Designing and Developing Performance Portable Network Codes

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Outline

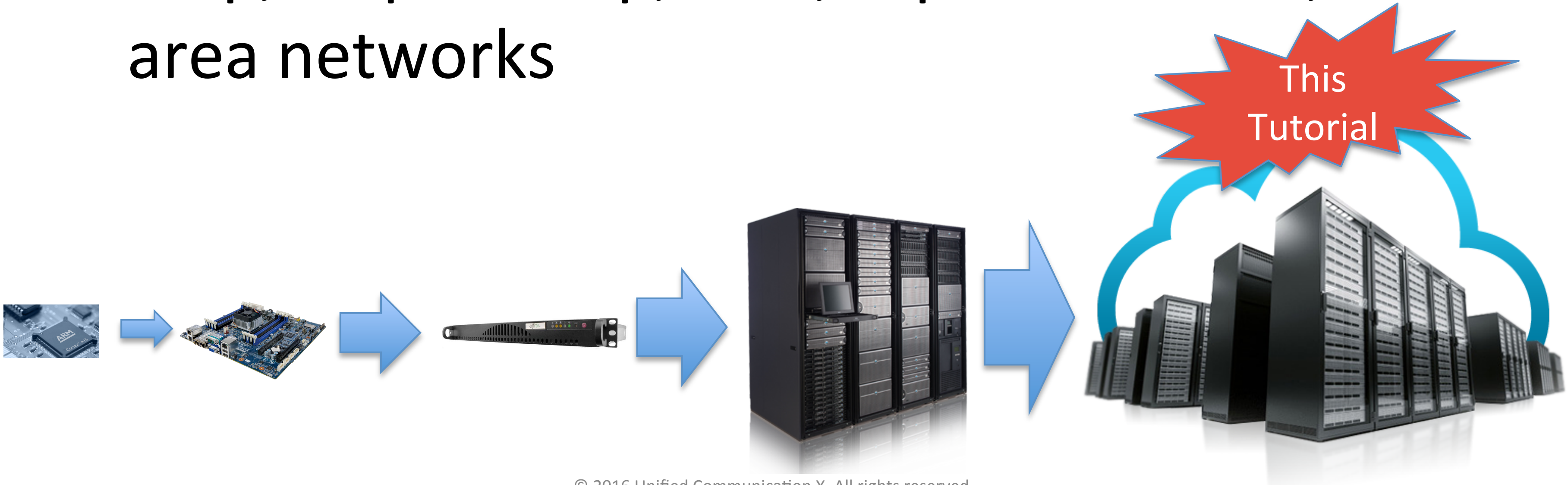
- Modern Interconnect Technologies
  - Overview of existing technologies
  - Software interfaces
  - Unified Communication X Framework
- UCX programming by example
  - OpenMPI
  - OpenSHMEM
- UCX Examples

Pavel Shamis (Pasha), ARM Research

MODERN INTERCONNECT TECHNOLOGIES

Interconnects

- Interconnects are everywhere: System-on-Chip, chip-to-chip, rack, top-of-the-rack, wide area networks

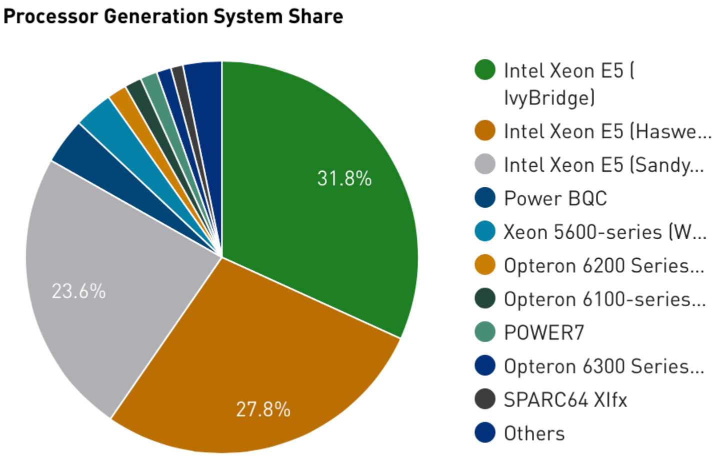


Ethernet

- Used Everywhere
- Typically used in combination with TCP/UD/IP
- Socket API
- 10/25/50/100 Gb/s
- Not covered in this tutorial
- What is covered ? – HPC Interconnects

Modern HPC Systems

- Not that "special" anymore
  - Commodity CPUs
  - Commodity Accelerators
  - Commodity Memories
- Still "somewhat" special
  - Form factor
  - System density
  - Cooling technologies (warm water, liquid cooling ,etc.)
- The "secret sauce" – Interconnect
  - Fujitsu Tofu, IBM Torus, SGI NumaLink, Cray Aries/Gemini, TH Express-2, InfiniBand
  - Software stack – MPI + OpenMP/OpenACC

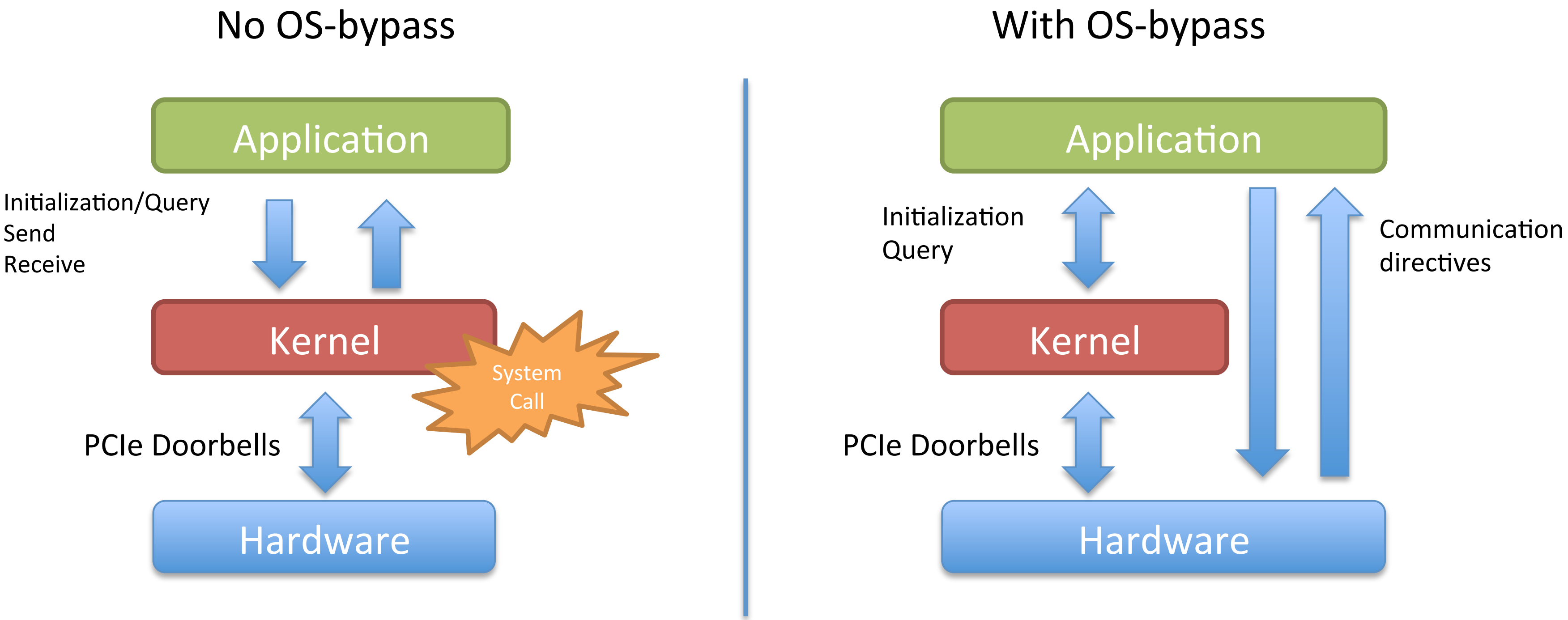


http://www.top500.org

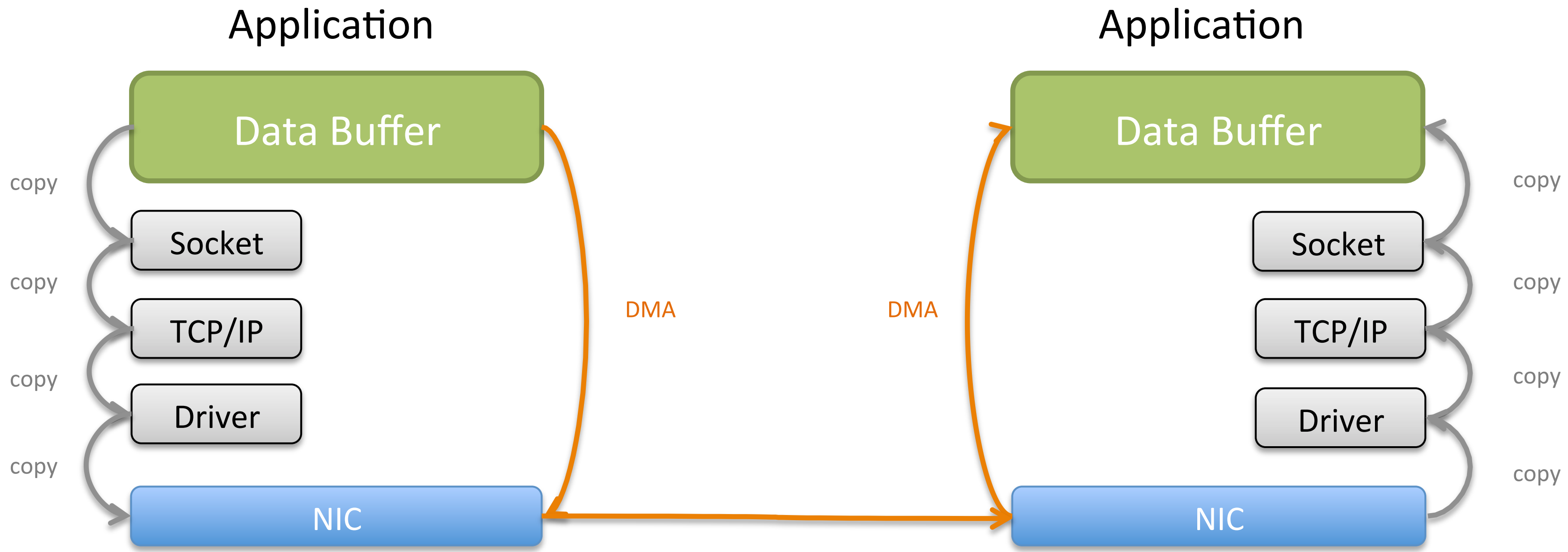
The “secret sauce”

- Low Latency (< 1 usec)
- High Bandwidth (> 100 Gb/s)
- High injection rates (> 150M messages/sec)
- Network topologies and adaptive routing
- Scalability – efficient support for communication with millions of cores
- OS bypass (direct access to the hardware from the user level)
- Remote Direct Memory Access (avoid memory copies in communication stack)
  - Read, Write, Atomics
- Offloads
  - Collective operations, support for non-contiguous data, GPU-Direct, Peer-Direct, tag-matching, etc.
- Highly optimized network software stack (MPI + OpenMP/ACC, PGAS, etc.)
  - Low software overheads 0.6-1.2 micro-sec (MPI latency)
  - Low memory footprint (avoid O(n) memory allocations)
  - Performance portable APIs

OS Bypass


No OS-bypass
Application
Initialization/Query
Send
Receive
Kernel
System
Call
PCIe Doorbells
Hardware
With OS-bypass
Application
Initialization
Query
Kernel
PCIe Doorbells
Hardware
Communication
directives

RDMA



Application
Data Buffer
Socket
TCP/IP
Driver
NIC
copy
copy
copy
copy
DMA
DMA
Application
Data Buffer
Socket
TCP/IP
Driver
NIC
copy
copy
copy
copy

Advanced Semantics

- RDMA Read and Write
- Send / Receive
  - Send / Receive with TAG matching
- Atomic Operations on Remote Memory
  - SWAP
  - CSWAP
  - ADD
  - XOR
- Group Communication directives
  - Reduce, Allreduce, Scatter, Gather, AlltoAll

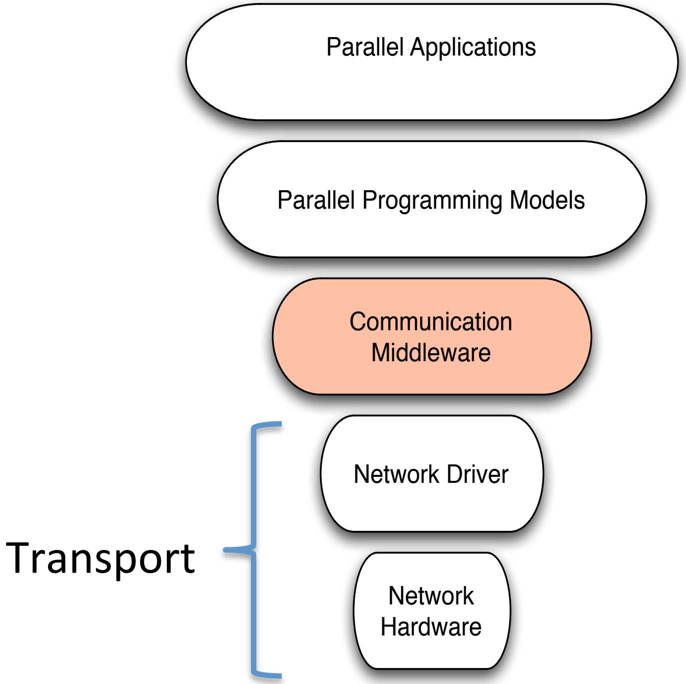
Socket API:
send() and recv(), or write() and read(), or sendto() and recvfrom()

