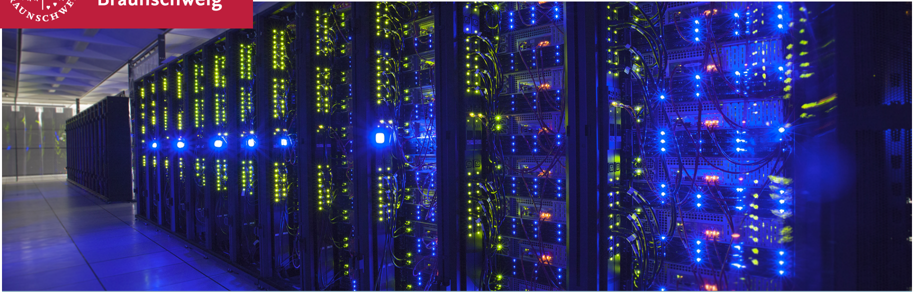
Technische Universität Braunschweig

Funded by DFG



Towards Low-Latency Byzantine Agreement Protocols Using RDMA

DSN Workshop on Byzantine Consensus and Resilient Blockchains

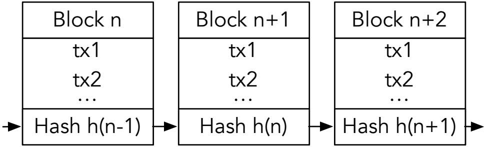
Signe Rüsch, Ines Messadi, Rüdiger Kapitza, 2018-06-25

ruesch@ibr.cs.tu-bs.de

Technische Universität Braunschweig, Germany

Blockchain and Cryptocurrencies

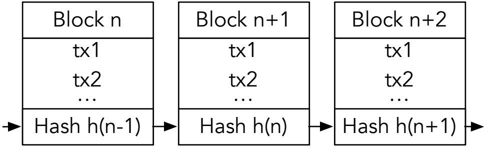
- **Permissionless:** Proof-of-Work for ordering agreement
  - Scalability and energy consumption issues
- **Permissioned:** e.g. for companies' SCM
  - Blocks can be created by dedicated nodes in data centers
  - Crash-fault tolerant protocols: Hyperledger Fabric with Kafka



Blockchain and Cryptocurrencies

- **Permissionless:** Proof-of-Work for ordering agreement
  - Scalability and energy consumption issues
- **Permissioned:** e.g. for companies' SCM
  - Blocks can be created by dedicated nodes in data centers
  - Crash-fault tolerant protocols: Hyperledger Fabric with Kafka

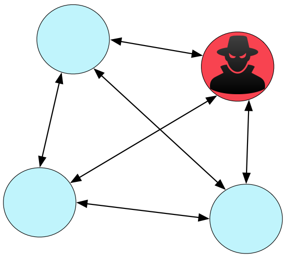
→ Additional security of **Byzantine fault tolerant (BFT)** protocols!



BFT Protocols

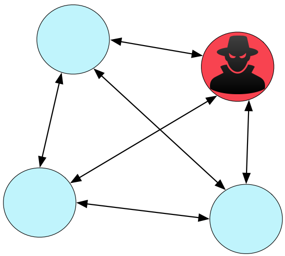
- $3f + 1$ nodes reach **consensus** on order of requests
- High **throughput** requirements: blockchain to replace company's database
- Multiple rounds of message exchanges
- Broadcast steps

→ High **message complexity and latency**!



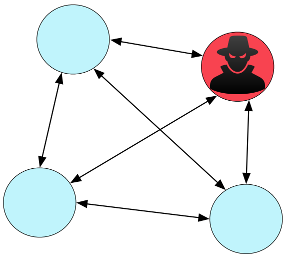
BFT Protocols

- Message complexity optimization focusing on **protocol level**
  - E.g. hybrid BFT protocols
- Current BFT protocols achieve necessary throughput
  - ≈1 Million operations/second (Behl et al., EuroSys'17)



BFT Protocols

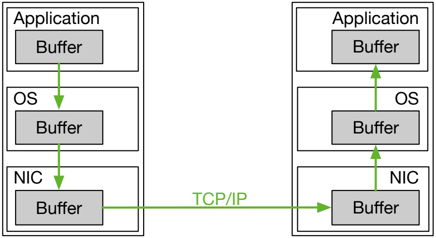
- Message complexity optimization focusing on **protocol level**
  - E.g. hybrid BFT protocols
- Current BFT protocols achieve necessary throughput
  - $\approx$1 Million operations/second (Behl et al., EuroSys'17)



Our focus: reduce latency on **network layer** with technology available in data centers!

