RDMA – Technical Details

Objects, Connection Management, Verbs, On the Wire

RDMA Operations

Channel Semantics: Send / Recv

Send Operation: Sender sends a message to the receiver.

Receive Operation: Receiver needs a corresponding operation to handle the incoming data.

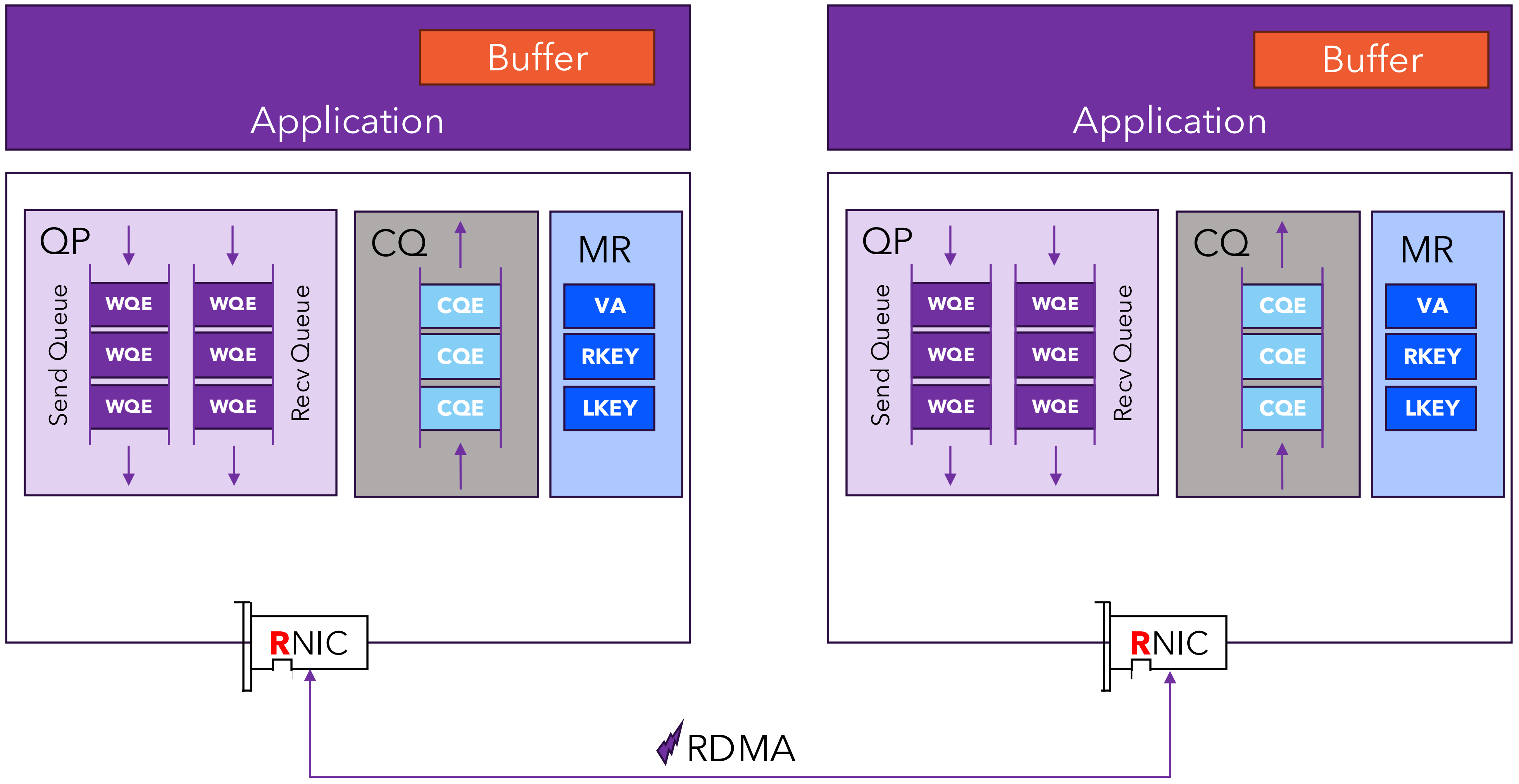
Memory Semantics: Read / Write / Atomic

Read: Reads data from the remote memory into the local memory.

Write: Writes data directly to a specified location in the remote memory.

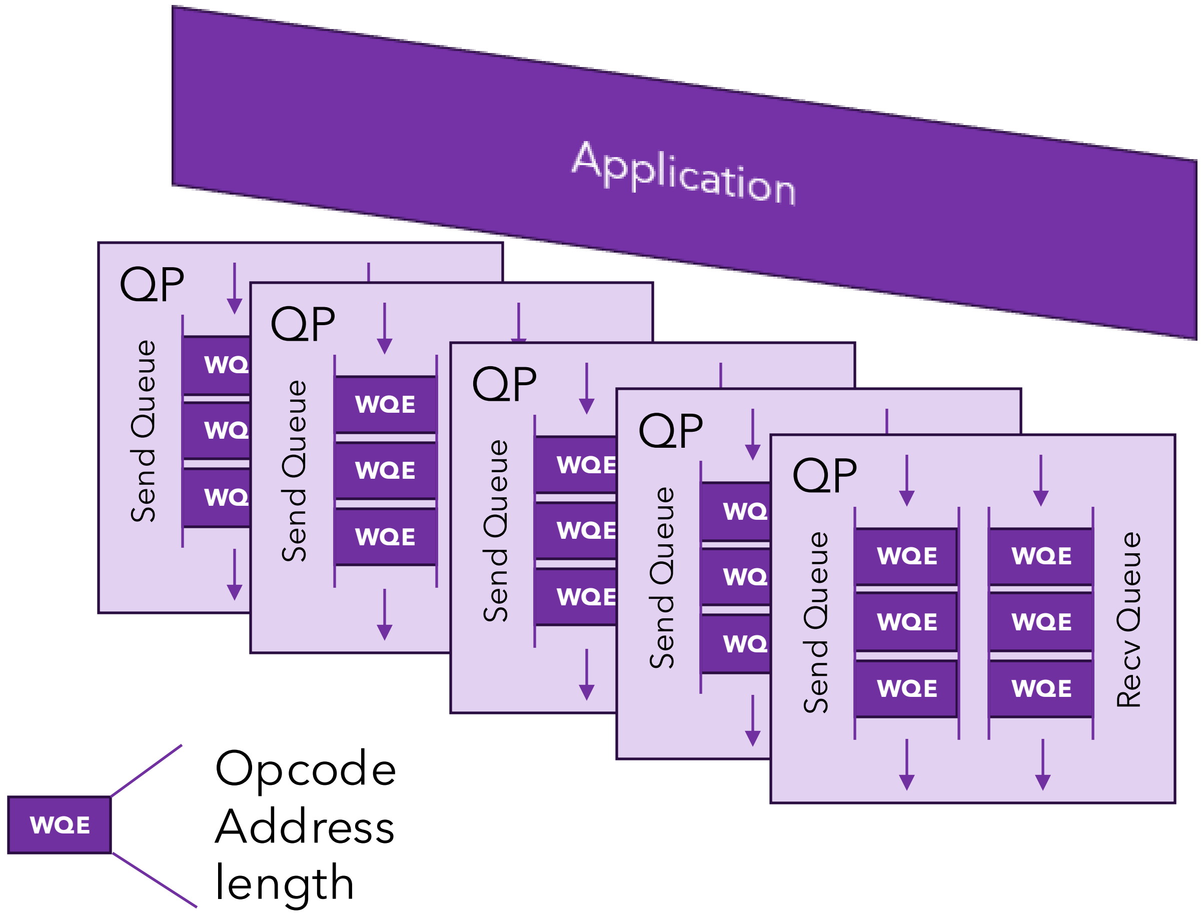
Atomic Operations: Performs atomic read-modify-write operations on remote memory.

RDMA Main Objects



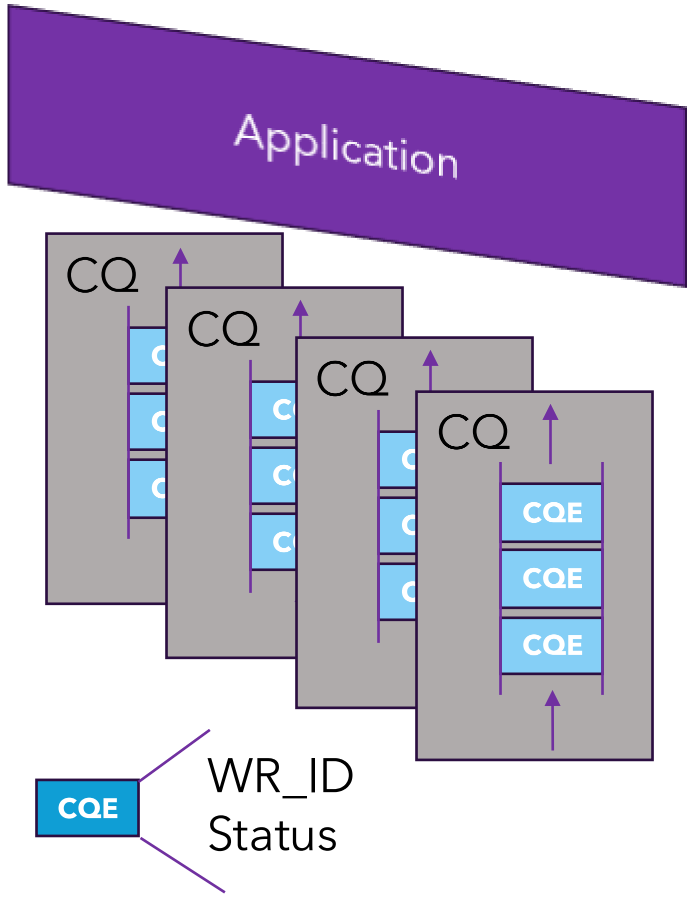
Queue-Pairs (QP)

- Used by consumer (application) to submit operations to the RNIC
- QP consists of
  - Send-Queue (SQ)
  - Receive-Queue (RQ)
- Each consumer can have multiple QPs
- WQEs – Work Queue Elements posted on the SQ / RQ