Interconnects Overview

	InfiniBand	RoCE	iWarp	RapidIO	NVIDIA NVLINK	Intel OmniPath	Bull BXI	Extoll
Standard	Open IBTA	Open IBTA	Open IETF	Open RapidIO	Proprietary	Proprietary	Proprietary	Proprietary
Production BW (Mb/s)	100Gb/s	100Gb/s	40Gb/s	40Gb/s	640Gb/s – 1600Gb/s	100Gb/s	100Gb/s	100Gb/s
Latency (us)	0.6	0.98	3.4	<1	<1	<1	<1	0.6-08
Hardware Terminated	No	No	No	Yes	Yes	No	No	No
Offload	HW/SW	HW/SW	HW/SW	HW	HW	HW/SW	HW/SW (?)	HW/SW (?)
RDMA	Yes	Yes	Yes	Yes	?	Yes	Yes	Yes
Market	HPC, Data Center	Data Center, HPC	Data Center, HPC	Tele, Aero, Data Center	HPC, Machine Learning	HPC, Data Center	HPC	HPC

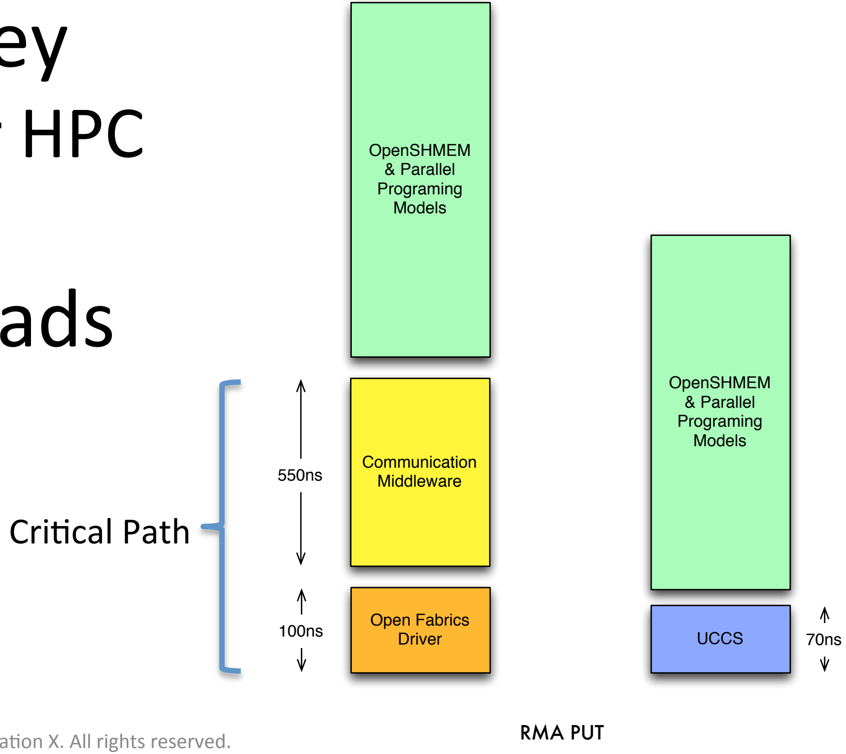
Typical HPC Software Stack

- Applications
  - CAMD, NAMD, Fluent, Lsdyna, etc.
- Programming models
  - MPI, UPC, OpenSHMEM/SHMEM, Co-array Fortran, X10, Chapel
- Middleware
  - GasNET, MXM, ARMCI, etc.
  - Part of programming model implementation
  - Sometimes “merged” with driver
- Driver
  - OFA Verbs, Cray uGNI, etc.
- Hardware
  - InfiniBand, Cray Aries, Intel OmniPath, BXI, etc.



Why we care about software stack ?

- Network latency is a key
  - Sub Micro is typical for HPC Network
- Software stack overheads



Network Programming Interfaces (beyond sockets)

- **Open Fabric Alliance**: Verbs, Udapl, SDP, libfabrics, …
- **Research**: Portals, CCI, UCCS
- **Vendors**: Mellanox MXM, Cray uGNI/DMAPP, Intel PSM, Atos Portals, IBM PAMI, OpenMX
- **Programming model driven**: MVAPICH-X, GasNET, ARMCI
- **Enterprise App oriented**: OpenDataPlane, DPDK, Accelio

Vendors Specific APIs

Pros

- Production Quality
- Optimized for Performance
- Support and maintenance

Cons

- Often "vendor" locked
- Optimized for particular technology
- Co-design lags behind

Open Source APIs

Pros

- Community (a.k.a. user) driven
- Easy to modify and extend
- Good for research

Cons

- Typically not as optimized as commercial/vendor software
- Maintenance is challenge

Research API

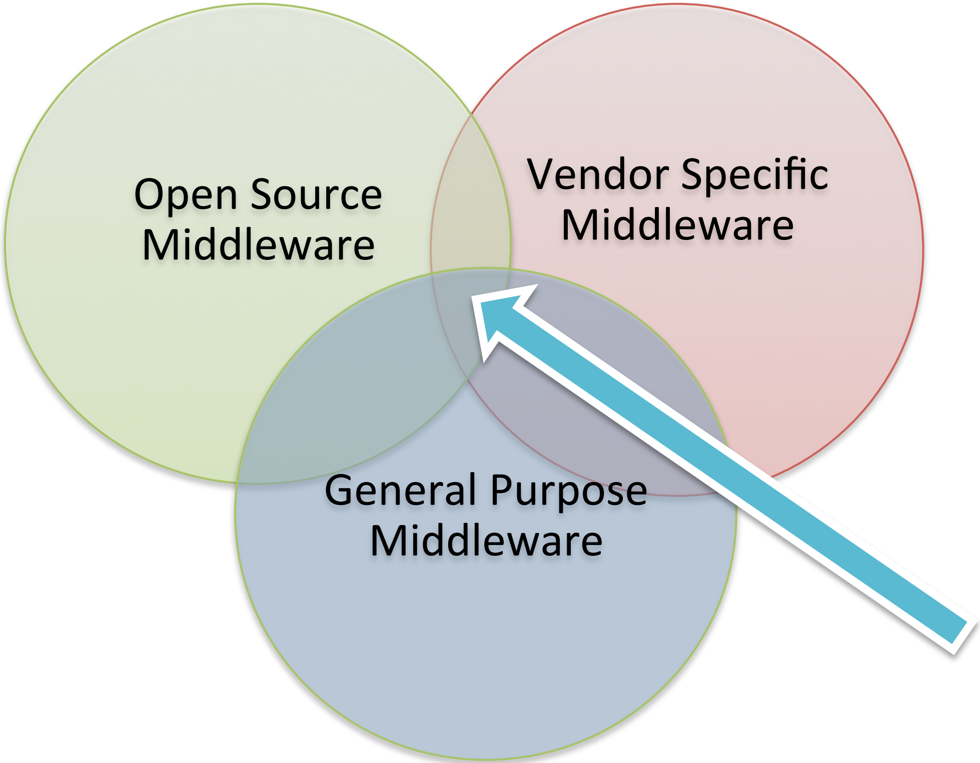
Pros

- Innovative and forward looking
  - A lot of good ideas for “free”

Cons

- Support, support, support
- Typically narrow focus

Network Programming Interfaces



Unified Communication - X Framework

UCX

History

MXM

- Developed by Mellanox Technologies
- HPC communication library for InfiniBand devices and shared memory
- Primary focus: MPI, PGAS

UCCS

- Developed by ORNL, UH, UTK
- Originally based on Open MPI BTL and OPAL layers
- HPC communication library for InfiniBand, Cray Gemini/Aries, and shared memory
- Primary focus: OpenSHMEM, PGAS
- Also supports: MPI

PAMI

- Developed by IBM on BG/Q, PERCS, IB VERBS
- Network devices and shared memory
- MPI, OpenSHMEM, PGAS, CHARM++, X10
- C++ components
- Aggressive multi-threading with contexts
- Active Messages
- Non-blocking collectives with hw accleration support

Decades of community and industry experience in development of HPC software

What we don't want to do…

Borrowed from: https://xkcd.com/927

UCX Framework Mission

- Collaboration between industry, laboratories, and academia
- Create open-source production grade communication framework for HPC applications
- Enable the highest performance through co-design of software-hardware interfaces
- Unify industry - national laboratories - academia efforts

API

Exposes broad semantics that target data centric and HPC programming models and applications

Performance oriented

Optimization for low-software overheads in communication path allows near native-level performance

Production quality

Developed, maintained, tested, and used by industry and researcher community

Community driven

Collaboration between industry, laboratories, and academia

Research

The framework concepts and ideas are driven by research in academia, laboratories, and industry

Cross platform

Support for Infiniband, Cray, various shared memory (x86-64, Power, ARM), GPUs

Co-design of Exascale Network APIs

A Collaboration Efforts

- Mellanox co-designs network API and contributes MXM technology
  - Infrastructure, transport, shared memory, protocols, integration with OpenMPI/SHMEM, MPICH
- ORNL co-designs network API and contributes UCCS project
  - InfiniBand optimizations, Cray devices, shared memory
- LANL co-designs network API
- ARM co-designs the network API and contributes optimizations for ARM eco-system
- NVIDIA co-designs high-quality support for GPU devices
  - GPUDirect, GDR copy, etc.
- IBM co-designs network API and contributes ideas and concepts from PAMI
- UH/UTK focus on integration with their research platforms

What's new about UCX?

- **Simple, consistent, unified API**
- Choosing between low-level and high-level API allows easy integration with a wide range of applications and middleware.
- Protocols and transports are selected by capabilities and performance estimations, rather than hard-coded definitions.
- Support thread contexts and dedicated resources, as well as fine-grained and coarse-grained locking.
- Accelerators are represented as a transport, driven by a generic "glue" layer, which will work with all communication networks.

UCX Framework

UC-P for Protocols

High-level API uses UCT framework to construct protocols commonly found in applications

Functionality:
Multi-rail, device selection, pending queue, rendezvous, tag-matching, software-atomics, etc.

UC-T for Transport

Low-level API that expose basic network operations supported by underlying hardware. Reliable, out-of-order delivery.

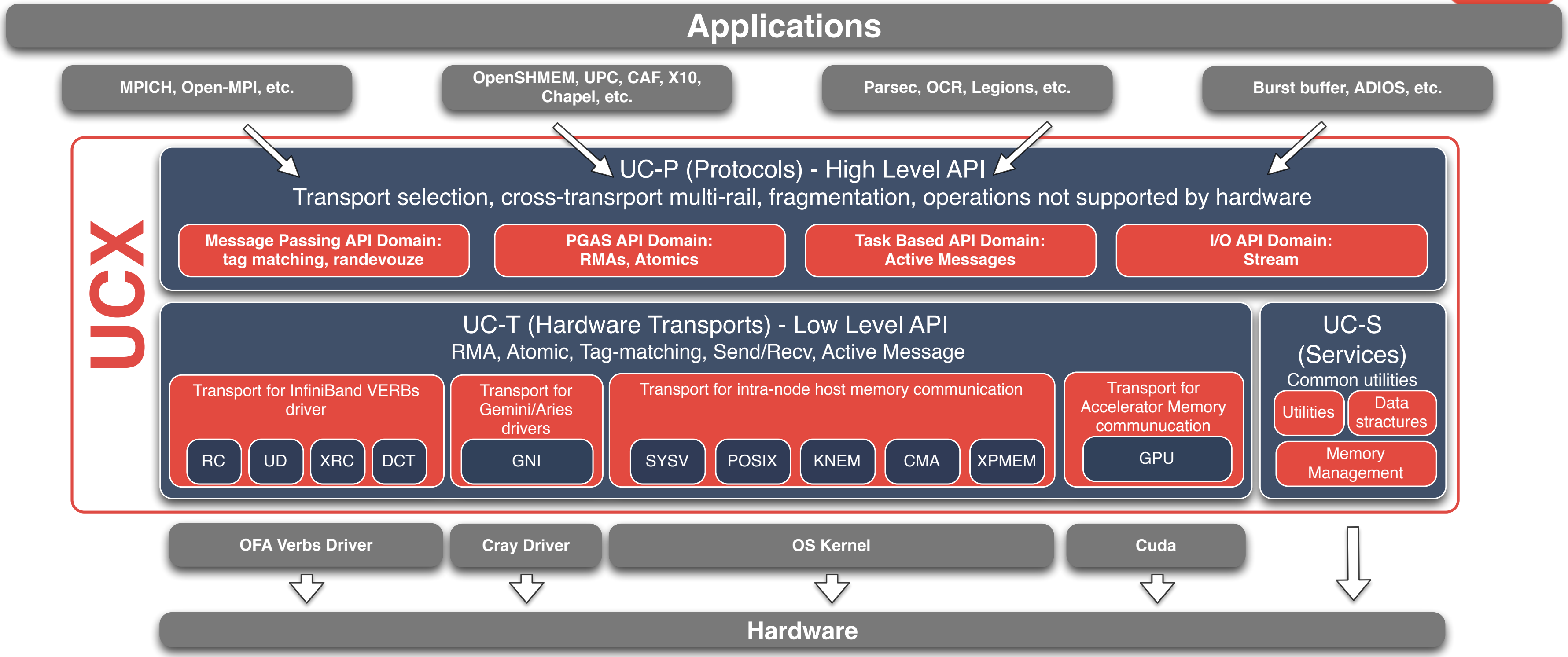
Functionality:
Setup and instantiation of communication operations.