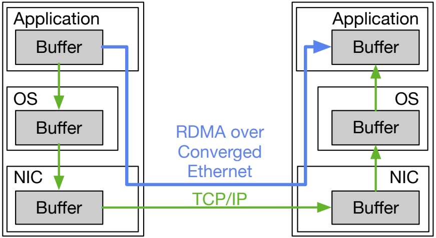
TCP Overhead

- Two intermediate **data copy** steps per host
  - Application $\rightarrow$ kernel $\rightarrow$ network
  - Network $\rightarrow$ kernel $\rightarrow$ application
- **>50 %** of TCP latency due to data copying (Frey et al., ICDCS'09)



TCP Overhead

- Two intermediate **data copy** steps per host
  - Application → kernel → network
  - Network → kernel → application
- **>50 %** of TCP latency due to data copying (Frey et al., ICDCS'09)



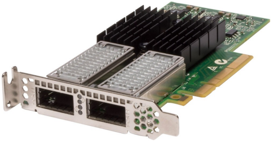
Reduce latency of BFT protocols with
Remote Direct Memory Access (RDMA)
communication framework!

Overview

- Remote Direct Memory Access
- Design of RUBIN
- Evaluation of RUBIN
- Conclusion

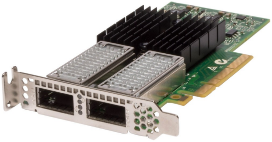
Remote Direct Memory Access

- **Zero-copy** communication protocol
- Kernel bypassing
- Data transfer directly into remote memory
- Applications **register memory** with RDMA NIC
- Message-oriented and asynchronous operations
- Often employed in **data centers**



Remote Direct Memory Access

- **Zero-copy** communication protocol
- Kernel bypassing
- Data transfer directly into remote memory
- Applications **register memory** with RDMA NIC
- Message-oriented and asynchronous operations
- Often employed in **data centers**



Low latency, high throughput, CPU efficient!
But possible **security issues** due to direct memory access?

RDMA Consensus Protocols

DARE (Poke et al, HPDC'15)

- RDMA-tailored SMR protocol
- Achieve low **latency** in replica communication

APUS (Wang et al., SoCC'17)

- Combine RDMA with Paxos
- **Scalability** regarding concurrent connections

Derecho (Jha et al., 2017)

- C++ library for replicated crash-fault tolerant services built on Paxos

RDMA Consensus Protocols

DARE (Poke et al, HPDC'15)

- RDMA-tailored SMR protocol
- Achieve low **latency** in replica communication

APUS (Wang et al., SoCC'17)

- Combine RDMA with Paxos
- **Scalability** regarding concurrent connections

Derecho (Jha et al., 2017)

- C++ library for replicated crash-fault tolerant services built on Paxos

$\rightarrow$ Only crash faults are considered, **no previous work** on BFT!
How to implement **RDMA communication for BFT frameworks**?

Requirements

① **Easy integration** into existing BFT prototypes

② **Security** guarantees even in the presence of malicious nodes

③ **Zero-copy** communication

① Easy Integration

- RDMA communication for multiple BFT frameworks
  - BFT-SMaRt (Bessani et al., DSN'14)
  - UpRight (Clement et al., SOSP'09)
  - **Reptor** (Behl et al., Middleware'15)
- BFT frameworks very **complex**, e.g. Reptor:
  - Core: 50,000 LOC (Java)
  - Deployment, benchmarking: 14,000 LOC (Python)
- High development effort
  - ≈20 years of BFT research
  - Limited number of BFT frameworks

① Easy Integration

- RDMA communication for multiple BFT frameworks
  - BFT-SMaRt (Bessani et al., DSN'14)
  - UpRight (Clement et al., SOSP'09)
  - **Reptor** (Behl et al., Middleware'15)
- BFT frameworks very **complex**, e.g. Reptor:
  - Core: 50,000 LOC (Java)
  - Deployment, benchmarking: 14,000 LOC (Python)
- High development effort
  - ≈20 years of BFT research
  - Limited number of BFT frameworks

Direct integration is far too much overhead!