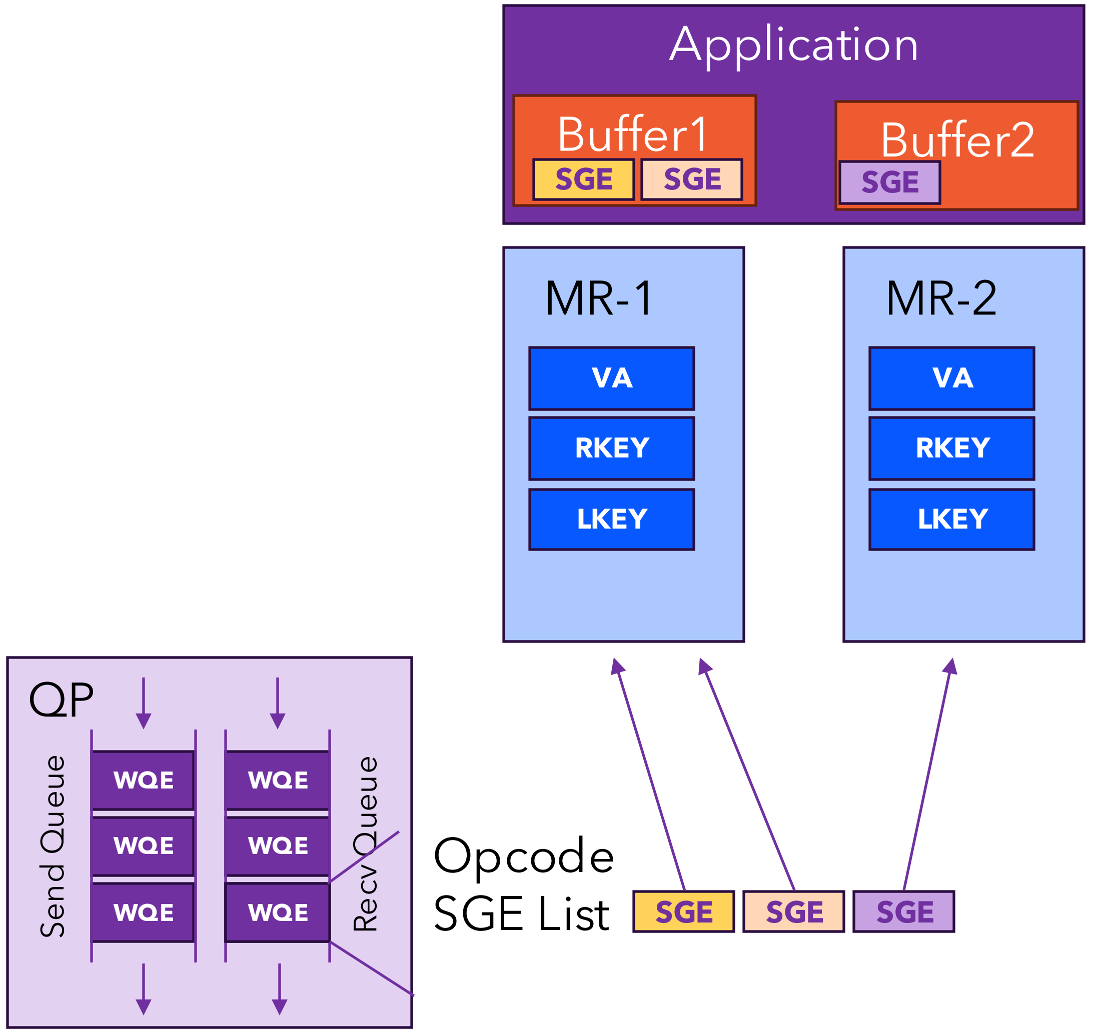
Completion Queues (CQs)

- CQs indicate completions for WQEs placed on SQ and RQ
- Consumer can have multiple CQ-s
- SQs and RQs are mapped to a CQ
- CQ can serve multiple SQs/RQs **NOT** a 1:1 mapping
- Two methods for processing CQs:
  - **Polling mode**: Low latency, high throughput but CPU intensive
  - **Interrupt-based mode**: Reduces CPU usage and power. Higher latency complexity

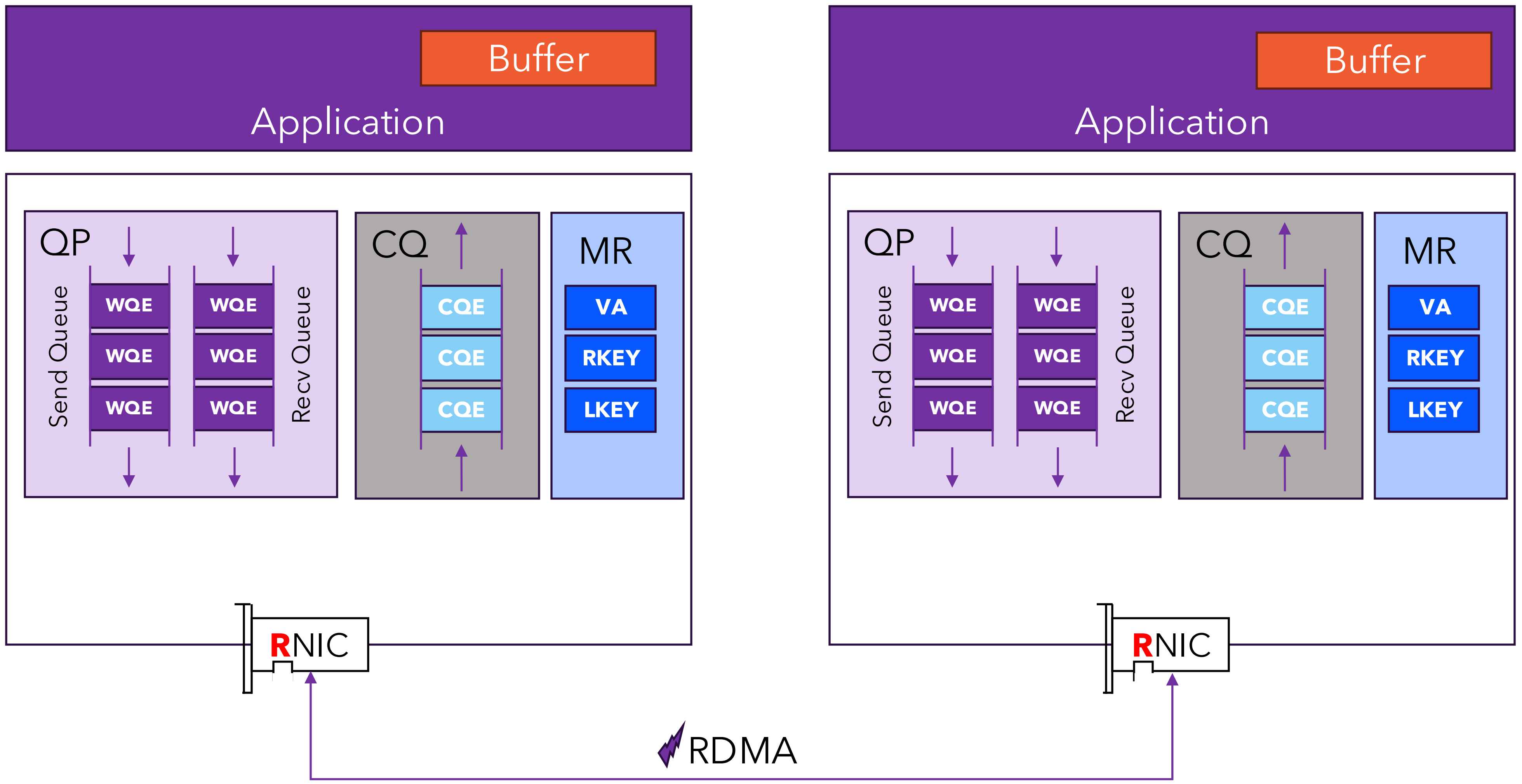


Memory Region (MR)

- Application register region of memory – MR
- Allows RNIC to read/write from this memory
- Registration pins the memory location
- RNIC returns L-KEY and R-KEY
  - L-KEY – used by local APP
  - R-KEY – used by remote APP
- L_Key / R_Key, with the offset in the MR and length, identify the location from which to read / write.



Revisiting…



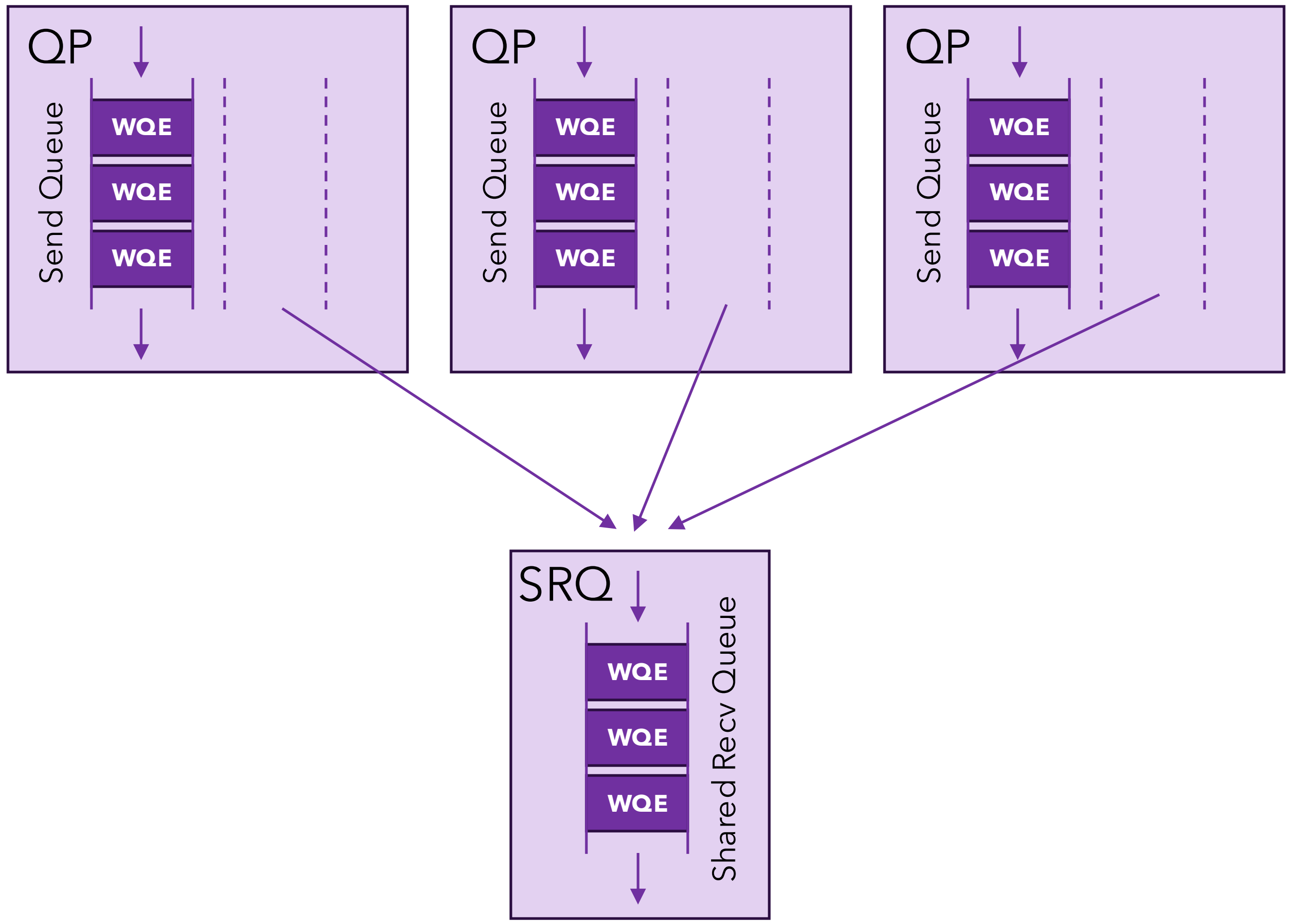
Buffer
Application
QP
Send Queue
WQE
WQE
WQE
WQE
WQE
WQE
Recv Queue
CQ
CQE
CQE
CQE
MR
VA
RKEY
LKEY
RNIC
Buffer
Application
QP
Send Queue
WQE
WQE
WQE
WQE
WQE
WQE
Recv Queue
CQ
CQE
CQE
CQE
MR
VA
RKEY
LKEY
RNIC
RDMA

