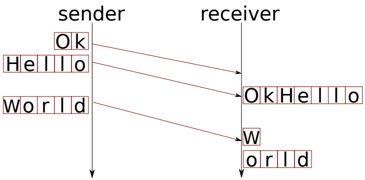


Message vs. Byte Stream Semantics

Message Transfer (RDMA, UDP, SOCK_SEQPACKET)



Byte Stream Transfer (TCP/IP)



Issue: O_NONBLOCK is *not* asynchronous

- Try-and-fail
  - **recv**: if no data in buffer, fail immediately with EAGAIN
  - **send**: if buffer is full, fail immediately with EAGAIN
- POSIX poll/select notify when an operation can start, **not** when operations complete
  - **recv**: poll/select returns when data in buffer
  - **send**: poll/select returns when empty space in buffer
- This is **incompatible** with RDMA semantics
  - RDMA: send or recv **queued**, call returns immediately, proceeds in background

Issue: Implementing "Zero-copy"

- Memory to be used for RDMA must (currently) be **registered**
- Existing sockets programs do not register memory to be used in I/O operations
  - May use any malloc'd/stack variable
  - May be freed at any time
  - Sockets programmers assume memory can be reused as soon as send() returns
- Not respecting adapter's natural alignment can cause severe performance degradation, especially on FDR adapters

Prior Implementations of Sockets over RDMA

- Sockets Direct Protocol (SDP) (defined by InfiniBand specification [InfiniBand 2011])
    - BCopy (buffering on both sides)
    - ZCopy (zero-copy, send() blocks) [Goldenberg 2005]
    - AZ-SDP (asynchronous, zero-copy, segfault handler) [Balaji 2006]
- uStream (asynchronous but not zero-copy) [Lin 2009]

Current Implementations of Sockets over RDMA

- SMC-R (100% compatibility with TCP/IP and sockets)
- rsockets (high-performance sockets replacement) [Hefty 2012]
- UNH EXS (extended sockets) [ISC 2005, Russell 2009, MacArthur 2014]

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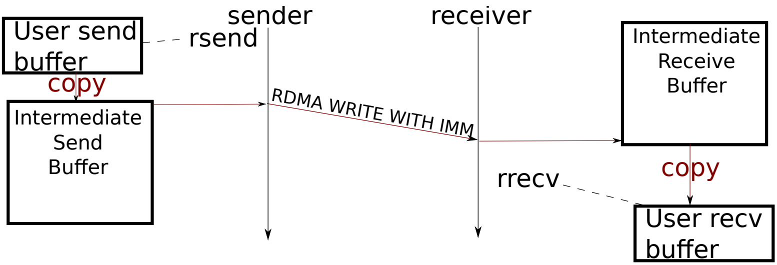
RSockets

- Goal: compatibility with sockets, high performance
- Built on RDMA, so kernel bypass for data transfer path
- Buffer copies on both sides of connection
- Supports SOCK_STREAM (TCP-like) and SOCK_DGRAM (UDP-like) modes
- API is currently synchronous only

RSocket Data Transfer with rsend/rrecv



all in user space

"Zero-copy" with rsockets

- Can perform zero-copy using riomap and riowrite
- **riomap** maps a virtual memory region to an **offset**
- **riowrite** directly transfers data to iomap'd buffer identified by offset

Example

```
/*************** at receiver ****************/
off_t target_offset = riomap(fd, target_buf, len, PROT_WRITE, -1);
rsend(fd, &target_offset, sizeof(target_offset), 0);
rrecv(fd, empty, sizeof(empty), MSG_WAITALL);

/*************** at sender ****************/
off_t target_offset;
rrecv(fd, &target_offset, sizeof(target_offset), MSG_WAITALL);
/* write big buffer to server */
riowrite(fd, local_buf, length, target_offset, 0);
/* notify recipient of completion */
rsend(fd, &empty, sizeof(empty), 0);
```

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UNH EXS (Extended Sockets)

- Based on ES-API (Extended Sockets API) published by the Open Group [ISC 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

UNH EXS Programming

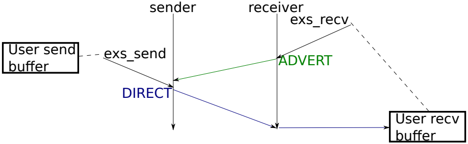
Example

Example asynchronous send operation

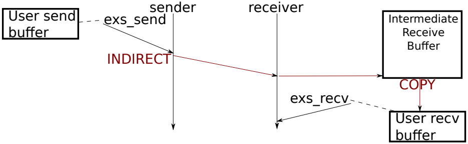
```
exs_mhandle_t mh = exs_mregister(buf, bufsize, EXS_ACCESS_READ);
exs_qhandle_t qh = exs_qcreate(10);

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/%d␣bytes␣complete␣with␣errno=%d\n",
        bufsize, ev.exs_evt_union.exs_evt_xfer.exs_evt_length,
        ev.exs_evt_errno);
```

UNH EXS Protocol

Direct Transfer (SOCK_STREAM and SOCK_SEQPACKET)



Indirect Transfer (SOCK_STREAM only)