① Easy Integration

- BFT frameworks often written in **Java**
- Use **Java NIO** for high-performance communication
  - With clients (BFT-SMaRt), replicas (UpRight), or both (Reptor)
- Frameworks optimized to reduce data copy steps
- Need suitable level of abstraction
  - Not as low-level as the native RDMA interface
  - Not as high-level as JSOR: socket interface, but intermediate data copies by default (Thirugnanapandi, 2014)

① Easy Integration

- BFT frameworks often written in **Java**
- Use **Java NIO** for high-performance communication
  - With clients (BFT-SMaRt), replicas (UpRight), or both (Reptor)
- Frameworks optimized to reduce data copy steps
- Need suitable level of abstraction
  - Not as low-level as the native RDMA interface
  - Not as high-level as JSOR: socket interface, but intermediate data copies by default (Thirugnanapandi, 2014)

→ Modeled after **Java NIO**

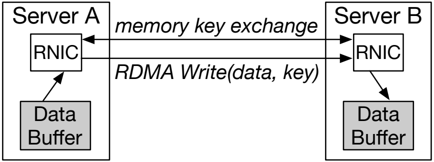
→ Interface similar to **Java socket interface**

→ Easy switch between **RDMA and TCP** communication

② Security: RDMA Semantics

Read/Write

- Used in **APUS** and **DARE**
- **Fastest** communication mode
- Exchange memory key specifying buffer location
- Receiver not notified
- **Security risks** in BFT setting: get memory key, corrupt memory



② Security: RDMA Semantics

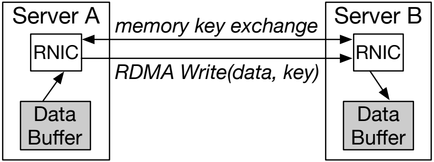
Read/Write

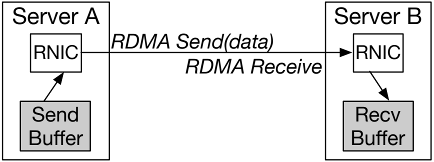
- Used in **APUS** and **DARE**
- **Fastest** communication mode
- Exchange memory key specifying buffer location
- Receiver not notified
- **Security risks** in BFT setting: get memory key, corrupt memory

Send/Receive

- **Two sides** active
- Receiver notified
- **No known** memory key
- Remote memory locations decided by application

→ No memory corruption!





② Security: RDMA Semantics

Read/Write

- Used in **APUS** and **DARE**
- **Fastest** communication mode
- Exchange memory key specifying buffer location
- Receiver not notified
- **Security risks** in BFT setting: get memory key, corrupt memory

Send/Receive

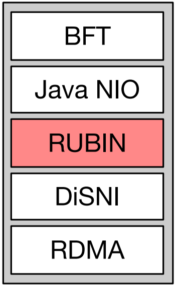
- **Two sides** active
- Receiver notified
- **No known** memory key
- Remote memory locations decided by application

→ No memory corruption!

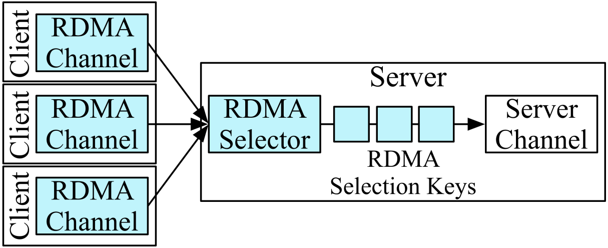
Send/Receive has higher **security**
→ no memory corruption and MitM attack possible!