Protection Domains (PD)

- Group objects that can work together
- Associated with QPs, MRs, SRQs MWs.
- RNIC validates that the MR has the same PD domain as the QP on which it is posted / received.
  - If not, there will be a completion with error

Shared Receive Queue (SRQ)

- Shared Receive Queue between QPs
- QP can be created with SRQ instead of RQ
- More efficient in memory consumption



Connection Management

- Four types of QP-s are supported:
  - Reliable connection (RC) – mostly used (somewhat comparable to TCP)
  - Unreliable connection (UC)
  - Reliable datagram (RD)
  - Unreliable datagram (UD) (somewhat comparable to UDP)
- Connections are established out-of-band.
  - Each wire protocol uses a different scheme.
    - Infiniband defines protocol running over UD.
    - iWARP defines a protocol running over TCP.
    - Since it's out-of-band can be emulated over sockets

XRC – Extended Reliable Connection

- XRC allows significant savings in the number of QPs required to establish all to all process connectivity in large clusters.
- Single XRC Initiator QP a process in one node can communicate with ALL processes on one remote node, thus reducing by a factor of p the number of overall QPs required for full connectivity (as compared RC QPs)
- $QPs = N_{nodes} \times N_{processes}$
- Decrease from $N_{nodes} \times N_{processes}^{2}$

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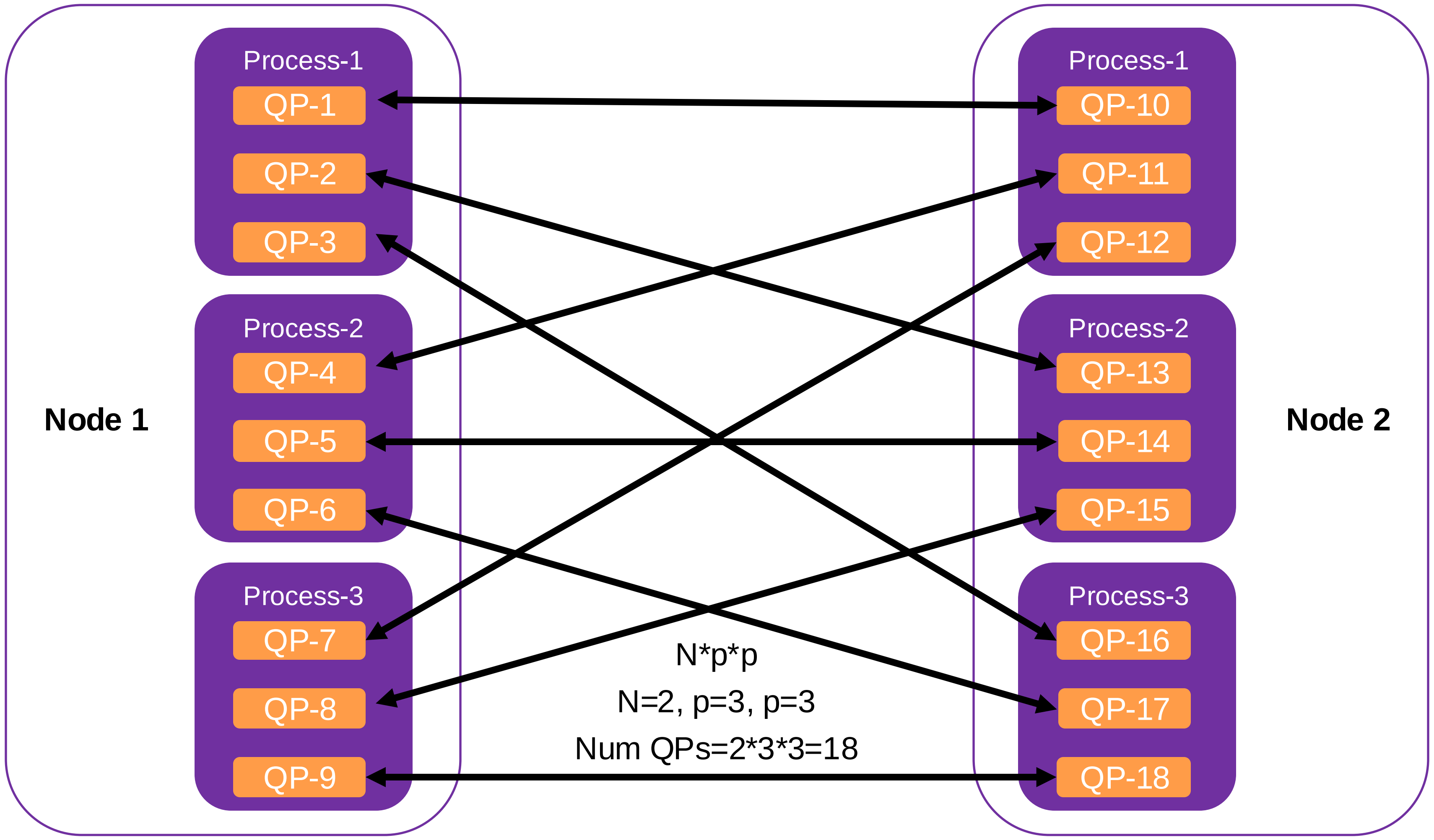
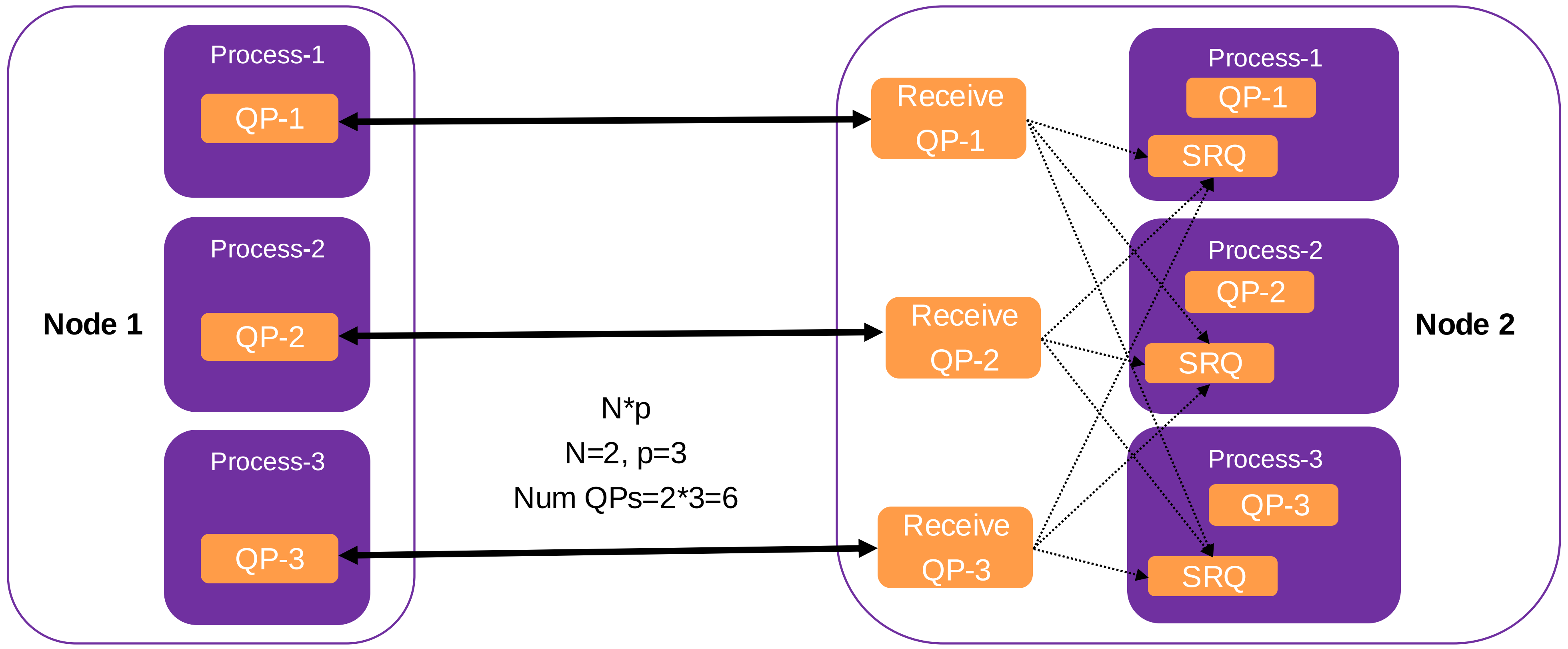
QP – RC Connection Example



QP – XRC Connection Example



Shown in one direction for simplicity, but the QPs on each side are symmetrical

RDMA Verbs

Verbs provide an abstract definition of the functionality provided to a host by a RDMA NIC.

An operating system may expose some or all of the verb functionality through its programming interface.

Same Verbs for all wire-protocols.

Slow-Path Verbs Operations

Slow-path operations involve privileged driver, Main verbs:

Device related	Open / close device
PD (Protection Domain)	Allocate / De-allocate
MR (Memory Region)	Register / de-register
QP (Queue Pair)	Create / destroy / modify
CQ (Completion Queue)	Create / resize / destroy
SRQ (Shared Queue Pair)	Create / resize / destroy

Fast-Path / Data-Path Verbs

Fast-path operations can be done from either user-space or a privileged driver.