UC-S for Services

This framework provides basic infrastructure for component based programming, memory management, and useful system utilities

Functionality:
Platform abstractions, data structures, debug facilities.

A High-level Overview



Clarifications

- UCX is not a device driver
- UCX is a communication framework
  - Close-to-hardware API layer
  - Providing an access to hardware's capabilities
- UCX relies on drivers supplied by vendors

Project Management

- API definitions and changes are discussed within developers (mail-list, github, conf call)
- PRs with API change have to be approved by ALL maintainers
- PR within maintainer “domain” has to be reviewed by the maintainer or team member (Example: Mellanox reviews all IB changes)

Licensing

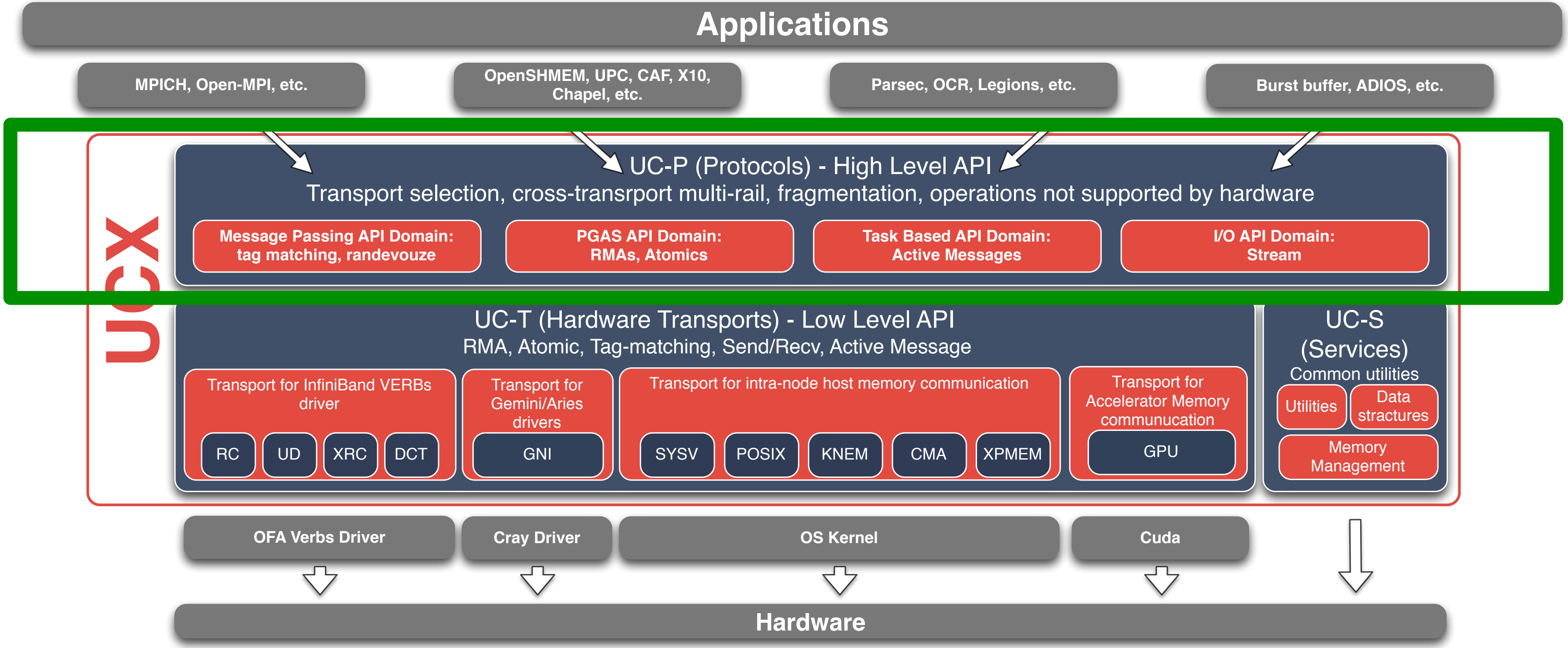
- BSD 3 Clause license
- Contributor License Agreement – BSD 3 based

UCX Advisory Board

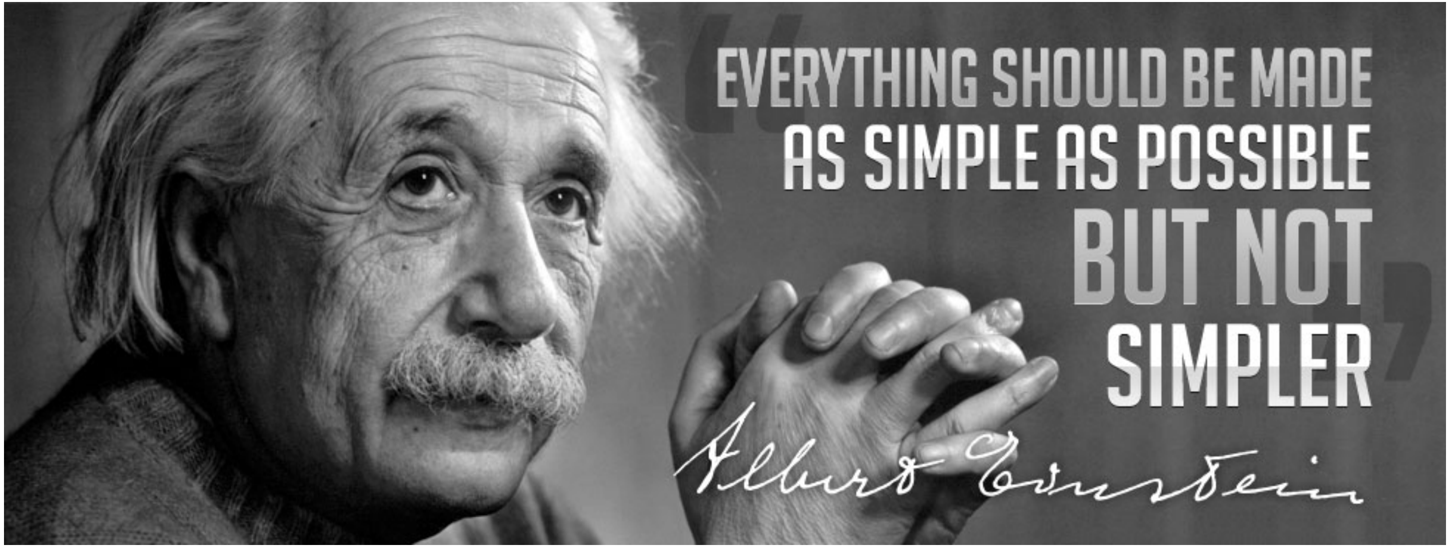
- Arthur Barney Maccabe (ORNL)
- Bronis R. de Supinski (LLNL)
- Donald Becker (NVIDIA)
- George Bosilca (UTK)
- Gilad Shainer (Mellanox Technologies)
- Pavan Balaji (ANL)
- Pavel Shamis (ARM)
- Richard Graham (Mellanox Technologies)
- Sameer Kumar (IBM)
- Sameh Sharkawi (IBM)
- Stephen Poole (Open Source Software Solutions)

API Overview

UCP - Protocol Layer



UCP Protocol



Protocol Layer

- Selects the best network for the application
  - Does not have to be the same vendor
- Optimized by default
  - Protocols are optimized for the message size and underlying network semantics
  - Intelligent fragmentation
- Multi-rail, multi-interconnect communication
- Emulates unsupported semantics in software
  - No “ifdefs” in user code
  - Software atomics, tag-matching, etc.
- Abstracts connection setup
- Handles 99% of “corner” cases
  - Network out of resources
  - Reliability
  - No message size limit
  - ….and many more

UCP Objects

- **ucp_context_h**
  - A global context for the application. For example, hybrid MPI/SHMEM library may create on context for MPI, and another for SHMEM.
- **ucp_worker_h**
  - Communication and progress engine context. One possible usage is to create one worker per thread.
- **ucp_ep_h**
  - Communication peer. Used to initiate communications directives

UCP Initialization

ucp_context_h

ucp_init (const ucp_params_t * *params*, const ucp_config_t * *config*, ucp_context_h * *context_p*)

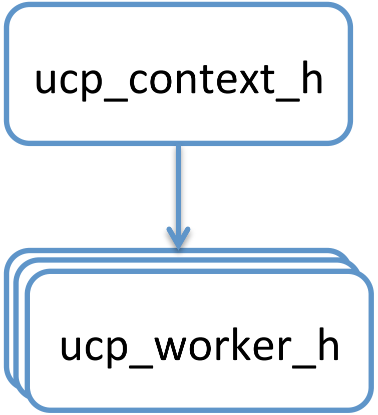
in	*config*	UCP configuration descriptor allocated through ucp_config_read() routine.
in	*params*	User defined tunings for the UCP application context.
out	*context_p*	Initialized UCP application context.

This routine creates and initializes a UCP application context.

This routine checks API version compatibility, then discovers the available network interfaces, and initializes the network resources required for discovering of the network and memory related devices. This routine is responsible for initialization all information required for a particular application scope, for example, MPI application, OpenSHMEM application, etc.

Related routines: ucp_cleanup, ucp_get_version

UCP Initialization



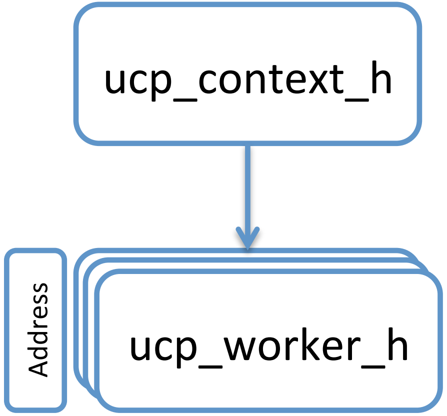
ucs_status_t **ucp_worker_create** (ucp_context_h *context,* ucs_thread_mode_t *thread_mode,* ucp_worker_h **worker_p*)

in	*context*	Handle to UCP application context.
in	*thread_mode*	Thread safety mode for the worker object and resources associated with it.
out	*worker_p*	A pointer to the worker object allocated by the UCP library

This routine allocates and initializes a worker object. Each worker is associated with one and only one application context. In the same time, an application context can create multiple workers in order to enable concurrent access to communication resources. For example, application can allocate a dedicated worker for each application thread, where every worker can be progressed independently of others.

Related routines: ucp_worker_destroy, ucp_worker_get_address, ucp_worker_release_address, ucp_worker_progress, ucp_worker_fence, ucp_worker_flush

UCP Initialization

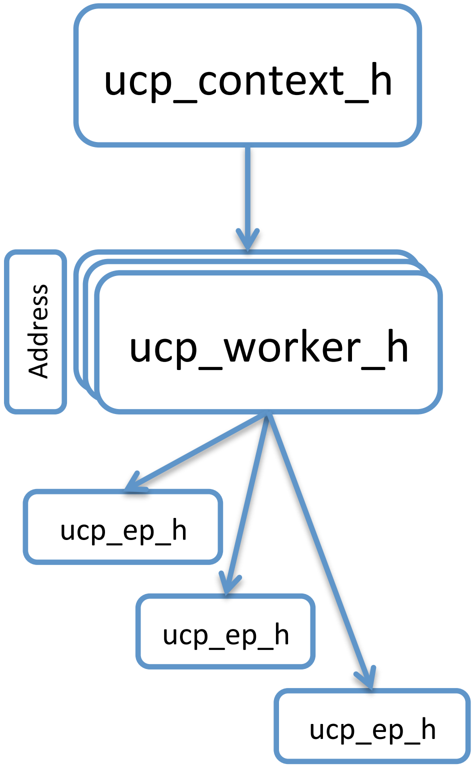


ucs_status_t **ucp_worker_get_address** (ucp_worker_h *worker*, ucp_address_t ** *address_p*, size_t * *address_length_p*)

in	*worker*	Worker object whose address to return.
out	*address_p*	A pointer to the worker address.
out	*address_↵ length_p*	The size in bytes of the address.

This routine returns the address of the worker object. This address can be passed to remote instances of the UCP library in order to to connect to this worker. The memory for the address handle is allocated by this function, and must be released by using ucp_worker_release_address() routine.