Our Framework: RUBIN

- Modeled after **Java NIO** and socket interface
- **Integration** in several BFT frameworks possible
- Use RDMA **Send/Receive** semantics for security
- Integrate into **Reptor** framework
- Use **DiSNI** library for RDMA communication in Java

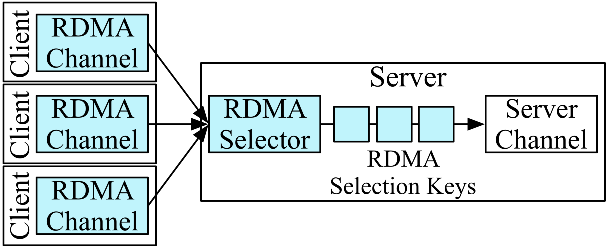


RUBIN Components



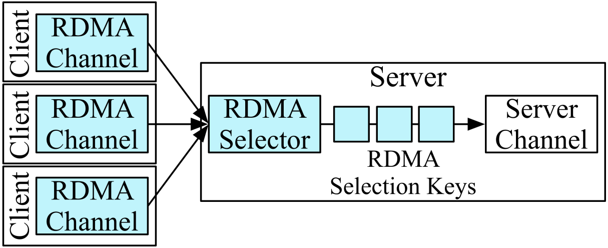
- **RDMA Channel:** Java NIO SocketChannel with RDMA resources

Rubin Components



- **RDMA Channel:** Java NIO SocketChannel with RDMA resources
- **RDMA Selector:** efficiently handle multiple channels with one thread
  - Select channels that are ready for certain events
  - Avoids expensive context switching

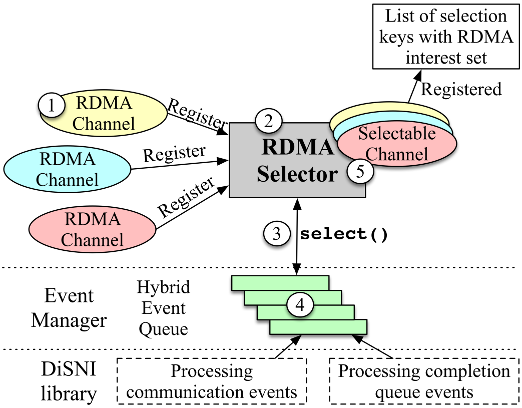
Rubin Components



- **RDMA Channel:** Java NIO SocketChannel with RDMA resources
- **RDMA Selector:** efficiently handle multiple channels with one thread
  - Select channels that are ready for certain events
  - Avoids expensive context switching
- **RDMA Selection Keys:** channel operation
  - Send, receive message, connection establishment