Send operations	Send operation consumes a RQ entry in the peer All memory used in transfers **must be registered**
Receive operations	Post RQ receive user application must ensure a send is not posted on one side before a corresponding recv has been posted on the other side
RDMA operations	RDMA write, RDMA read Atomic operations (fetch and add, compare and swap)
Memory operations	Bind MW, Fast register MR Local invalidate

Putting it all together: How does an app look? What goes on the wire?

Typical App Stages Overview

HOSTS INITIALIZE CONTEXT AND REGISTER MEMORY REGIONS

ESTABLISH CONNECTION

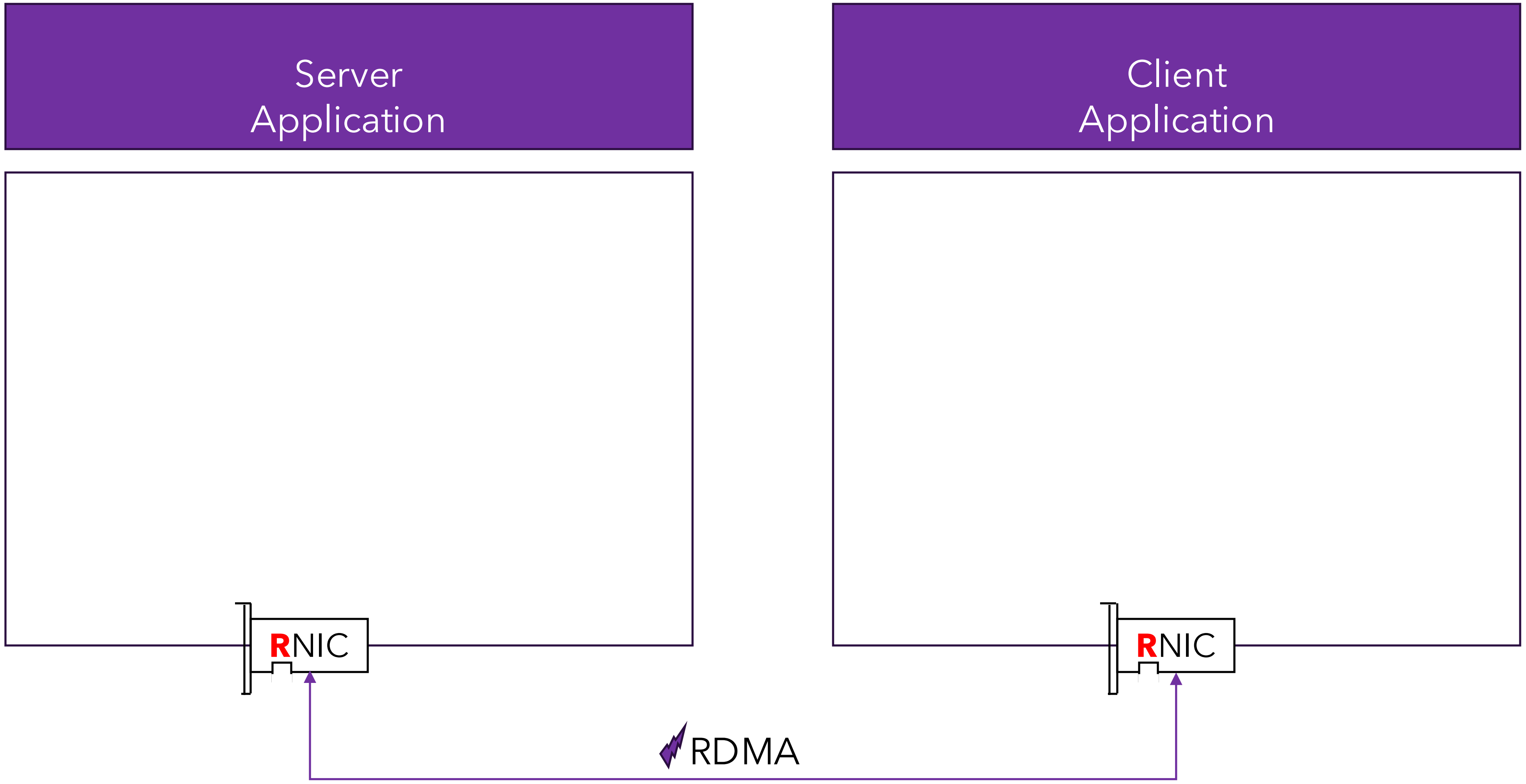
USE SEND/RECEIVE MODEL TO EXCHANGE MEMORY REGION KEYS BETWEEN PEERS

POST READ/WRITE OPERATIONS

DISCONNECT

Initialization

HOSTS INITIALIZE CONTEXT AND REGISTER MEMORY REGIONS



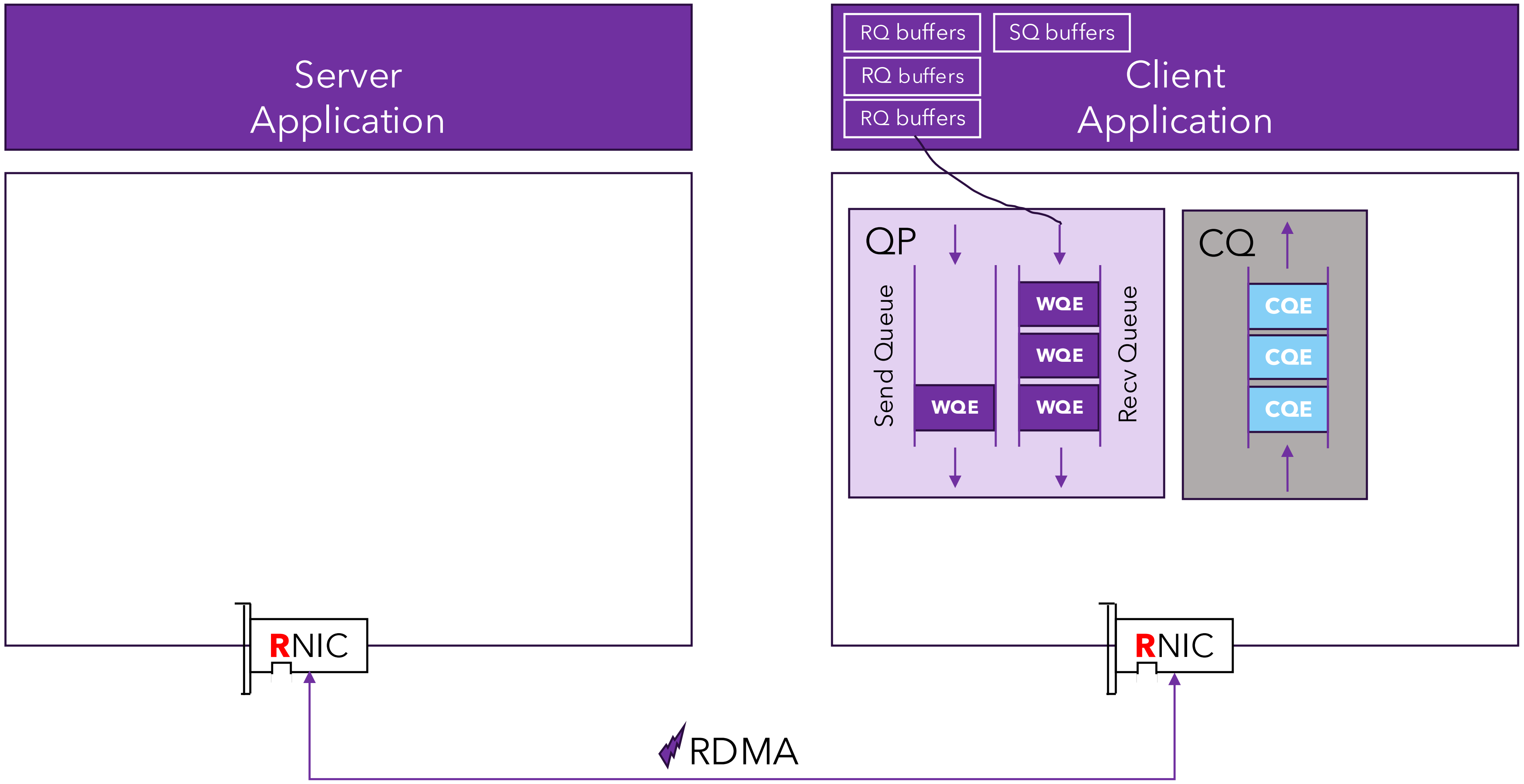
Initialization

HOSTS INITIALIZE CONTEXT AND REGISTER MEMORY REGIONS

Target (Server)	**Initiator (Client)**
Create an event channel to receive rdmacm events connection-request connection-established notifications	Create an event channel to receive rdmacm events address-resolved route-resolved connection-established notifications
Bind to an address	Create a connection identifier
Create a listener and return the port/address	Resolve the peer's address, which binds the connection identifier to a local RDMA device
Wait for a connection request	Resolve the route to the peer
	Create a PD, CQ, QP