UCP Initialization



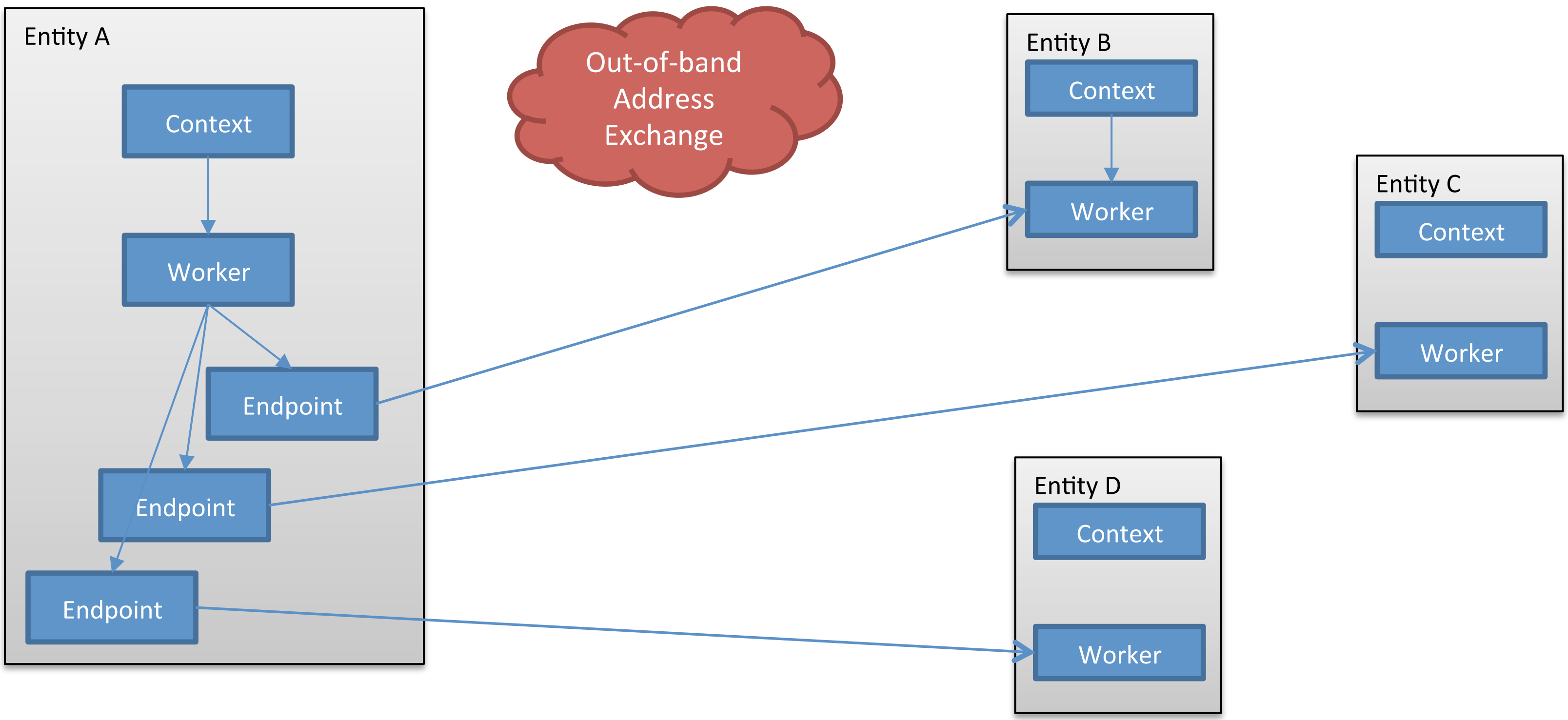
ucs_status_t **ucp_ep_create** (ucp_worker_h *worker*, const ucp_address_t * *address*, ucp_ep_h * *ep_p*)

in	*worker*	Handle to the worker; the endpoint is associated with the worker.
in	*address*	Destination address; the address must be obtained using ucp_worker_get_address() routine.
out	*ep_p*	A handle to the created endpoint.

This routine creates and connects an endpoint on a local worker for a destination address that identifies the remote worker. This function is non-blocking, and communications may begin immediately after it returns. If the connection process is not completed, communications may be delayed. The created endpoint is associated with one and only one worker.

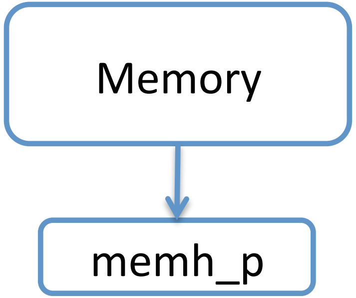
Related routines: ucp_ep_flush, ucp_ep_fence, ucp_ep_destroy

UCP API



Entity A
Context
Worker
Endpoint
Endpoint
Endpoint
Out-of-band Address Exchange
Entity B
Context
Worker
Entity C
Context
Worker
Entity D
Context
Worker

UCP Memory Management



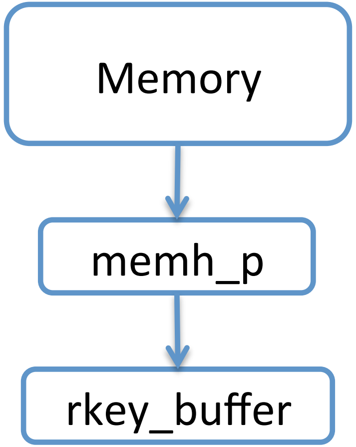
ucs_status_t **ucp_mem_map** (ucp_context_h context, void **address_p, size_t length, unsigned flags, ucp_mem_h *memh_p)

in	*context*	Application context to map (register) and allocate the memory on.
in,out	*address_p*	If the pointer to the address is not NULL, the routine maps (registers) the memory segment. if the pointer is NULL, the library allocates mapped (registered) memory segment and returns its address in this argument.
in	*length*	Length (in bytes) to allocate or map (register).
in	*flags*	Allocation flags (currently reserved - set to 0).
out	*memh_p*	UCP handle for the allocated segment.

This routine maps or/and allocates a user-specified memory segment with UCP application context and the network resources associated with it. If the application specifies NULL as an address for the memory segment, the routine allocates a mapped memory segment and returns its address in the *address_p* argument. The network stack associated with an application context can typically send and receive data from the mapped memory without CPU intervention; some devices and associated network stacks require the memory to be mapped to send and receive data. The memory handle includes all information required to access the memory locally using UCP routines, while remote registration handle provides an information that is necessary for remote memory access.

Related routines: ucp_mem_unmap

UCP Memory Management



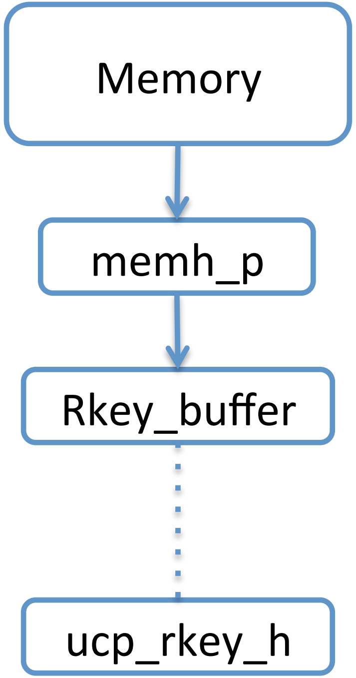
ucs_status_t **ucp_rkey_pack** (ucp_context_h context, ucp_mem_h memh, void **rkey_buffer_p, size_t *size_p)

in	*context*	Application context which was used to allocate/map the memory.
in	*memh*	Handle to memory region.
out	*rkey_buffer_p*	Memory buffer allocated by the library. The buffer contains packed RKEY.
out	*size_p*	Size (in bytes) of the packed RKEY.

This routine allocates memory buffer and packs into the buffer a remote access key (RKEY) object. RKEY is an opaque object that provides the information that is necessary for remote memory access. This routine packs the RKEY object in a portable format such that the object can be unpacked on any platform supported by the UC← P library. In order to release the memory buffer allocated by this routine the application is responsible to call the ucp_rkey_buffer_release() routine.

Related routines: ucp_rkey_buffer_release

UCP Memory Management



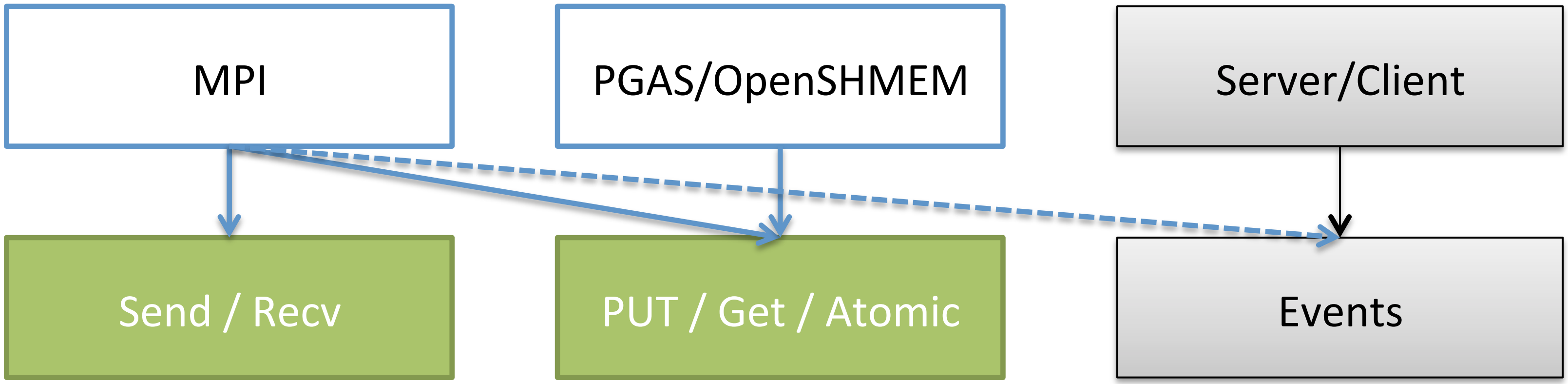
ucs_status_t **ucp_ep_rkey_unpack** (ucp_ep_h ep, void *rkey_buffer, ucp_rkey_h *rkey_p)

in	*ep*	Endpoint to access using the remote key.
in	*rkey_buffer*	Packed rkey.
out	*rkey_p*	Remote key handle.

This routine unpacks the remote key (RKEY) object into the local memory such that it can be accesses and used by UCP routines. The RKEY object has to be packed using the ucp_rkey_pack() routine. Application code should not make any alternations to the content of the RKEY buffer.

Related routines: ucp_rkey_destroy

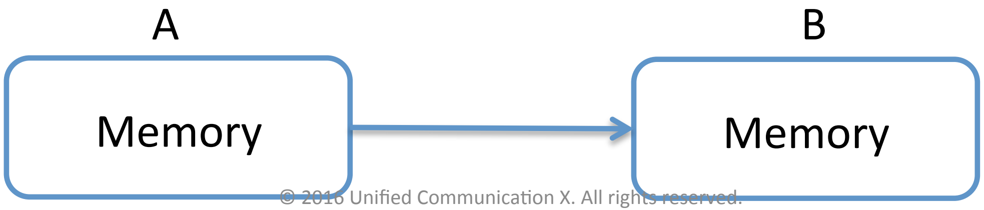
Communication Directives



Put

ucs_status_t **ucp_put_nbi** (ucp_ep_h *ep*, const void **buffer*, size_t *length*, uint64_t *remote_addr*, ucp_rkey_h *rkey*)

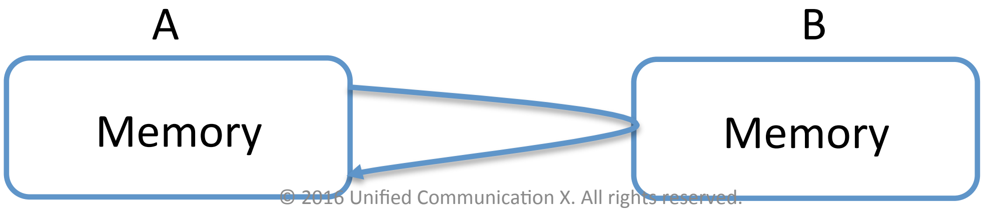
in	*ep*	Remote endpoint handle.
in	*buffer*	Pointer to the local source address.
in	*length*	Length of the data (in bytes) stored under the source address.
in	*remote_addr*	Pointer to the destination remote address to write to.
in	*rkey*	Remote memory key associated with the remote address.



Get

ucs_status_t **ucp_get_nbi** (ucp_ep_h *ep*, void **buffer*, size_t *length*, uint64_t *remote_addr*, ucp_rkey_h *rkey*)

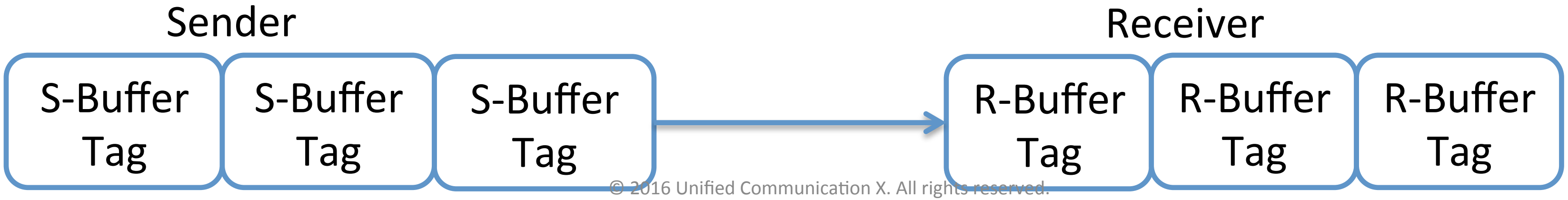
in	*ep*	Remote endpoint handle.
in	*buffer*	Pointer to the local source address.
in	*length*	Length of the data (in bytes) stored under the source address.
in	*remote_addr*	Pointer to the destination remote address to write to.
in	*rkey*	Remote memory key associated with the remote address.



Send

ucs_status_ptr_t **ucp_tag_send_nb** (ucp_ep_h *ep,* const void **buffer,* size_t *count,* ucp_datatype_t *datatype,* ucp_tag_t *tag,* ucp_send_callback_t *cb*)

`in`	*ep*	Destination endpoint handle.
`in`	*buffer*	Pointer to the message buffer (payload).
`in`	*count*	Number of elements to send
`in`	*datatype*	Datatype descriptor for the elements in the buffer.
`in`	*tag*	Message tag.
`in`	*cb*	Callback function that is invoked whenever the send operation is completed. It is important to note that the call-back is only invoked in a case when the operation cannot be completed in place.