Workflow of Rubin

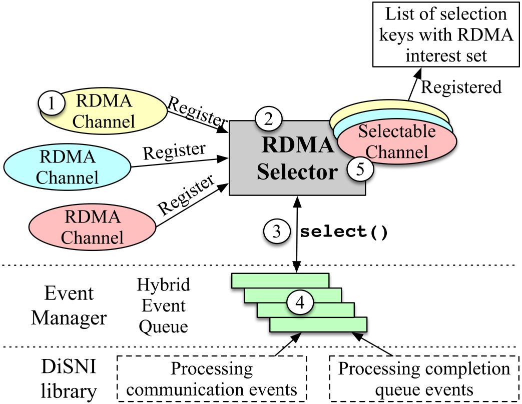
① Channel registration, set interest



Workflow of Rubin

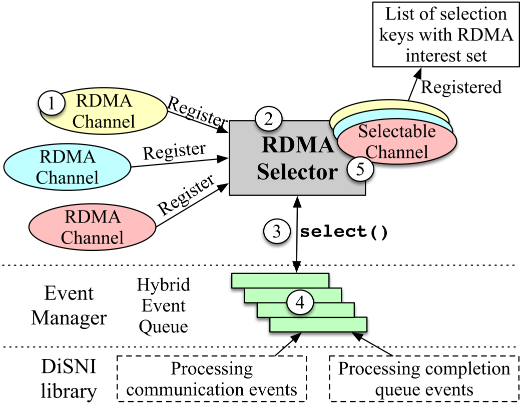
① Channel registration, set interest

② Selection Key creation



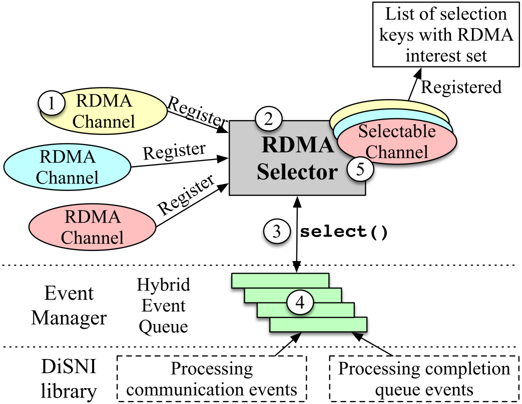
Workflow of Rubin

1. Channel registration, set interest
2. Selection Key creation
3. Non-/Blocking `select()`



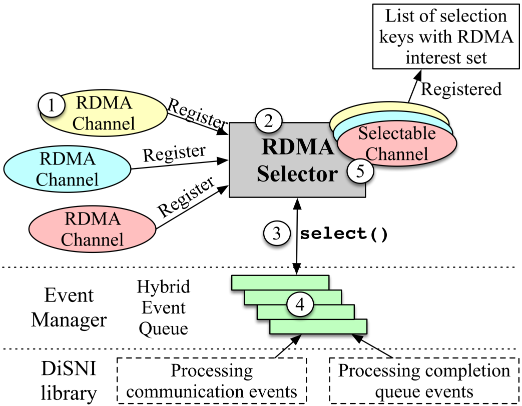
Workflow of RUBIN

1. Channel registration, set interest
2. Selection Key creation
3. Non-/Blocking `select()`
4. Hybrid event queue, notify selector



Workflow of RUBIN

1. Channel registration, set interest
2. Selection Key creation
3. Non-/Blocking `select()`
4. Hybrid event queue, notify selector
5. Select responsible channel



③ Zero-Copy Communication

- Pool of pre-allocated RDMA-registered application buffers
- Optimization: **selective signaling** to reduce notification overhead

→ **Challenge: Buffer Copy**

- Sender: register application buffers, no buffer copy
- Receiver: **copy** data to application buffer due to incompatibility

  → DiSNI requires direct buffers, but also heap buffers used in Reptor

Evaluation Setup

- 2 server machines: 4-core Xeon v2 CPUs and 16GB RAM
- 10Gbps switched network
- Mellanox ConnectX-3 RDMA NICs

- Q1: How does **RDMA communication** compare to **TCP**?
- Q2: What is the performance of **Rubin**?

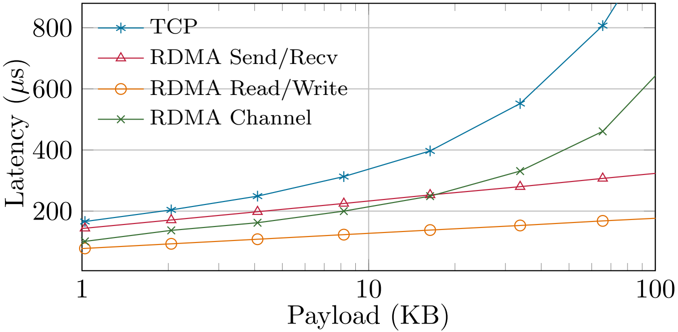
Evaluation Setup

- 2 server machines: 4-core Xeon v2 CPUs and 16GB RAM
- 10Gbps switched network
- Mellanox ConnectX-3 RDMA NICs

- Q1: How does **RDMA communication** compare to **TCP**?
- Q2: What is the performance of **Rubin**?