Initialization

HOSTS INITIALIZE CONTEXT AND REGISTER MEMORY REGIONS



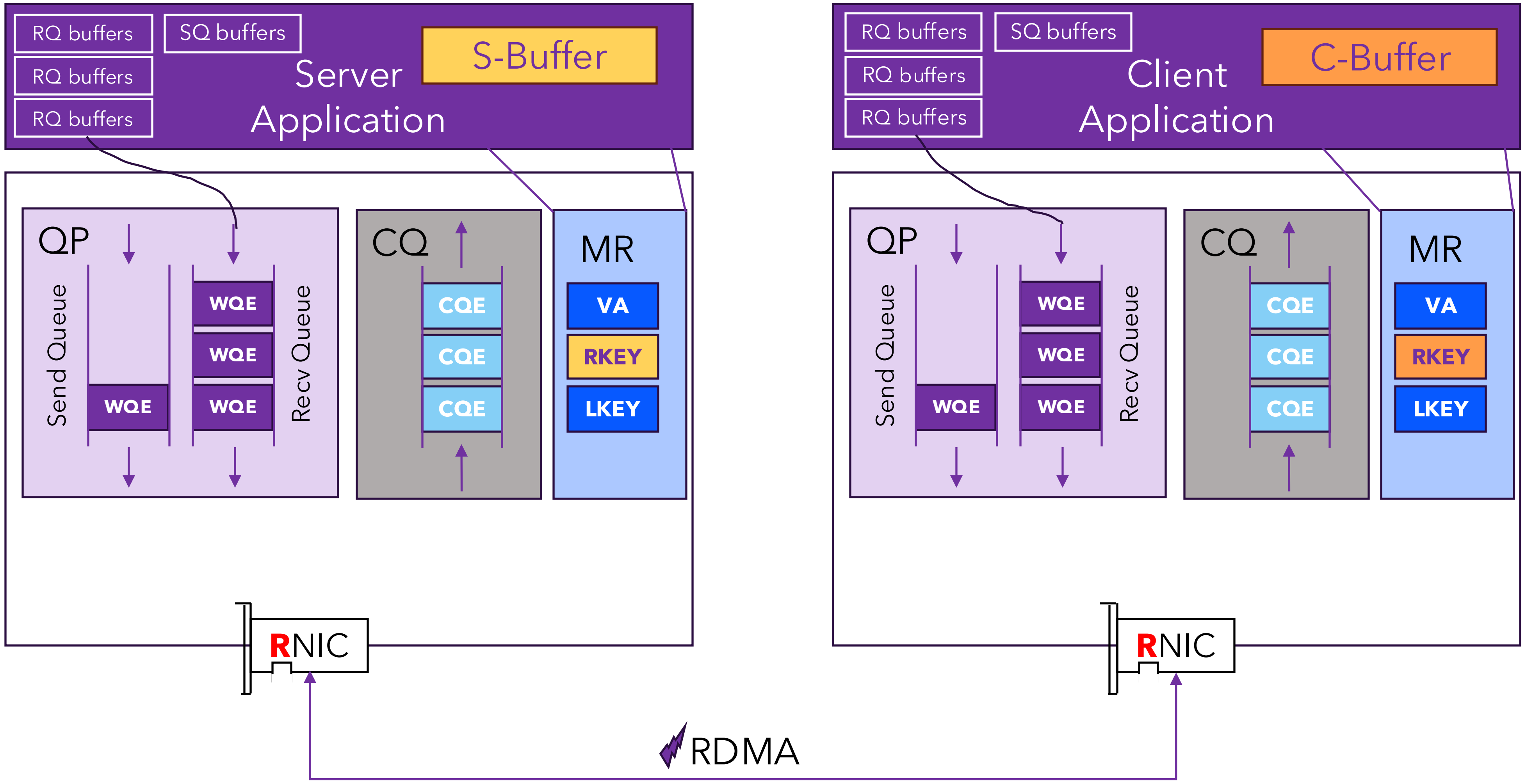
Initialization

ESTABLISH CONNECTION

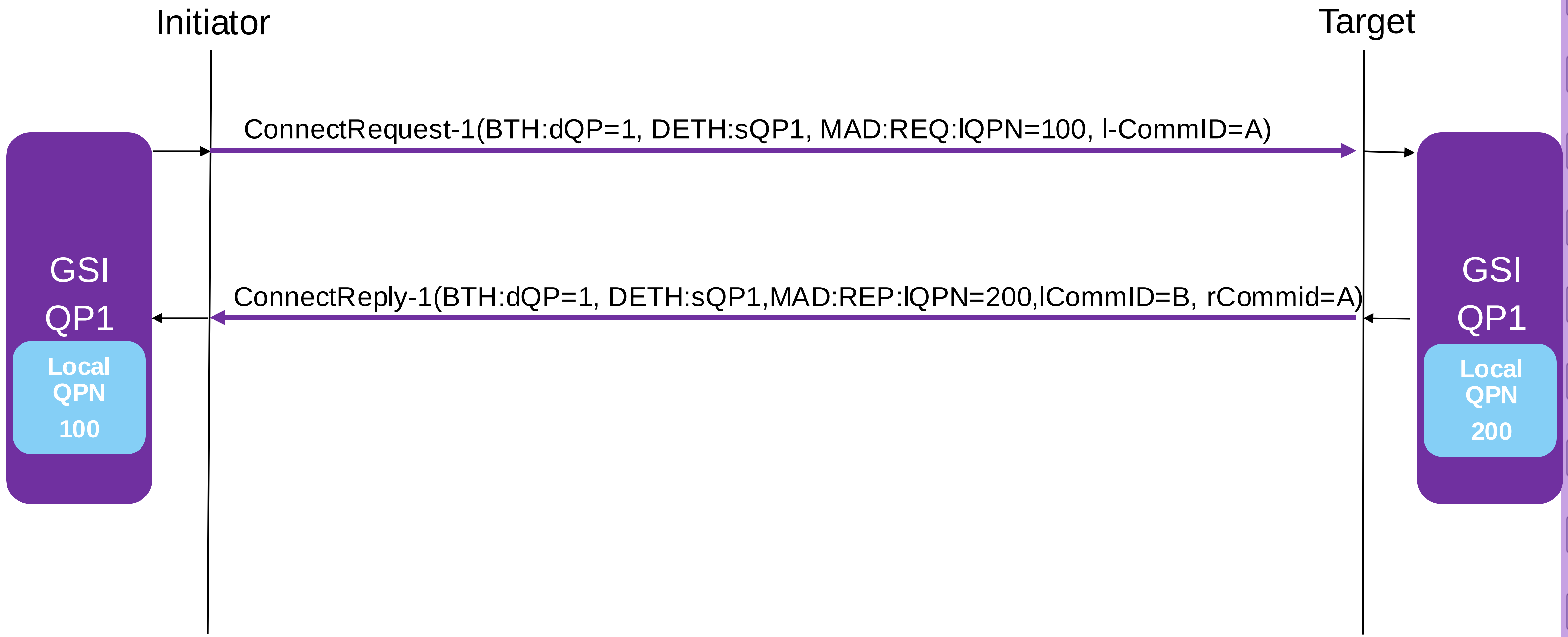
SERVER (Passive)	Client (Active)
Create an event channel to receive rdmacm events connection-request connection-established notifications	Create an event channel to receive rdmacm events address-resolved route-resolved connection-established notifications
Bind to an address	Create a connection identifier
Create a listener and return the port/address	Resolve the peer's address, which binds the connection identifier to a local RDMA device
Wait for a connection request	Create a PD, CQ, QP
Create a PD, CQ, QP	Resolve the route to the peer
Accept the connection request	Connect
Wait for connection to be established	Wait for connection to be established
Post operations as appropriate	Post operations as appropriate

Initialization

ESTABLISH CONNECTION

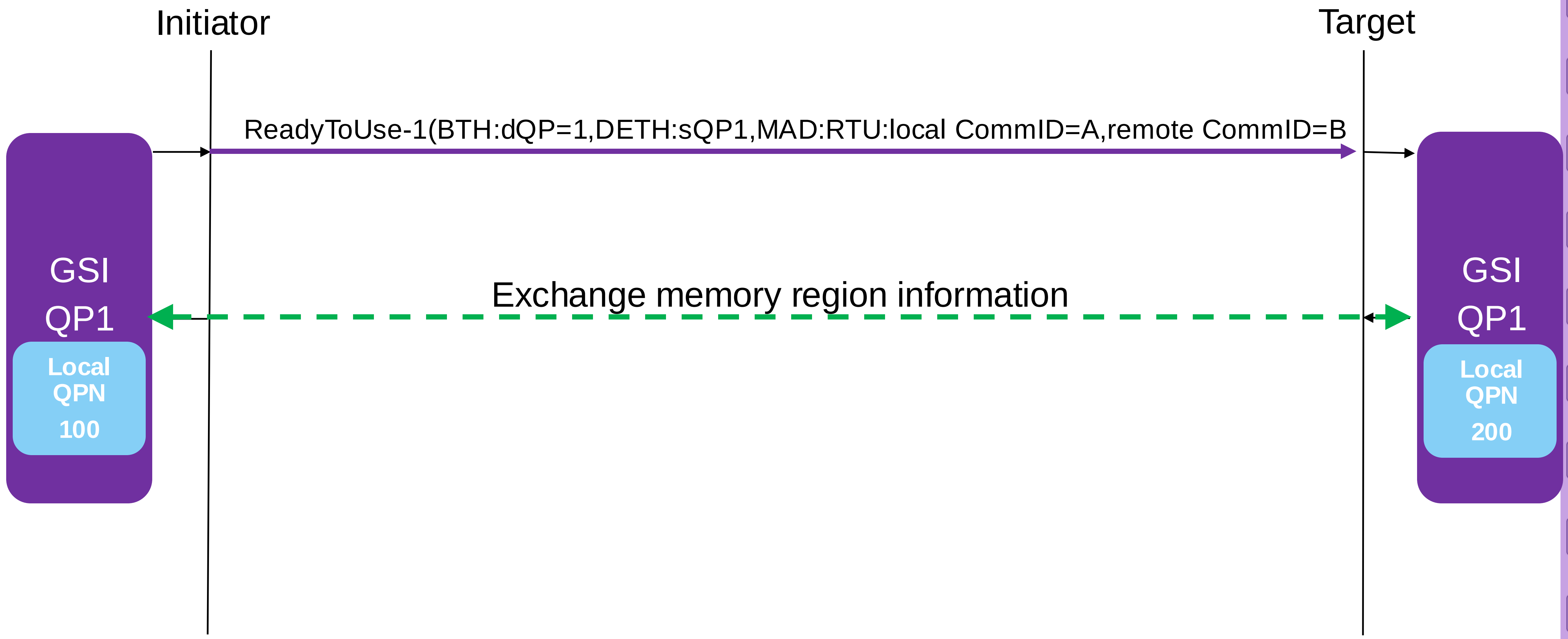


Connection Setup


Initiator
Target
ConnectRequest-1(BTH:dQP=1, DETH:sQP1, MAD:REQ:lQPN=100, l-CommID=A)
ConnectReply-1(BTH:dQP=1, DETH:sQP1,MAD:REP:lQPN=200,lCommID=B, rCommid=A)
GSI
QP1
Local QPN
100
GSI
QP1
Local QPN
200

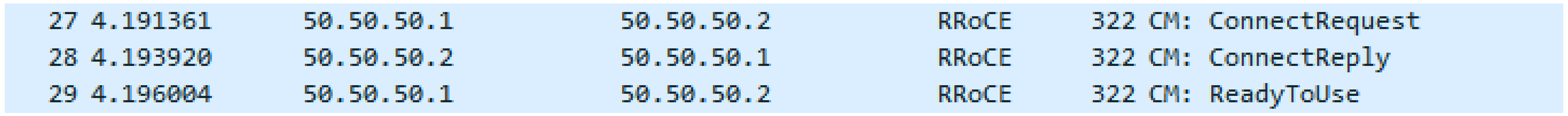
Example IB Initialization & Connection Setup-1-Create “Admin” Connection & QP

Connection Setup - Ready-to-Use


Initiator
Target
ReadyToUse-1(BTH:dQP=1,DETH:sQP1,MAD:RTU:local CommID=A,remote CommID=B
Exchange memory region information
GSI
QP1
Local QPN
100
GSI
QP1
Local QPN
200