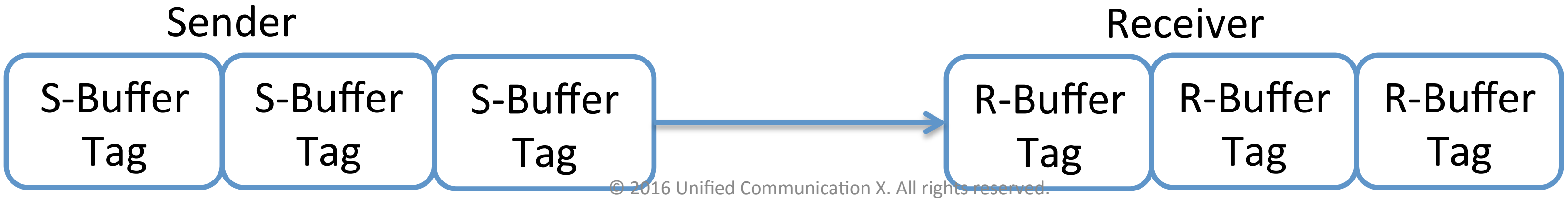
ucs_status_ptr_t

- UCS_OK - The send operation was completed immediately.
- UCS_PTR_IS_ERR(_ptr) - The send operation failed.
- otherwise - Operation was scheduled for send and can be completed in any point in time. The request handle is returned to the application in order to track progress of the message. The application is responsible to released the handle using ucp_request_release() routine.
- Request handling
  - int **ucp_request_is_completed** (void * *request*)
  - void **ucp_request_release** (void * *request*)
  - void **ucp_request_cancel** (ucp_worker_h *worker*, void * *request*)

Send-Sync

ucs_status_ptr_t **ucp_tag_send_sync_nb** (ucp_ep_h *ep*, const void * *buffer*, size_t *count*, ucp_datatype_t *datatype*, ucp_tag_t *tag*, ucp_send_callback_t *cb*)

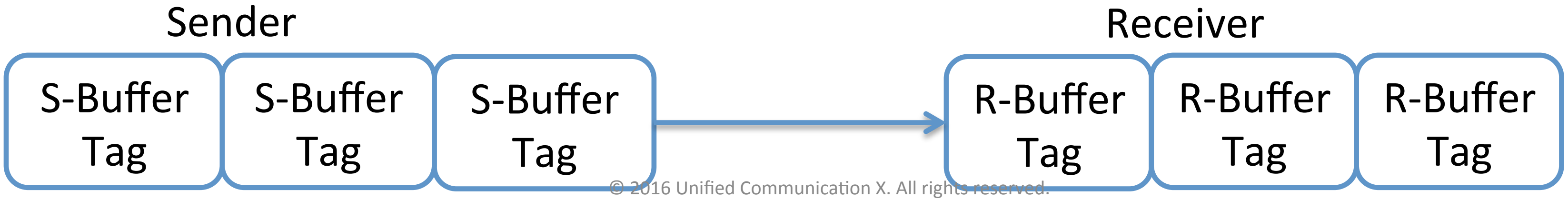
in	*ep*	Destination endpoint handle.
in	*buffer*	Pointer to the message buffer (payload).
in	*count*	Number of elements to send
in	*datatype*	Datatype descriptor for the elements in the buffer.
in	*tag*	Message tag.
in	*cb*	Callback function that is invoked whenever the send operation is completed.



Receive

ucs_status_ptr_t **ucp_tag_recv_nb** (ucp_worker_h *worker,* void **buffer,* size_t *count,* ucp_datatype_t *datatype,* ucp_tag_t *tag,* ucp_tag_t *tag_mask,* ucp_tag_recv_callback_t *cb*)

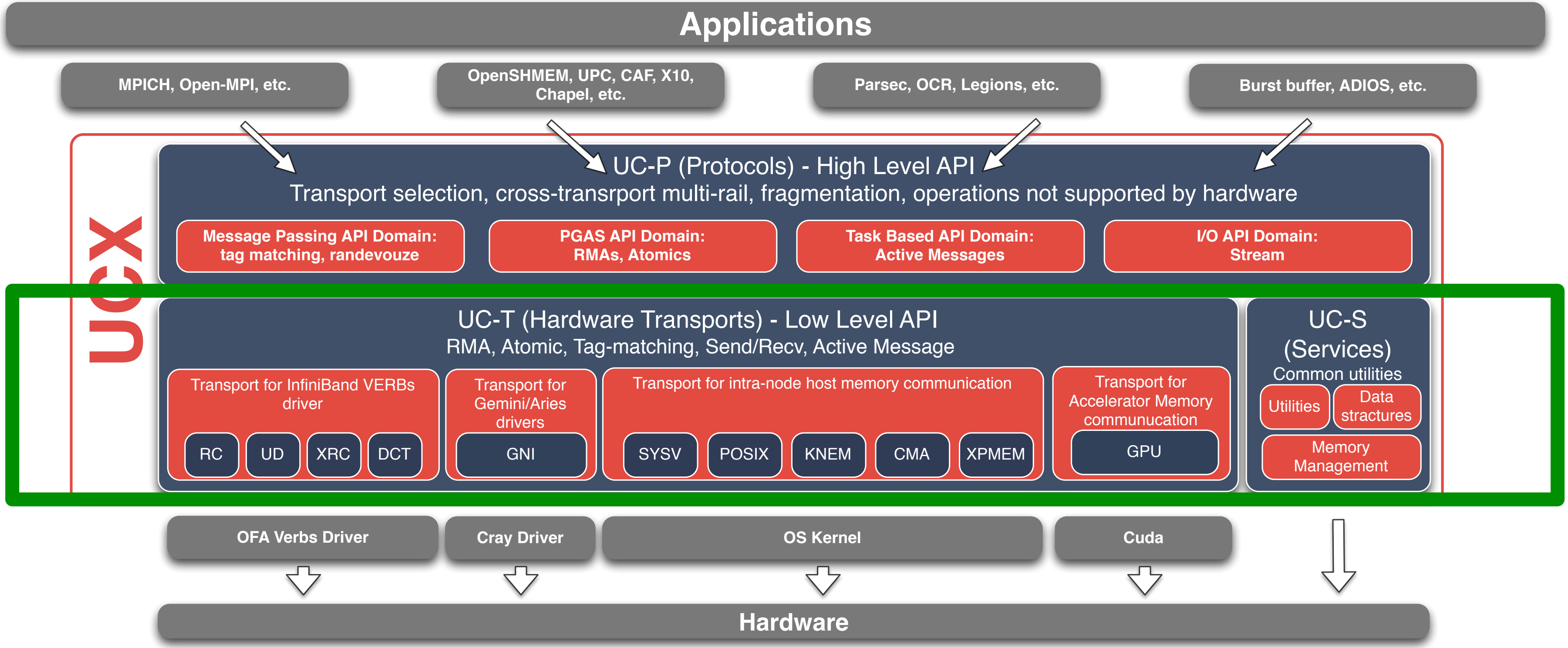
in	*worker*	UCP worker that is used for the receive operation.
in	*buffer*	Pointer to the buffer to receive the data to.
in	*count*	Number of elements to receive
in	*datatype*	Datatype descriptor for the elements in the buffer.
in	*tag*	Message tag to expect.
in	*tag_mask*	Bit mask that indicates the bits that are used for the matching of the incoming tag against the expected tag.
in	*cb*	Callback function that is invoked whenever the receive operation is completed and the data is ready in the receive *buffer*.



Atomic Operations

- ucs_status_t **ucp_atomic_add32** (ucp_ep_h *ep,* uint32_t *add,* uint64_t *remote_addr,* ucp_rkey_h *rkey*)
- ucs_status_t **ucp_atomic_add64** (ucp_ep_h *ep,* uint64_t *add,* uint64_t *remote_addr,* ucp_rkey_h *rkey*)
- ucs_status_t **ucp_atomic_fadd32** (ucp_ep_h *ep,* uint32_t *add,* uint64_t *remote_addr,* ucp_rkey_h *rkey,* uint32_t * *result*)
- ucs_status_t **ucp_atomic_fadd64** (ucp_ep_h *ep,* uint64_t *add,* uint64_t *remote_addr,* ucp_rkey_h *rkey,* uint64_t * *result*)
- ucs_status_t **ucp_atomic_swap32** (ucp_ep_h *ep,* uint32_t *swap,* uint64_t *remote_addr,* ucp_rkey_h *rkey,* uint32_t **result*)
- ucs_status_t **ucp_atomic_swap64** (ucp_ep_h *ep,* uint64_t *swap,* uint64_t *remote_addr,* ucp_rkey_h *rkey,* uint64_t * *result*)
- ucs_status_t **ucp_atomic_cswap32** (ucp_ep_h *ep,* uint32_t *compare,* uint32_t *swap,* uint64_t *remote_addr,* ucp_rkey_h *rkey,* uint32_t * *result*)
- ucs_status_t **ucp_atomic_cswap64** (ucp_ep_h *ep,* uint64_t *compare,* uint64_t *swap,* uint64_t *remote_addr,* ucp_rkey_h *rkey,* uint64_t * *result*)

UCT – Transport Layer

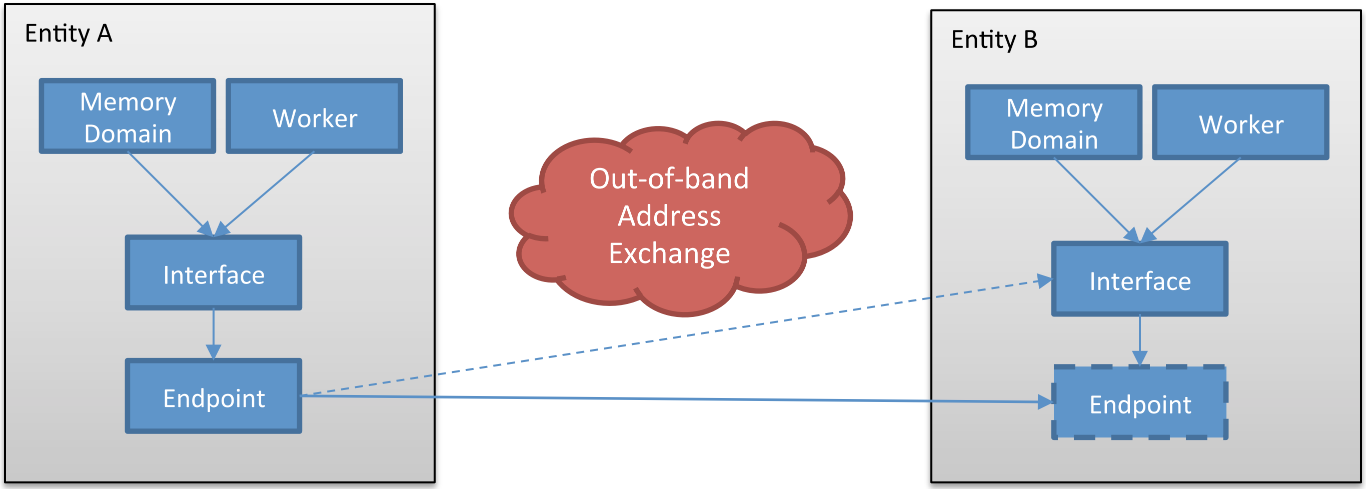


UCT

UCT (Transport layer) objects

- **uct_worker_h** - A context for separate progress engine and communication resources. Can be either thread-dedicated or shared
- **uct_md_h** - Memory registration domain. Can register user buffers and/or allocate registered memory
- **uct_iface_h** - Communication interface, created on a specific memory domain and worker. Handles incoming active messages and spawns connections to remote interfaces
- **uct_ep_h** - Connection to a remote interface. Used to initiate communications

UCT initialization



Memory Domain Routines

- Register/de-register memory within the domain
  - Can potentially use a cache to speedup memory registration
- Allocate/de-allocate registered memory
- Pack memory region handle to a remote-key-buffer
  - Can be sent to another entity
- Unpack a remote-key-buffer into a remote-key
  - Can be used for remote memory access

UCT Communication Routines

- Not everything has to be supported
  - Interface reports the set of supported primitives
  - UCP uses this info to construct protocols
  - UCP implement emulation of unsupported directives
- Send active message (active message id)
- Put data to a remote memory (virtual address, remote key)
- Get data from a remote memory (virtual address, remote key)
- Perform an atomic operation on a remote memory:
  - Add
  - Fetch-and-add
  - Swap
  - Compare-and-swap
- Communication Fence and Flush (Quiet)

UCT Data Classes

- UCT communications have a size limit
  - Interface reports max. allowed size for every operation
  - Fragmentation, if required, should be handled by user / UCP
- Several data “classes” are supported
  - “short” – small buffer
  - “bcopy” – a user callback which generates data (in many cases, “memcpy” can be used as the callback)
  - “zcopy” – a buffer and it’s memory region handle. Usually large buffers are supported.
- Atomic operations use a 32 or 64 bit values

UCT Completion Semantics

- All operations are non-blocking
- Return value indicates the status:
  - OK – operation is completed
  - INPROGRESS – operation has started, but not completed yet
  - NO_RESOURCE – cannot initiate the operation right now. The user might want to put this on a pending queue, or retry in a tight loop
  - ERR_xx – other errors
- Operations which may return INPROGRESS (get/atomics/zcopy) can get a completion handle
  - User initializes the completion handle with a counter and a callback
  - Each completion decrements the counter by 1, when it reaches 0 – the callback is called