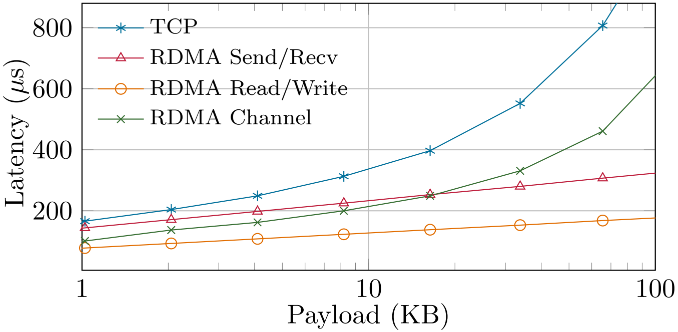
- Echo server application:
  - Q1: Distributed microbenchmark for RDMA Channel
  - Q2: Local microbenchmark for Rubin in Reptor communication stack

RDMA Microbenchmarks – Latency



- RDMA Channel **33 – 43 %** lower latency than TCP
- Optimizations: **30 %** less latency than Send/Recv for messages <16KB

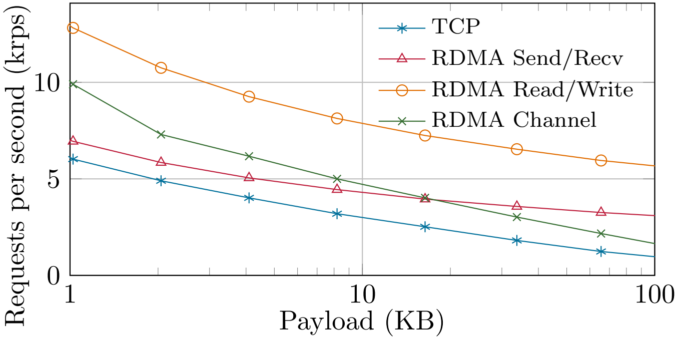
RDMA Microbenchmarks – Latency



- RDMA Channel **33 – 43 %** lower latency than TCP
- Optimizations: **30 %** less latency than Send/Recv for messages <16KB

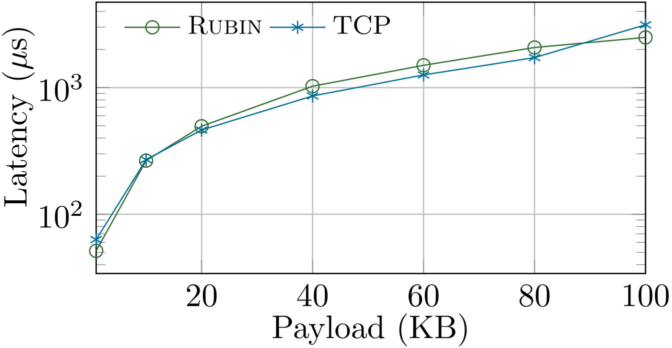
Performance degradation due to **remaining buffer copy**

RDMA Microbenchmarks – Throughput



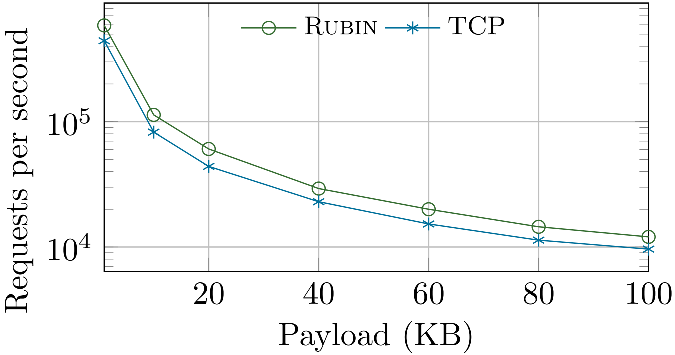
- RDMA Channel **33 – 43 %** higher throughput than TCP
- Optimizations: **30 %** higher throughput than Send/Recv

Rubin Microbenchmarks – Latency



- 1KB, 100KB: **19 – 20 %** lower latency
- 20KB – 80KB: **20 %** higher latency

Rubin Microbenchmarks – Throughput



- Rubin has **25 – 38 %** higher throughput than TCP

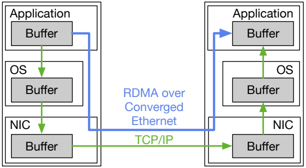
Limited by **buffer copy**
→ remove and optimize!