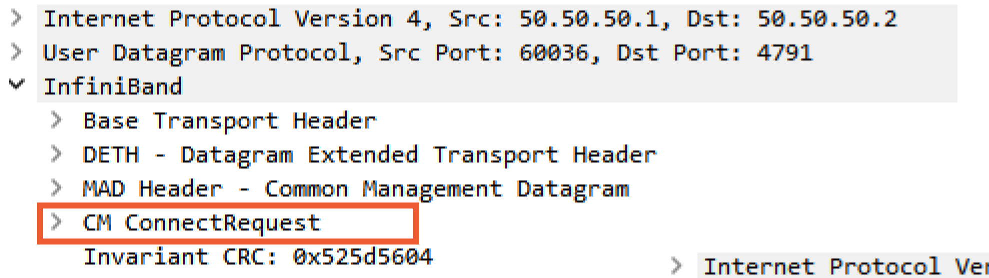
Example IB Initialization & Connection Setup-2-Send Ready To Use & Exchange Info

On the Wire…



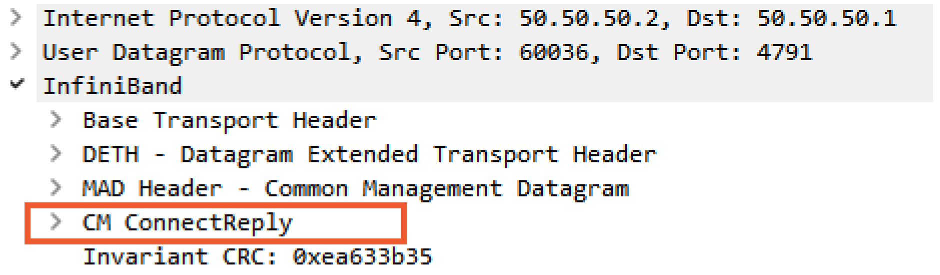
```
27 4.191361    50.50.50.1    50.50.50.2    RRoCE    322 CM: ConnectRequest
28 4.193920    50.50.50.2    50.50.50.1    RRoCE    322 CM: ConnectReply
29 4.196004    50.50.50.1    50.50.50.2    RRoCE    322 CM: ReadyToUse
```

ConnectRequest



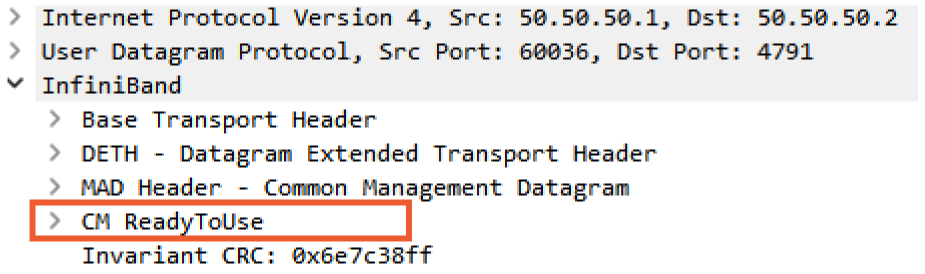
```
> Internet Protocol Version 4, Src: 50.50.50.1, Dst: 50.50.50.2
> User Datagram Protocol, Src Port: 60036, Dst Port: 4791
v InfiniBand
   > Base Transport Header
   > DETH - Datagram Extended Transport Header
   > MAD Header - Common Management Datagram
   > CM ConnectRequest
     Invariant CRC: 0x525d5604
```

ConnectReply



```
> Internet Protocol Version 4, Src: 50.50.50.2, Dst: 50.50.50.1
> User Datagram Protocol, Src Port: 60036, Dst Port: 4791
v InfiniBand
   > Base Transport Header
   > DETH - Datagram Extended Transport Header
   > MAD Header - Common Management Datagram
   > CM ConnectReply
     Invariant CRC: 0xea633b35
```

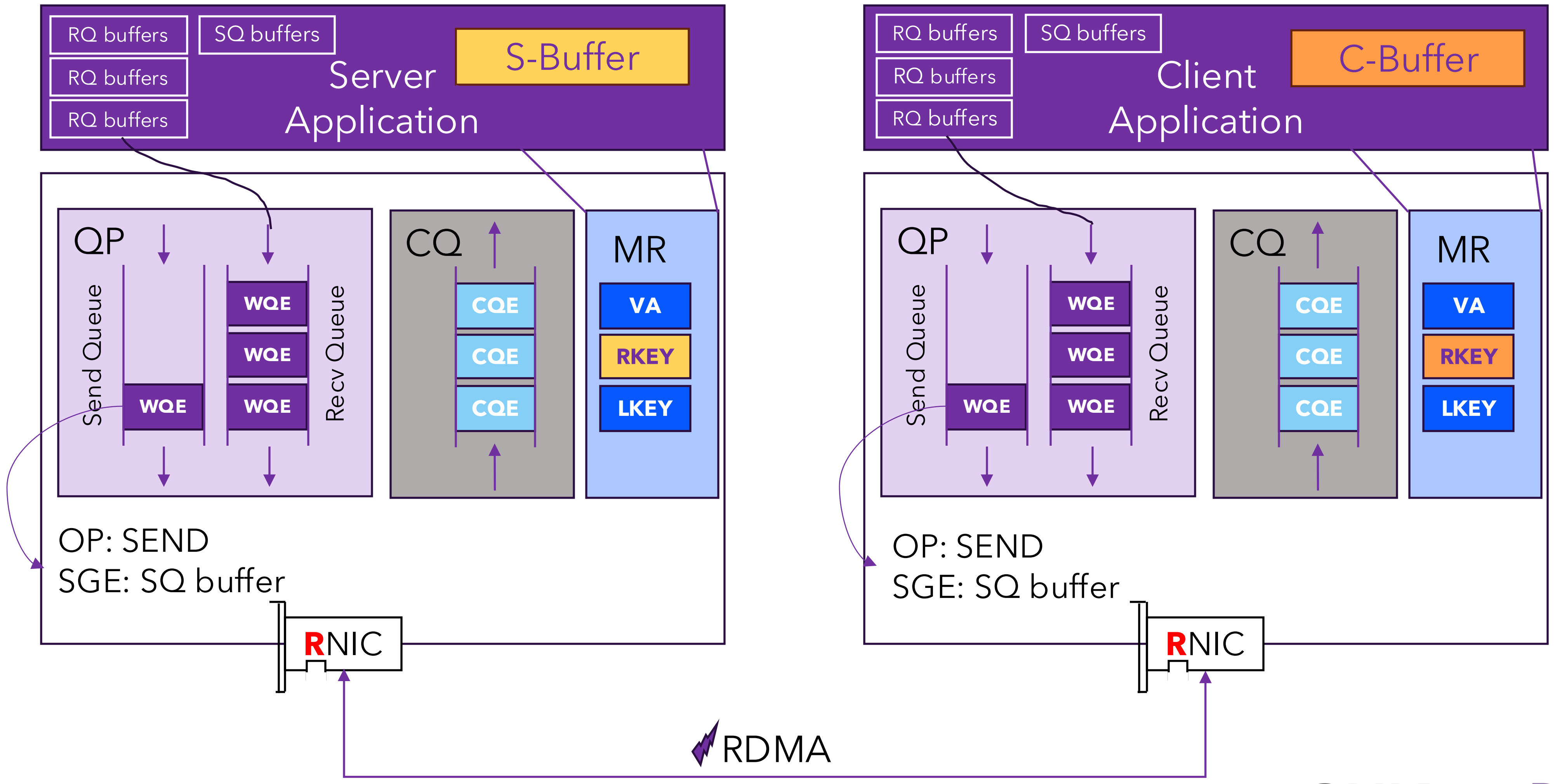
ReadyToUse



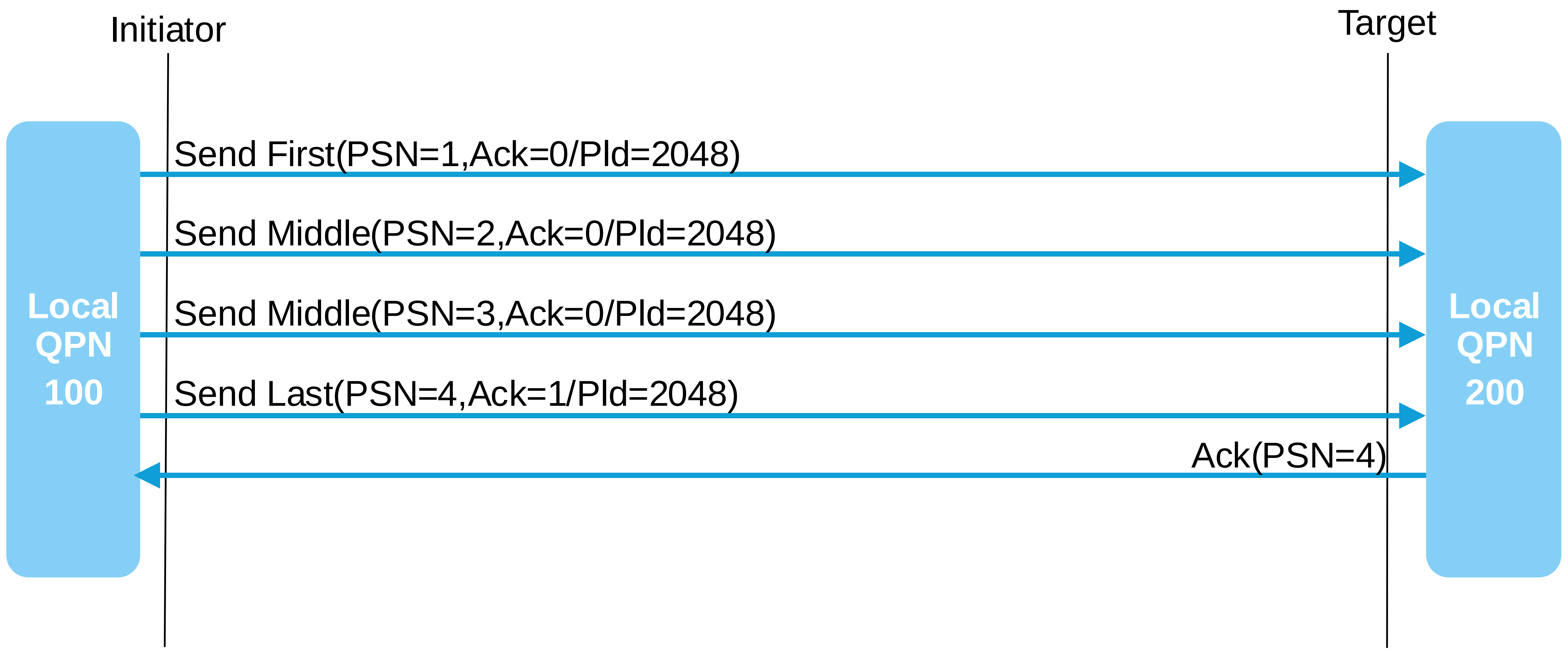
```
> Internet Protocol Version 4, Src: 50.50.50.1, Dst: 50.50.50.2
> User Datagram Protocol, Src Port: 60036, Dst Port: 4791
v InfiniBand
   > Base Transport Header
   > DETH - Datagram Extended Transport Header
   > MAD Header - Common Management Datagram
   > CM ReadyToUse
     Invariant CRC: 0x6e7c38ff
```