UCT API Snippet

```
typedef void (*uct_completion_callback_t)(uct_completion_t *self,
                                          ucs_status_t status);

typedef ucs_status_t (*uct_am_callback_t)(void *arg, void *data, size_t length,
                                          void *desc);

struct uct_completion {
    uct_completion_callback_t func;
    int                       count;
};

typedef size_t (*uct_pack_callback_t)(void *dest, void *arg);

typedef void *                   uct_mem_h;
typedef uintptr_t                uct_rkey_t;

ucs_status_t uct_iface_set_am_handler(uct_iface_h iface, uint8_t id,
                                      uct_am_callback_t cb, void *arg, uint32_t flags);


ucs_status_t uct_ep_put_short(uct_ep_h ep, const void *buffer, unsigned length,
                              uint64_t remote_addr, uct_rkey_t rkey)

ssize_t uct_ep_put_bcopy(uct_ep_h ep, uct_pack_callback_t pack_cb,
                         void *arg, uint64_t remote_addr,
                         uct_rkey_t rkey)

ucs_status_t uct_ep_put_zcopy(uct_ep_h ep, const void *buffer, size_t length,
                              uct_mem_h memh, uint64_t remote_addr,
                              uct_rkey_t rkey, uct_completion_t *comp)

ucs_status_t uct_ep_am_short(uct_ep_h ep, uint8_t id, uint64_t header,
                             const void *payload, unsigned length)

ucs_status_t uct_ep_atomic_cswap64(uct_ep_h ep, uint64_t compare, uint64_t swap,
                                   uint64_t remote_addr, uct_rkey_t rkey,
                                   uint64_t *result, uct_completion_t *comp)
```

Guidelines

Memory

- It is a limited resource
  - The goal is to maximize the availability of memory for the **application**
- Avoid O(n) memory allocations, where n is the number communication peers (endpoints)
- Keep the endpoint object as small as possible
- Keep the memory pools size limited
- Allocation has to be proportional to the number of in-flight-operations

Data Path

- Three main data paths:
  - Short messages – critical path
  - Medium messages
  - All the rest

Data Path / Short Messages

- Take care of the small-message case first
- Avoid function calls
- Avoid extra pointer dereference, especially store operations
- Avoid adding conditionals, if absolutely required use ucs_likely/ucs_unlikely macros
- Avoid bus-locked instructions (atomics)
- Avoid branches
- No malloc()/free() nor system calls
- Limit the scope of local variables (the time from first to last time it is used) - larger scopes causes spilling more variables to the stack
- Use benchmarks and performance analysis tools to analyze the impact on the latency and message rate

Data Path / Medium Messages

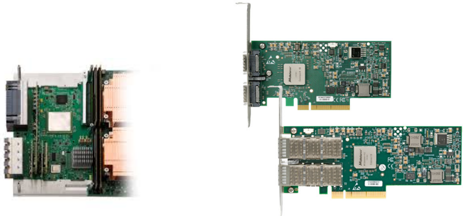
- Avoid locks if possible. If needed, use spinlock, no mutex.
- Reduce function calls
- Move error and slow-path handling code to non-inline functions, so their local variables will not add overhead to the prologue and epilogue of the fast-path function.

Data Path / “Slow” Path

- Performance is still important
- No system calls / malloc() / free()
- It's ok to reasonable add pointer dereferences, conditionals, function calls, etc.
  - Having a readable code here is more important than saving one conditional or function call.
- Protocol-level performance considerations are more important here, such as fairness between connections, fast convergence, etc.
- Avoid O(n) complexity. As a thumb rule, all scheduling mechanisms have to be O(1).

Summary

- UCX has been integrated with:
  - MPI: Open MPI, MPICH,
  - OpenSHMEM: Reference Implementation, OSHMEM
- Support multiple transports
  - IB/RoCE: RC, UD, DCT, CM
  - Aries/Gemini: FMA, SMSG, BTE
  - Shared Memory: SysV, Posix, CMA, KNEM, XPMEM



UCX

Unified Communication - X Framework

WEB:

www.openucx.org

https://github.com/openucx/ucx

Mailing List:

https://elist.ornl.gov/mailman/listinfo/ucx-group

ucx-group@elist.ornl.gov

Alina Sklarevich, Mellanox Technologies

OPEN MPI INTEGRATION WITH UCX

Overview

- OMPI supports UCX starting OMPI v1.10.
- UCX is a PML component in OMPI.
  To enable UCX:
  - mpirun -mca pml ucx … <APP>
- OMPI is integrated with the UCP layer.

Overview

- UCX mca parameters:
  - pml_ucx_verbose, pml_ucx_priority

- UCX environment parameters:
  - ucx_info -f

- For example:

  mpirun -mca pml ucx -x UCX_NET_DEVICES=mlx5_0:1 … <APP>

Overview

- The calls to the UCP layer will invoke UCT calls.
- UCX will select the best transport to use.
- OMPI uses Full/Direct modex with UCX.
- UCX will connect the ranks.

UCX Features - Recap

- Tag-matching
- Remote memory operations, one sided operations
- Atomic operations
- Supported transports:
  - IB - ud, rc, dc, accelerated verbs
  - shared memory
  - uGNI

UCX Main Objects - Recap

- **ucp_context_h**

A global context for the application - a single UCP communication instance.
Includes communication resources, memory and other communication information directly associated with a specific UCP instance.

- **ucp_worker_h**

Represents an instance of a local communication resource and an independent progress of communication. It contains the uct_iface_h's of all selected transports.
One possible usage is to create one worker per thread.

- **ucp_ep_h**

Represents a connection to a remote worker.
It contains the uct_ep_h's of the active transports.

UCX Main Objects - Recap

- **ucp_mem_h**

A handle to an allocated or registered memory in the local process. Contains details describing the memory, such as address, length etc.

- **ucp_rkey_h**

Remote key handle, communicated to remote peers to enable an access to the memory region. Contains an array of uct_rkey_t's.

- **ucp_config_t**

Configuration for ucp_context_h. Loaded from the run-time to set environment parameters for UCX.

UCX API

OMPI - UCX Stack

APPLICATION
OMPI
PML UCX
UCX LIBRARY
DRIVER
HARDWARE

Init Stage

MPI_Init ⟹ ompi_mpi_init

mca_pml_ucx_open

OpenMPI

ucp_config_read

ucp_init

ucp_config_release

UCX

Init Stage - Cont

mca_pml_ucx_init

ucp_worker_create

ucp_worker_get_address

ucp_worker_release_address

Init Stage - Cont

opal_progress_register(mca_pml_ucx_progress)

↓

ucp_worker_progress

Send Flow

MPI_Isend ⇒ mca_pml_ucx_isend

mca_pml_ucx_add_proc

ucp_ep_create

ucp_tag_send_nb

uct_ep_am_short

uct_ep_am_bcopy

uct_ep_am_zcopy

Send Flow - Cont

- If the send request isn't completed
  → progress it.

- Once completed
  → callback function is invoked

- Contiguous and non-contiguous datatypes are supported.

Receive Flow

MPI_Irecv → mca_pml_ucx_irecv

ucp_tag_recv_nb

Eager Receive

Rendezvous

Receive Flow - Cont

- Expected & Unexpected queues are used
- Can probe with ucp_tag_probe_nb
  → ucp_tag_msg_recv_nb
- If the receive request isn't completed
  → progress it.
- Once completed
  → callback function is invoked

Progress Flow

opal_progress

mca_pml_ucx_progress

ucp_worker_progress → uct_worker_progress

* Send/Receive Finished:

mca_pml_ucx_send/recv_completion

Finalization Stage

MPI_Finalize → ompi_mpi_finalize

mca_pml_ucx_del_procs

* Per remote peer:

ucp_ep_destroy

Finalization Stage - Cont

mca_pml_ucx_cleanup

opal_progress_unregister (mca_pml_ucx_progress)

ucp_worker _destroy

mca_pml_ucx_close

ucp_cleanup

PERFORMANCE

PERFORMANCE

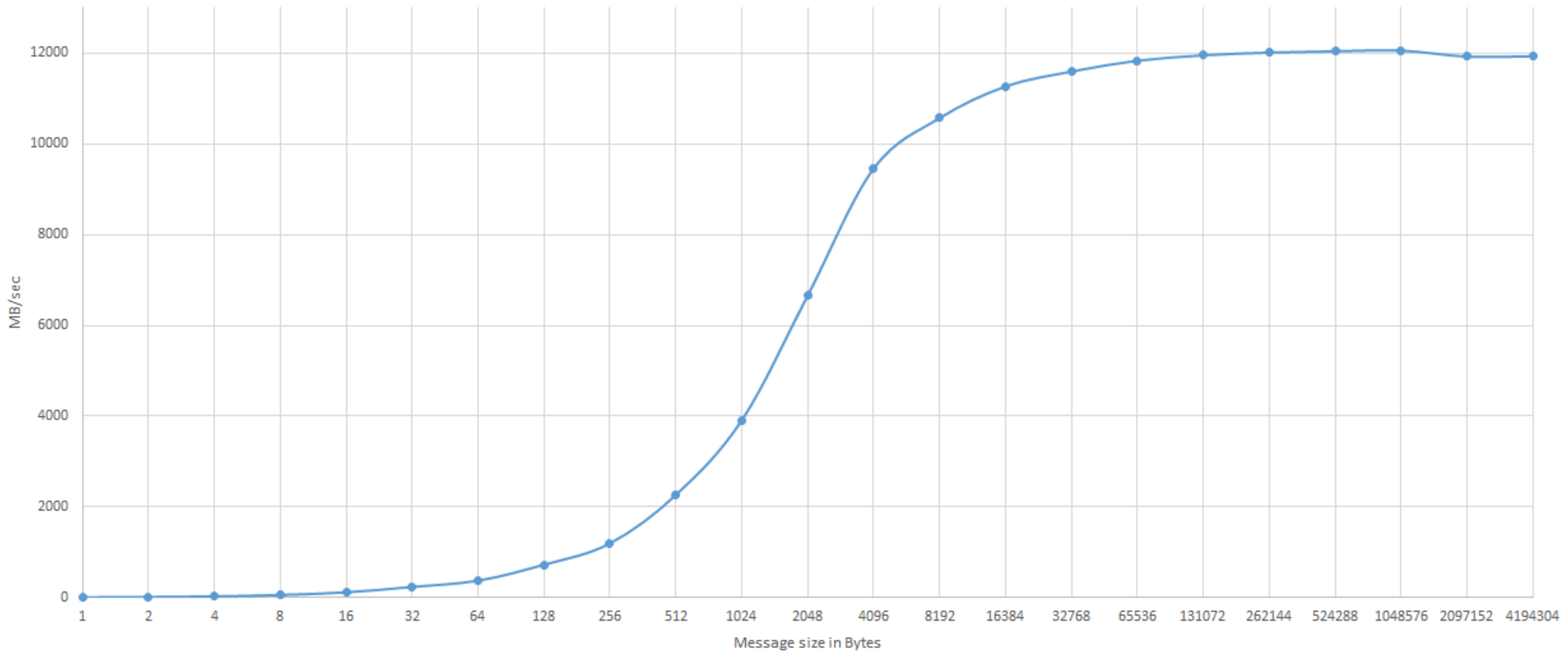
<u>Setup Details:</u>

MLNX_OFED_LINUX-3.3-1.0.0.0
ConnectX-4
EDR - 100Gb/sec
Intel(R) Xeon(R) CPU E5-2697 v3 @ 2.60GHz
2 hosts connected via switch

<u>Command Line:</u>

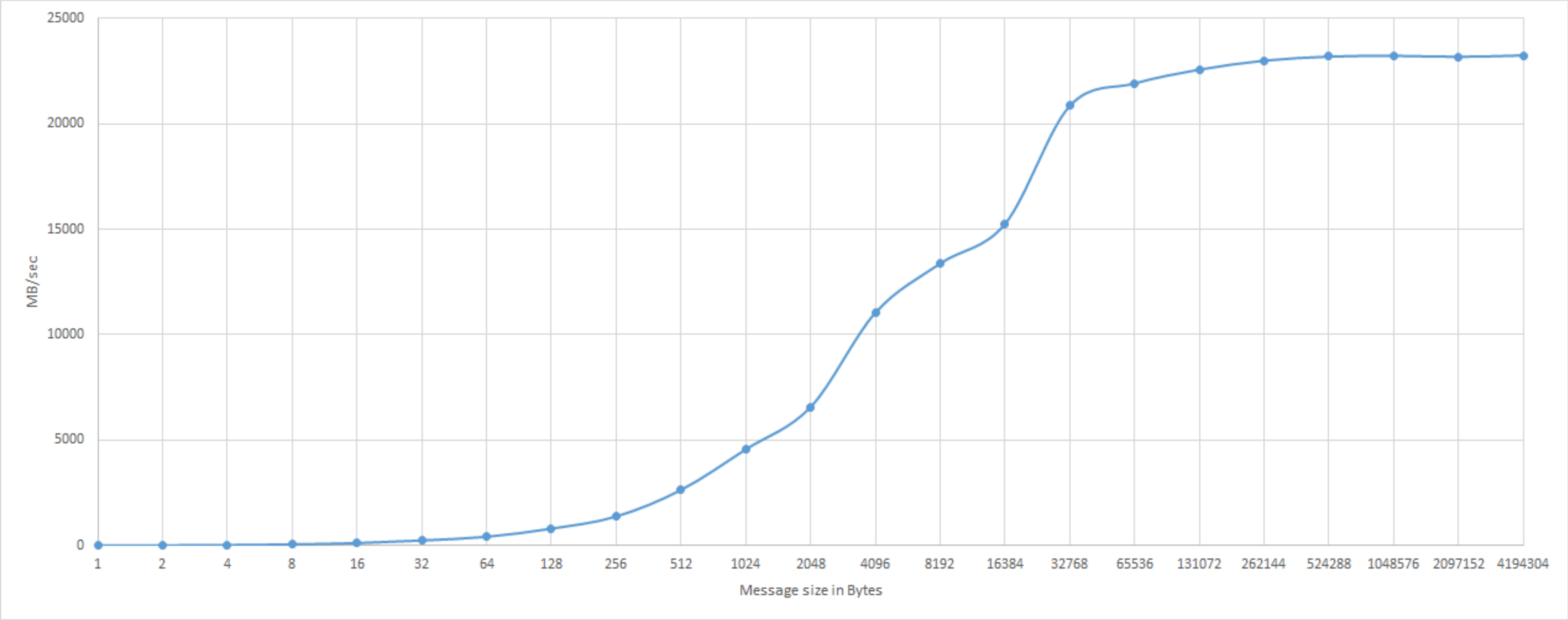
```
$mpirun -np 2 --bind-to core --map-by node -mca pml ucx
-x UCX_TLS=rc_mlx5,cm osu_bw
```