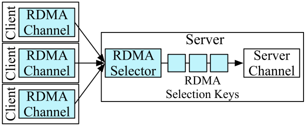
Future Work

- **Zero-copy**: remove any additional data copy steps
- Reptor: evaluate **fully replicated system** with Rubin communication
- Integration of Reptor into a **permissioned blockchain framework**
  - E.g. Hyperledger Fabric

Conclusion – Rubin

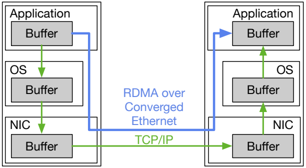
- **RDMA** framework for **BFT protocols**
- High-level abstraction to maintain **flexibility**
- **Easy integration:** modeled after Java NIO interface
- Up to **25 – 38 %** higher throughput
- Next: RDMA-capable BFT ordering service in permissioned **blockchain** setting

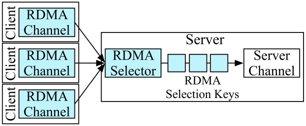




Conclusion – Rubin

- **RDMA** framework for **BFT protocols**
- High-level abstraction to maintain **flexibility**
- **Easy integration:** modeled after Java NIO interface
- Up to **25 – 38 %** higher throughput
- Next: RDMA-capable BFT ordering service in permissioned **blockchain** setting



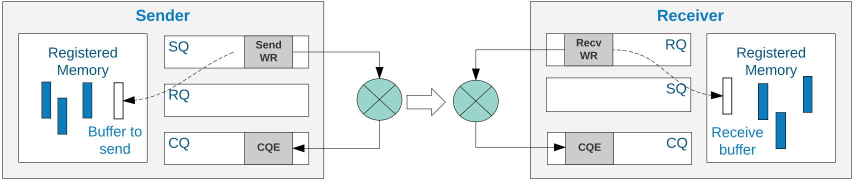


Questions?

ruesch@ibr.cs.tu-bs.de

Backup – RDMA Communication

- OS only used to establish connection
- Queue Pair: send/receive queue holding work requests
- Work Request: information about data to be sent/received
- Completion Queue: holds events notifying application about finished operation



Backup – Reptor Buffer Management

- DiSNI requires direct buffers in native memory
- Reptor uses both direct buffers and heap buffers in JVM memory
- Remote side needs pre-prepared buffers to receive data via RDMA
- Reptor has complex buffer management scheme, often replacing buffers

→ Redesign parts of buffer management

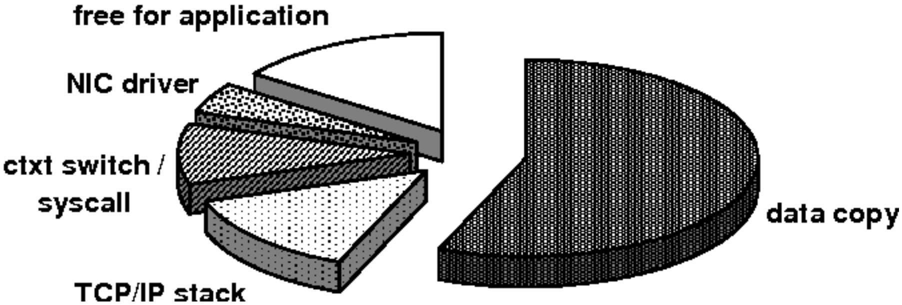
Backup – Reptor

- BFT framework implementing both PBFT and Hybster
- Hybster: hybrid BFT protocol with TSS using Intel SGX
- Consensus-oriented parallelization: parallel execution of consensus instances

Backup – Security Analysis

- RDMA mechanisms: Protection Domains and memory access permissions
- Security issues mostly relevant for Read/Write communication
- Read/Write: node reads data while it is overwritten $\rightarrow$ data corruption
- Steering Tag:
  - Buffer identifier
  - MitM attacks
  - Invalidate tag to prevent legitimate access

Backup – TCP Overhead



(Frey et al., ICDCS'09)

References

- ETB Technologies. Dell Mellanox CX324A CONNECTX-3 40Gb QSFP+ Dual Port Low Profile NIC - M9NW6. `https://goo.gl/Z8pVbM`
- mcwiggin. Datto Data Center Shots. `https://goo.gl/xZCPxd`