Send / Recv Model

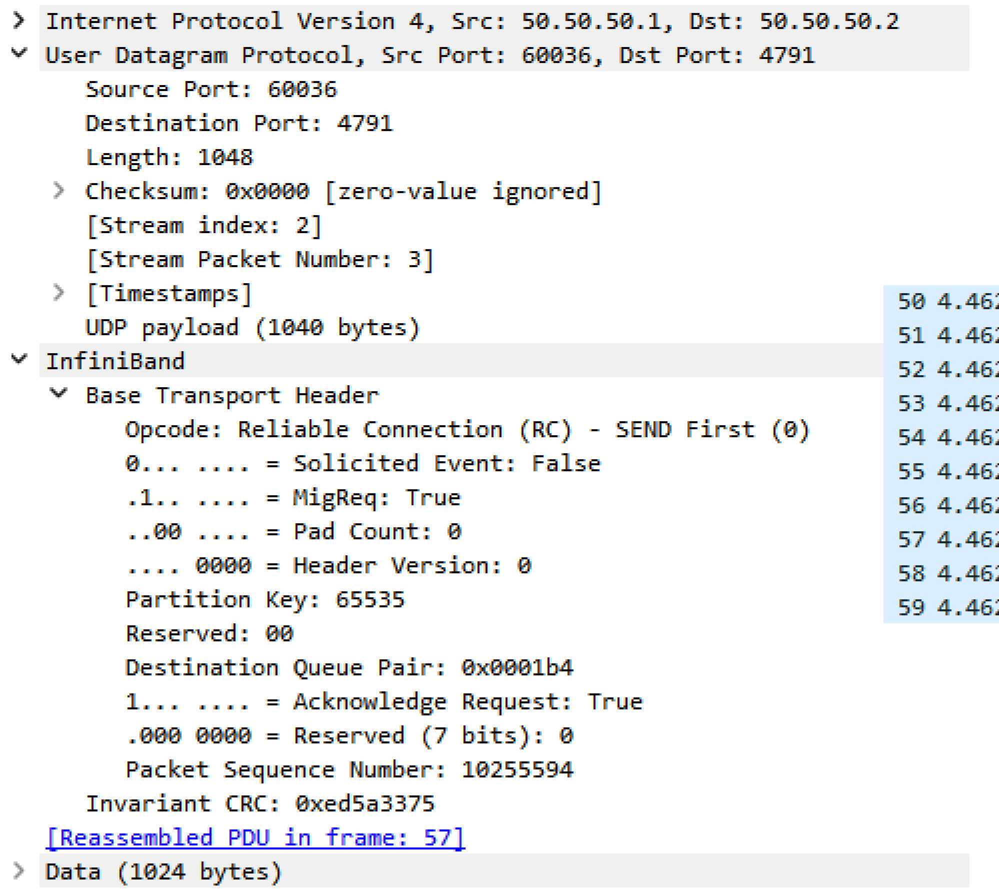
USE SEND/RECEIVE MODEL TO EXCHANGE MEMORY REGION KEYS BETWEEN PEERS



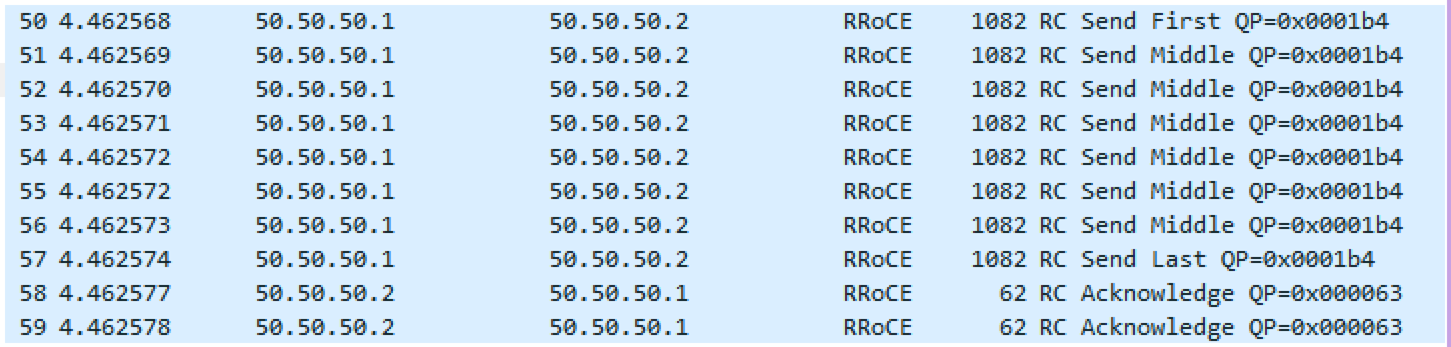
Example Send – 8k (MTU=2K)


Initiator
Target
Local QPN 100
Local QPN 200
Send First(PSN=1,Ack=0/Pld=2048)
Send Middle(PSN=2,Ack=0/Pld=2048)
Send Middle(PSN=3,Ack=0/Pld=2048)
Send Last(PSN=4,Ack=1/Pld=2048)
Ack(PSN=4)

On the Wire Send – 8K (MTU=1K)

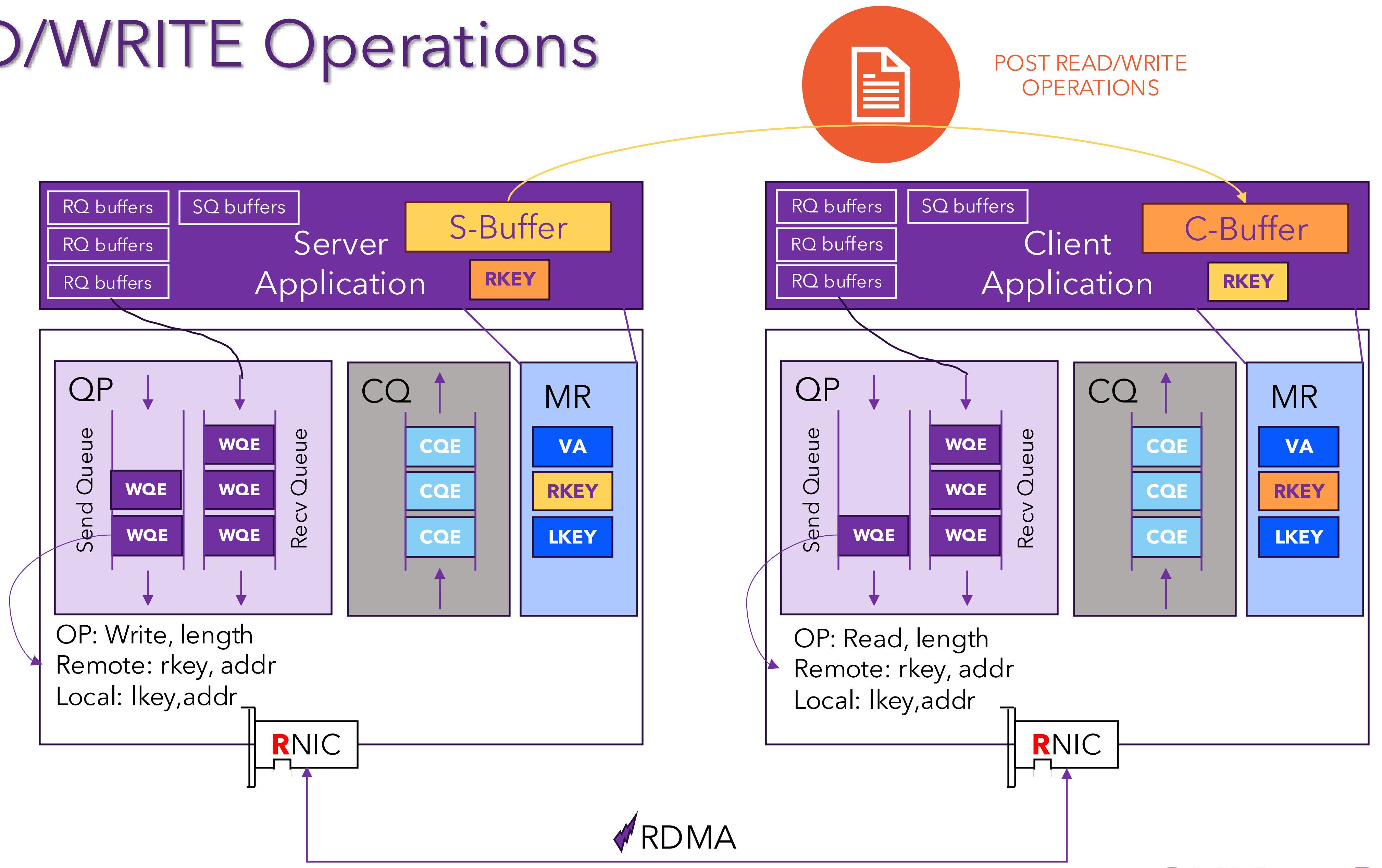


```
> Internet Protocol Version 4, Src: 50.50.50.1, Dst: 50.50.50.2
v User Datagram Protocol, Src Port: 60036, Dst Port: 4791
    Source Port: 60036
    Destination Port: 4791
    Length: 1048
  > Checksum: 0x0000 [zero-value ignored]
    [Stream index: 2]
    [Stream Packet Number: 3]
  > [Timestamps]
    UDP payload (1040 bytes)
v InfiniBand
  v Base Transport Header
      Opcode: Reliable Connection (RC) - SEND First (0)
      0... .... = Solicited Event: False
      .1.. .... = MigReq: True
      ..00 .... = Pad Count: 0
      .... 0000 = Header Version: 0
      Partition Key: 65535
      Reserved: 00
      Destination Queue Pair: 0x0001b4
      1... .... = Acknowledge Request: True
      .000 0000 = Reserved (7 bits): 0
      Packet Sequence Number: 10255594
    Invariant CRC: 0xed5a3375
  [Reassembled PDU in frame: 57]
> Data (1024 bytes)
```