osu_bw



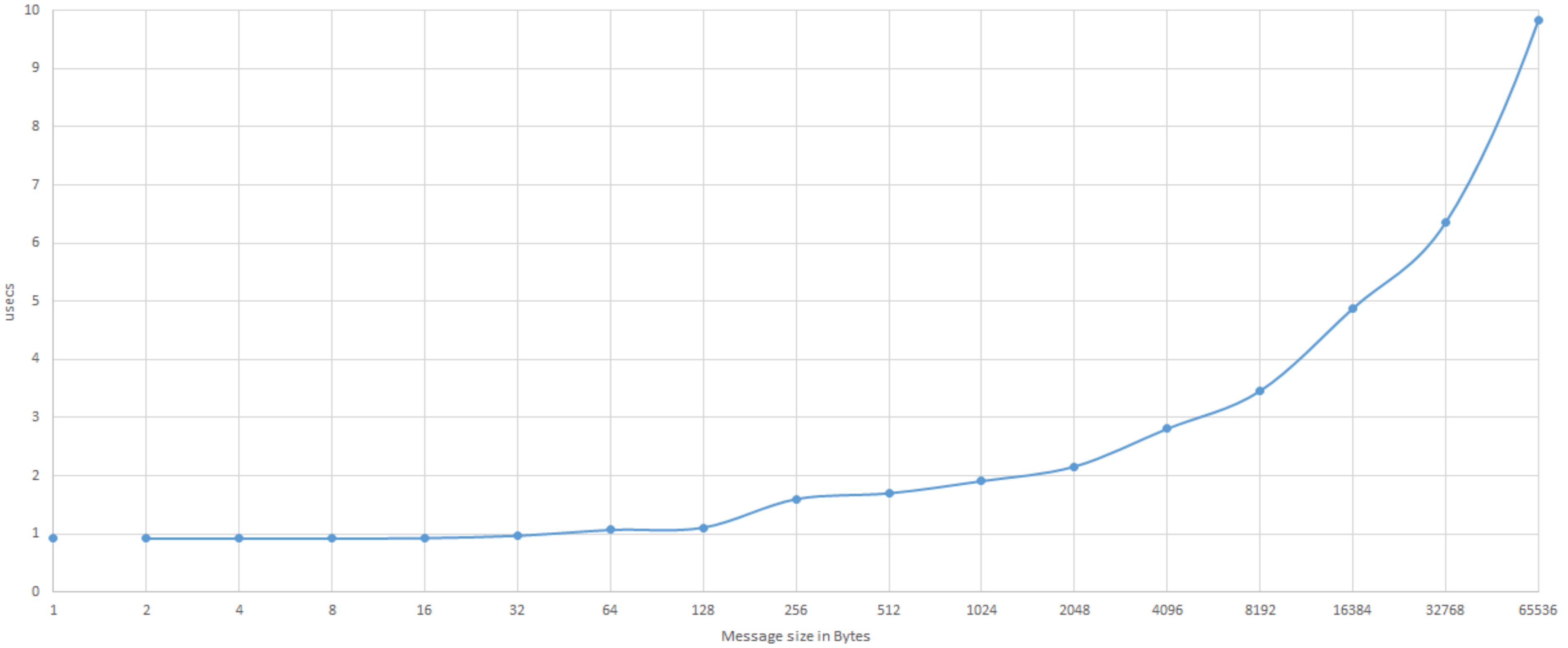
MB/sec
12000
10000
8000
6000
4000
2000
0
1
2
4
8
16
32
64
128
256
512
1024
2048
4096
8192
16384
32768
65536
131072
262144
524288
1048576
2097152
4194304
Message size in Bytes

osu_bibw



25000
20000
15000
10000
5000
0
MB/sec
1
2
4
8
16
32
64
128
256
512
1024
2048
4096
8192
16384
32768
65536
131072
262144
524288
1048576
2097152
4194304
Message size in Bytes

osu_latency



10
9
8
7
6
5
4
3
2
1
0
usecs
1
2
4
8
16
32
64
128
256
512
1024
2048
4096
8192
16384
32768
65536
Message size in Bytes

Swen Boehm, Oak Ridge National Laboratory

OPENSHMEM INTEGRATION WITH UCX

OpenSHMEM - Overview

- PGAS Library
- One-sided Communication
- Atomic operations
- Collectives

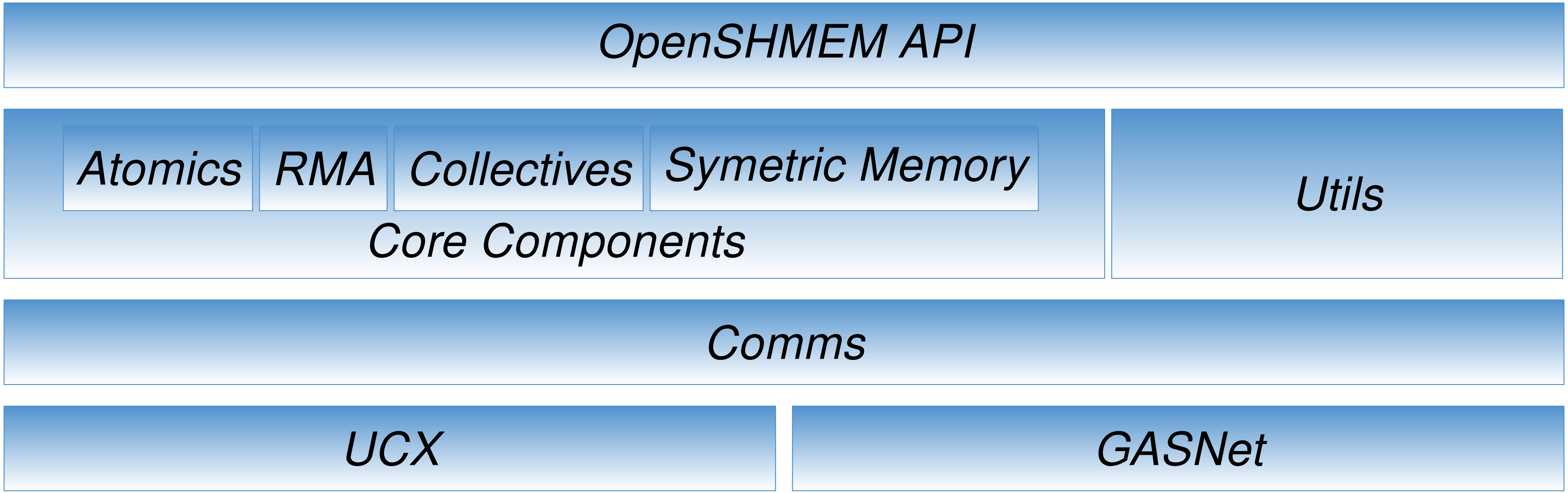
Symmetric Memory

- All Processing Elements (PE's) share an address space (symmetric heap)
- Symmetric heap is allocated on startup
- Heapsize can be customized via environment variable SMA_SYMMETRIC_SIZE
- Symmetric data objects must be allocated with shmem_malloc
- Symmetric data objects are accessible by remote PEs

Shared global address space

- Global and static variables are symmetric objects
- Accessibe by remote PEs

OpenSHMEM Reference Implementation



Initialization

shmem_init
    shmemi_comms_init
        ...
        ucp_config_read
        ucp_init
        ucp_config_release
        ucp_worker_create
        init_memory_regions (more on this later)
        ...
        ucp_ep_create (for each PE)
        ucp_config_release
        ...

Memory registration

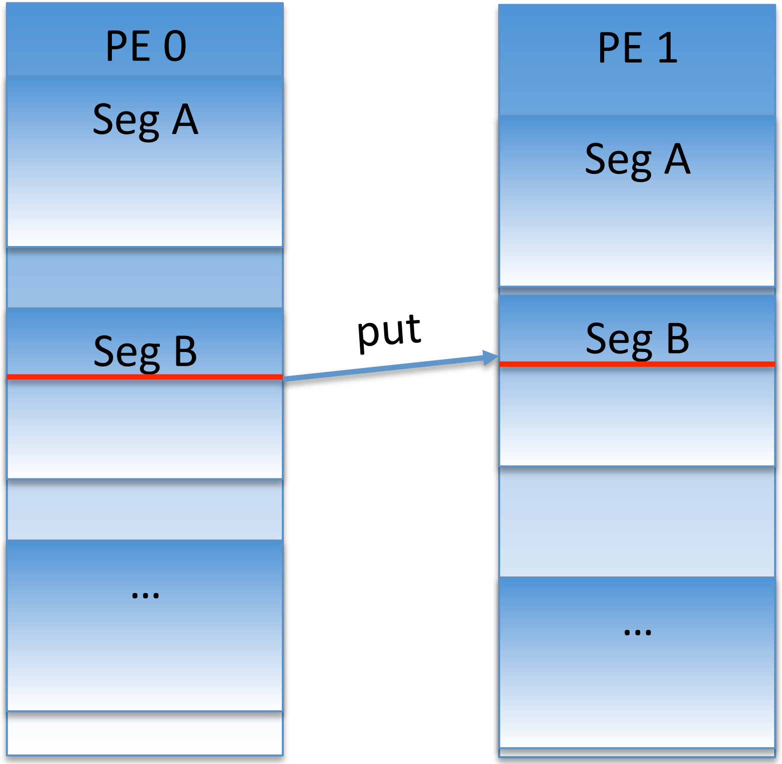
- OpenSHMEM registers global data (data and bss segment) and the symmetric heap
- `ucp_mem_map` maps the memory with the ucp context (returning `ucp_mem_h`)

RMA

- For RMA operations UCP needs Remote Memory Handle (remote key or rkey)
- rkeys require registered memory (`ucp_mem_h`)
- ucp_rkey_pack is used to generate packed representation
- The packed rkey is exchanged with remote PE(s)
- `ucp_ep_rkey_unpack` will return `rkey_t` handle

Translating symmetric addresses

- To access a remote address the rkey is needed
- Look up rkey with find_seg
- translate local buffer address into remote buffer address



RMA put

shmem_<TYPENAME>_put

- ucx_put
  - find_seg
  - translate_symmetric_address

ucp_put

- uct_ep_put_short
- uct_ep_put_bcopy
- uct_ep_put_zcopy*

RMA get

shmem_<TYPENAME>_get

- ucx_get
  - find_seg
  - translate_symmetric_address

ucp_get → uct_ep_get_bcopy

ucp_get → uct_ep_get_zcopy*

RMA atomics

shmem_<TYPENAME>_<OP>

- ucx_get
  - find_seg
  - translate_symmetric_address
  - ucp_atomic_<op,size>
    - uct_ep_atomic_<op,size>

PERFORMANCE

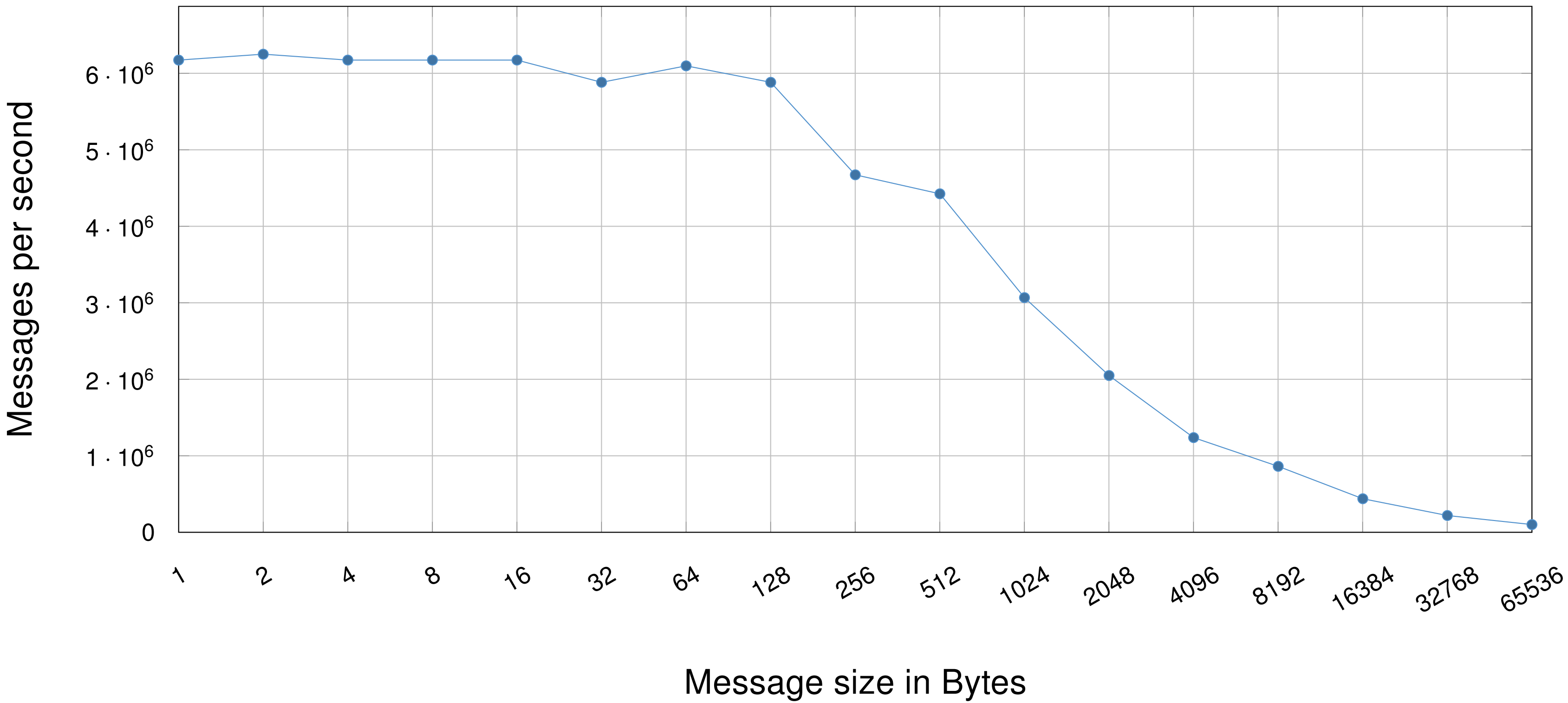
Setup:

- Turing Cluster @ ORNL
- Red Hat Enterprise Linux Server release 7.2 (3.10.0-327.13.1.el7.x86_64)
- Mellanox ConnectX-4 VPI
- EDR IB (100Gb/s)
- Intel Xeon E5-2660 v3 @ 2.6GHz

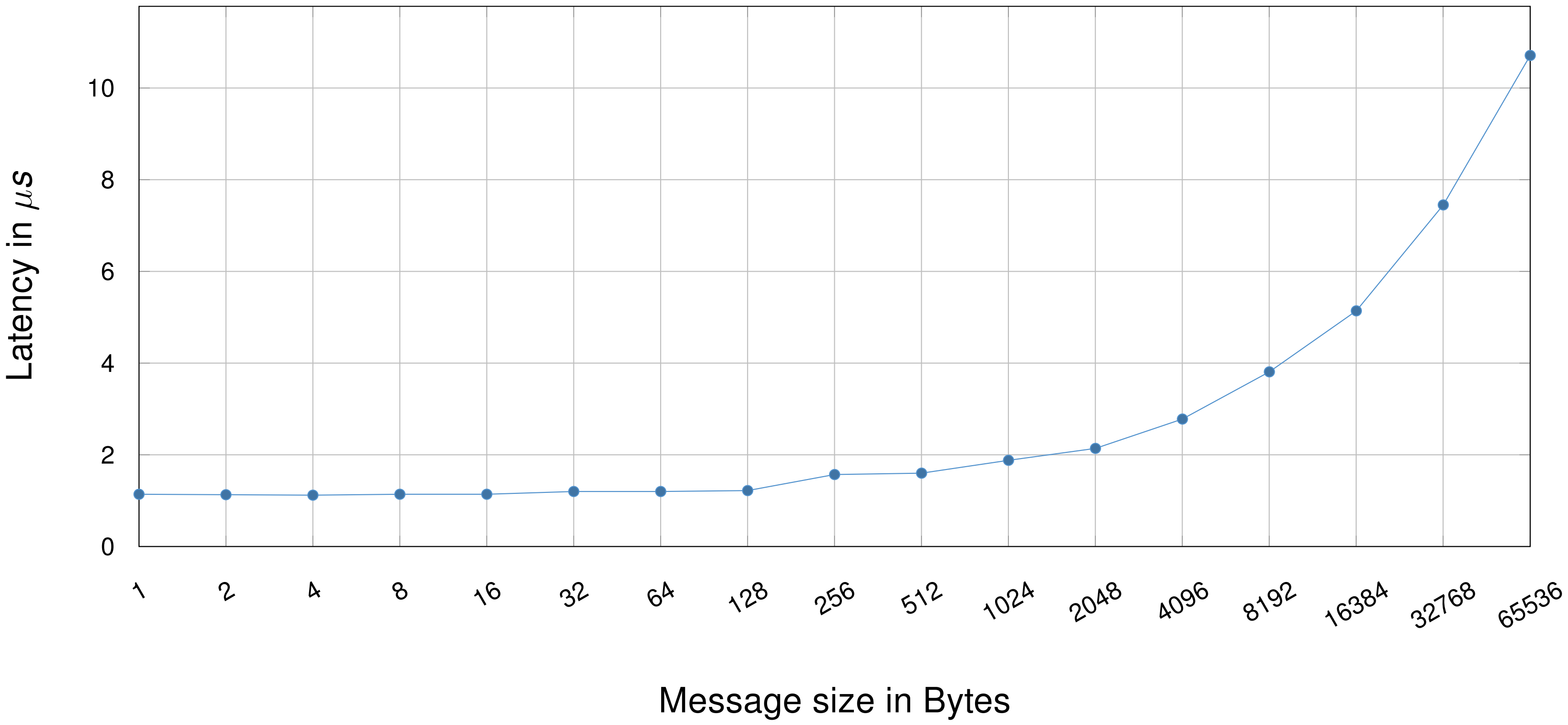
Command Line:

```
$ orterun -np 2 osu_oshmem_put_mr
```

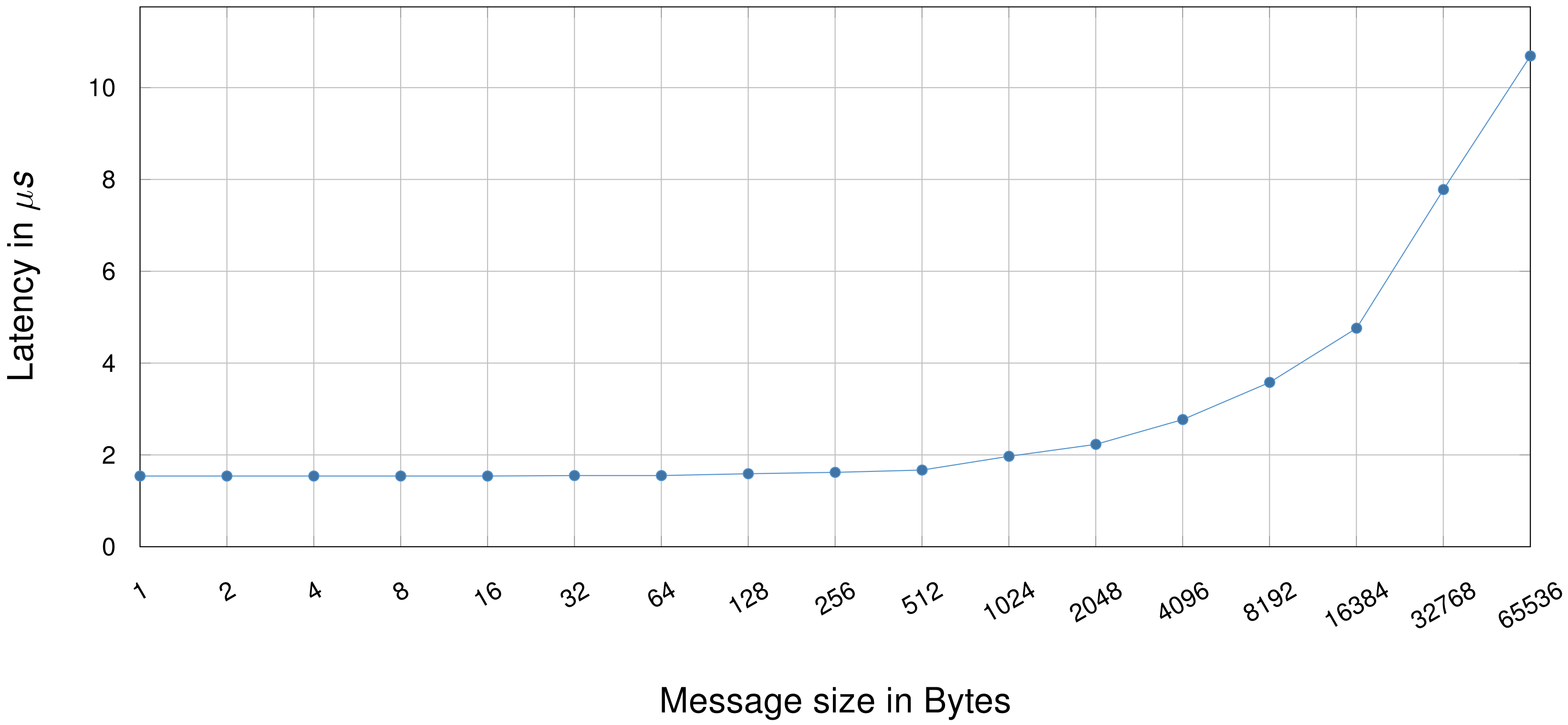
OSU Message Rate



OSU Put Latency



OSU Get Latency



Compiling UCX

```
$ ./autogen.sh
$ ./contrib/configure-release --prefix=$PWD/install
$ make -j8 install
```

Swen Boehm, Oak Ridge National Laboratory

EXAMPLES

Compile OpenMPI with UCX

```
$ ./autgen.pl
$ ./configure --prefix=$PWD/install \
    --with-ucx=$PWD/ucx
$ make && make install
```

Build OpenSHMEM on UCX

```
$ ./autogen.pl
$ ./configure --with-comms-layer=ucx \
  --with-ucx-root=$PWD/install \
  --with-rte-root=$PWD/install \
  --prefix=$PWD/install
$ make && make install
```

UCX – Hello World Example

[ucp_hello_world.c]

Alina Sklarevich, Mellanox Technologies

EXAMPLES

OSU_BW

```
mpirun -mca pml ucx -np 2 -H clx-orion-097,clx-orion-098 -x UCX_NET_DEVICES=mlx5_2:1 -x UCX_TLS=rc_mlx5,cm -x UCX_RNDV_THRESH=16384 --map-by node --bind-to core $OSU_TEST/osu_bw
```

```
# OSU MPI Bandwidth Test v5.0
# Size      Bandwidth (MB/s)
1                       7.43
2                      14.95
4                      30.01
8                      59.97
16                    120.13
32                    237.29
64                    421.77
128                   814.45
256                  1292.24
512                  2367.80
1024                 3870.03
2048                 6654.26
4096                 9460.64
8192                10598.88
16384               10485.12
32768               11607.45
65536               11847.64
131072              11958.01
262144              12014.55
524288              12044.04
1048576             12058.39
2097152             12010.11
4194304             12016.12
```

OSU_BIBW

```
mpirun -mca pml ucx -np 2 -H clx-orion-097,clx-orion-098 -x UCX_NET_DEVICES=mlx5_2:1 -x UCX_TLS=rc_mlx5,cm -x UCX_RNDV_THRESH=16384 --map-by node --bind
-to core $OSU_TEST/osu_bibw
```

```
# OSU MPI Bi-Directional Bandwidth Test v5.0
# Size      Bandwidth (MB/s)
1                       8.60
2                      17.56
4                      35.05
8                      68.69
16                    140.16
32                    281.43
64                    465.20
128                   917.45
256                  1506.33
512                  2651.08
1024                 4404.89
2048                 7059.17
4096                11430.23
8192                14035.32
16384               17408.31
32768               20972.95
65536               21929.01
131072              22647.14
262144              23015.46
524288              23186.88
1048576             23226.71
2097152             23284.50
4194304             23191.45
```

OSU_LATENCY

```
mpirun -mca pml ucx -np 2 -H clx-orion-097,clx-orion-098 -x UCX_NET_DEVICES=mlx5_2:1 -x UCX_TLS=rc_mlx5,cm -x UCX_RNDV_THRESH=16384 --map-by node --bind-to core $OSU_TEST/osu_latency
```

```
# OSU MPI Latency Test v5.0
# Size          Latency (us)
0                       0.92
1                       0.92
2                       0.92
4                       0.92
8                       0.92
16                      0.92
32                      0.97
64                      1.06
128                     1.10
256                     1.60
512                     1.73
1024                    1.96
2048                    2.20
4096                    2.78
8192                    3.48
16384                   5.74
32768                   7.11
65536                   9.83
131072                 15.25
262144                 26.12
524288                 47.98
1048576                92.41
2097152               181.23
4194304               355.95
```

UCX_PERFTEST

```
$./bin/ucx_perftest vegas06 -d mlx5_0:1 -t am_bw -x rc_mlx5 -c 1
+--------------+-----------------------------+---------------------+-----------------------+
|              |       latency (usec)        |   bandwidth (MB/s)  |  message rate (msg/s) |
+--------------+---------+---------+---------+----------+----------+-----------+-----------+
| # iterations | typical | average | overall |  average |  overall |   average |   overall |
+--------------+---------+---------+---------+----------+----------+-----------+-----------+
       1000000     0.080     0.080     0.080      95.24      95.24    12483016    12483016
```

UCX

Unified Communication - X Framework

WEB:

www.openucx.org

https://github.com/openucx/ucx

Mailing List:

https://elist.ornl.gov/mailman/listinfo/ucx-group

ucx-group@elist.ornl.gov

Acknowledgements

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