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Performance Evaluation

- Comparison of TCP, rsockets, and EXS using **rstream** and **riostream** tools
  - rsockets rrecv()/rsend(): rstream
  - rsockets riomap()/riowrite(): riostream
  - TCP: rstream
  - EXS: rstream-like utility modified to take advantage of asynchronous operations
- No optimization done for rsocket and TCP cases
- Systems used: Intel Xeon 2.40 GHz E5-2609 CPUs, 64 GB RAM, PCI-e Gen 3
- HCAs: Mellanox ConnectX-3 FDR InfiniBand HCAs connected via Mellanox SX6036 FDR InfiniBand switch

Throughput Comparison

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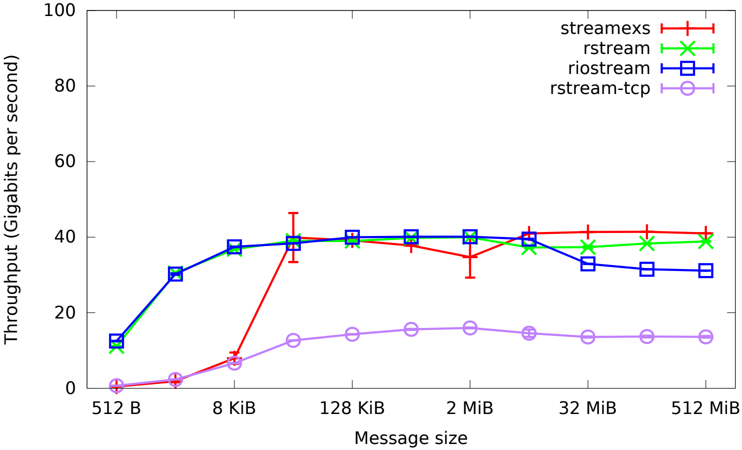
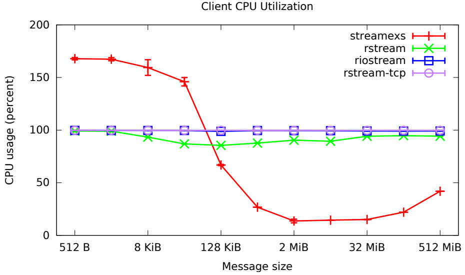
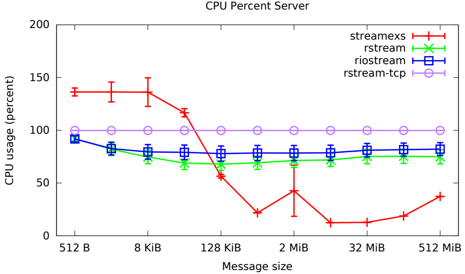
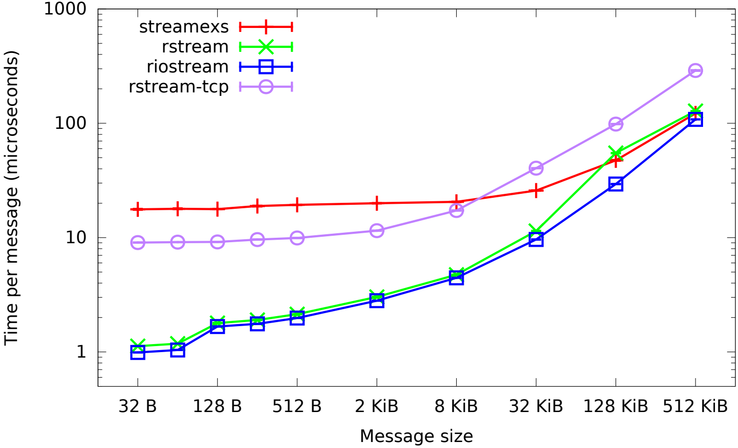


CPU Usage Comparison

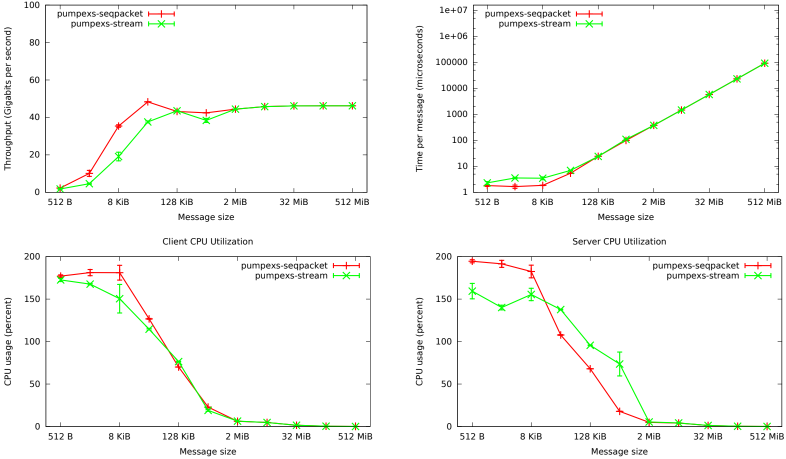




Latency Comparison



UNH EXS SOCK_SEQPACKET vs. SOCK_STREAM



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Conclusions

- Socket buffering is implicit in sockets API
- Efficient zero-copy requires extensions to API
  - ES-API provides asynchronous operation
  - rsockets provides riomap()/riowrite()
- Message-oriented is more efficient to implement over RDMA than byte stream-oriented

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References IV

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