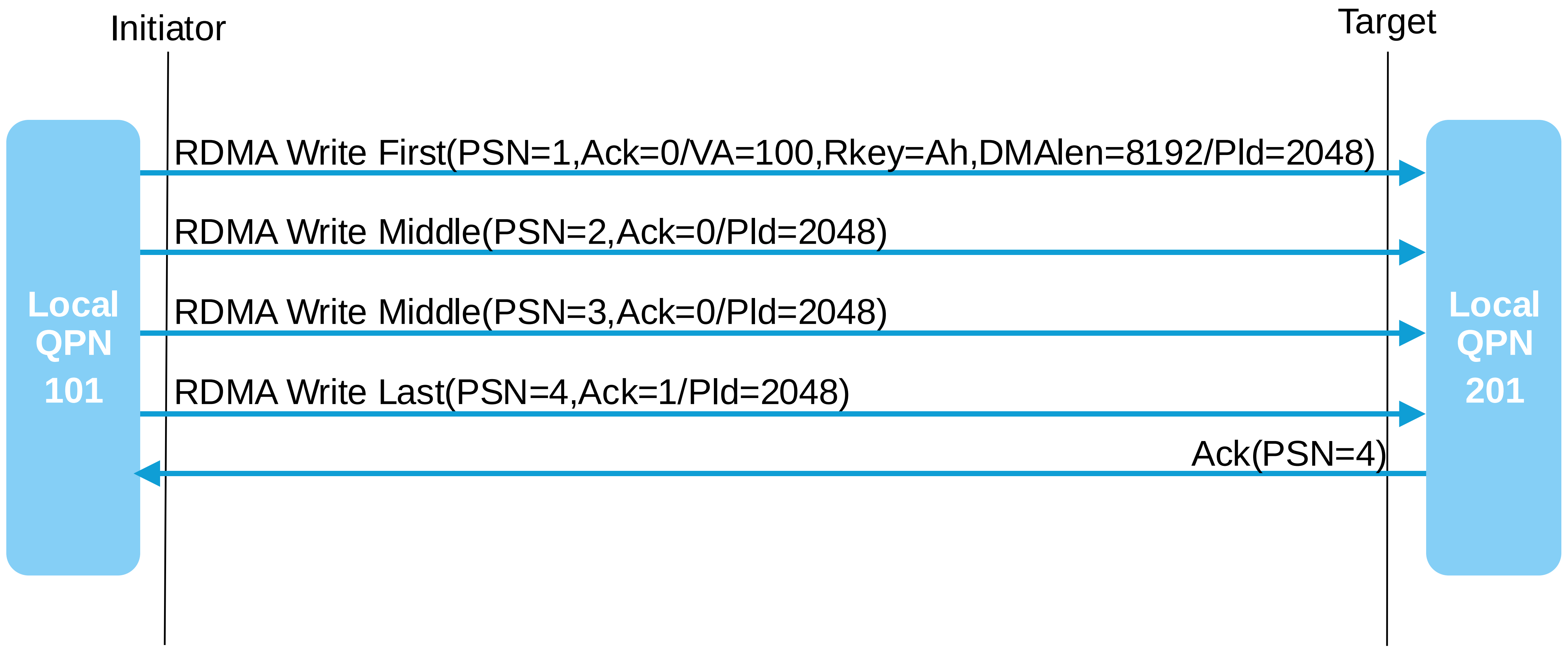


```
50 4.462568    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send First QP=0x0001b4
51 4.462569    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send Middle QP=0x0001b4
52 4.462570    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send Middle QP=0x0001b4
53 4.462571    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send Middle QP=0x0001b4
54 4.462572    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send Middle QP=0x0001b4
55 4.462572    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send Middle QP=0x0001b4
56 4.462573    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send Middle QP=0x0001b4
57 4.462574    50.50.50.1    50.50.50.2    RRoCE    1082 RC Send Last QP=0x0001b4
58 4.462577    50.50.50.2    50.50.50.1    RRoCE      62 RC Acknowledge QP=0x000063
59 4.462578    50.50.50.2    50.50.50.1    RRoCE      62 RC Acknowledge QP=0x000063
```

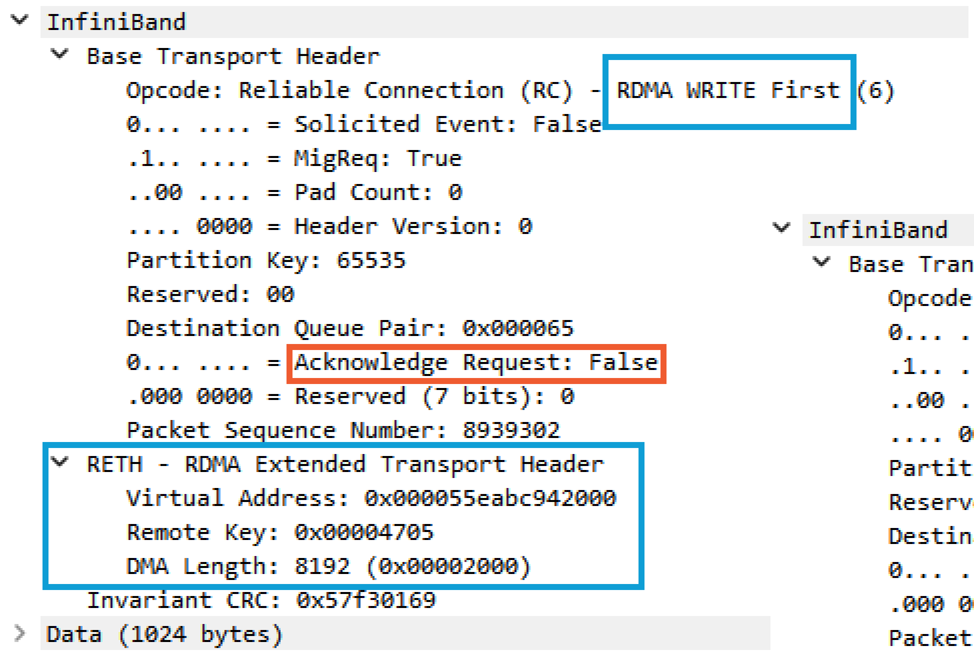
READ/WRITE Operations



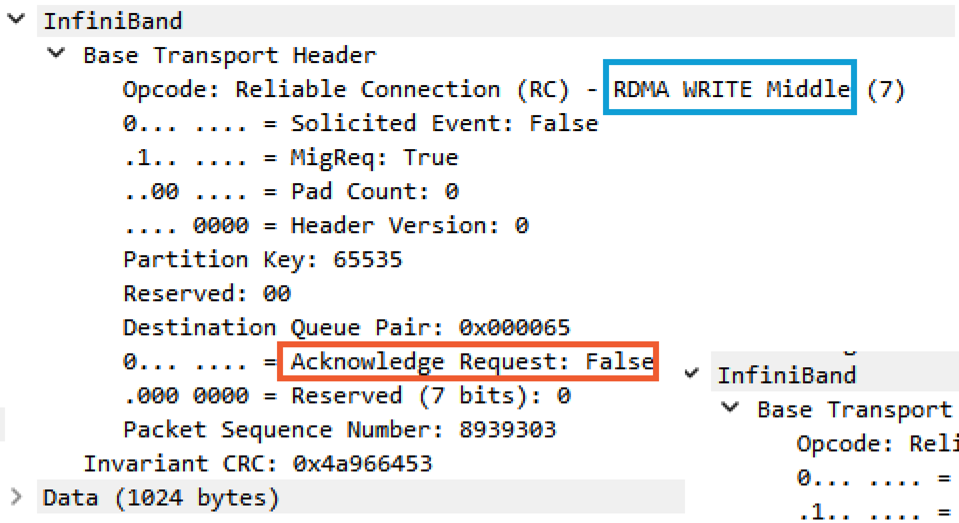
Example RDMA Write – 8k (MTU=2K)


Initiator
Target
Local QPN 101
Local QPN 201
RDMA Write First(PSN=1,Ack=0/VA=100,Rkey=Ah,DMAlen=8192/Pld=2048)
RDMA Write Middle(PSN=2,Ack=0/Pld=2048)
RDMA Write Middle(PSN=3,Ack=0/Pld=2048)
RDMA Write Last(PSN=4,Ack=1/Pld=2048)
Ack(PSN=4)

On the Wire RDMA Write (MTU=1K)

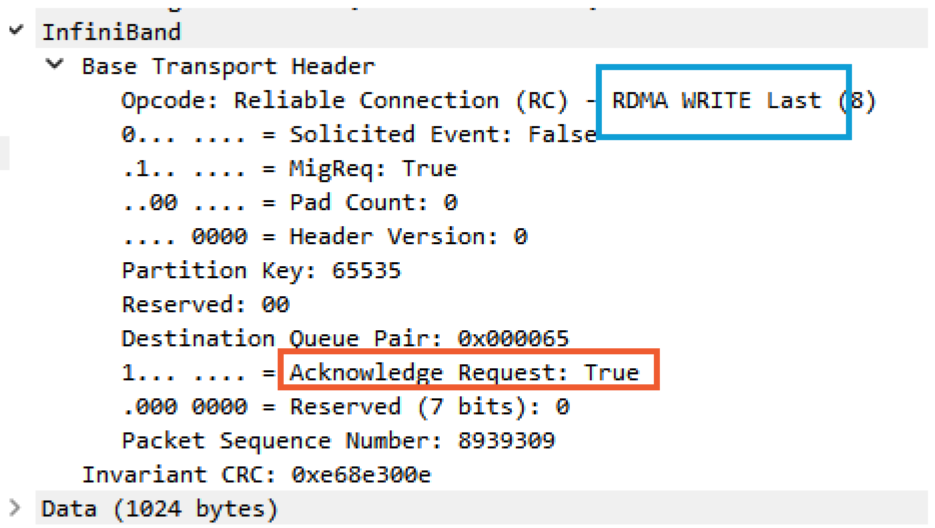


```
v InfiniBand
  v Base Transport Header
      Opcode: Reliable Connection (RC) - RDMA WRITE First (6)
      0... .... = Solicited Event: False
      .1.. .... = MigReq: True
      ..00 .... = Pad Count: 0
      .... 0000 = Header Version: 0
      Partition Key: 65535
      Reserved: 00
      Destination Queue Pair: 0x000065
      0... .... = Acknowledge Request: False
      .000 0000 = Reserved (7 bits): 0
      Packet Sequence Number: 8939302
  v RETH - RDMA Extended Transport Header
      Virtual Address: 0x000055eabc942000
      Remote Key: 0x00004705
      DMA Length: 8192 (0x00002000)
    Invariant CRC: 0x57f30169
> Data (1024 bytes)
```



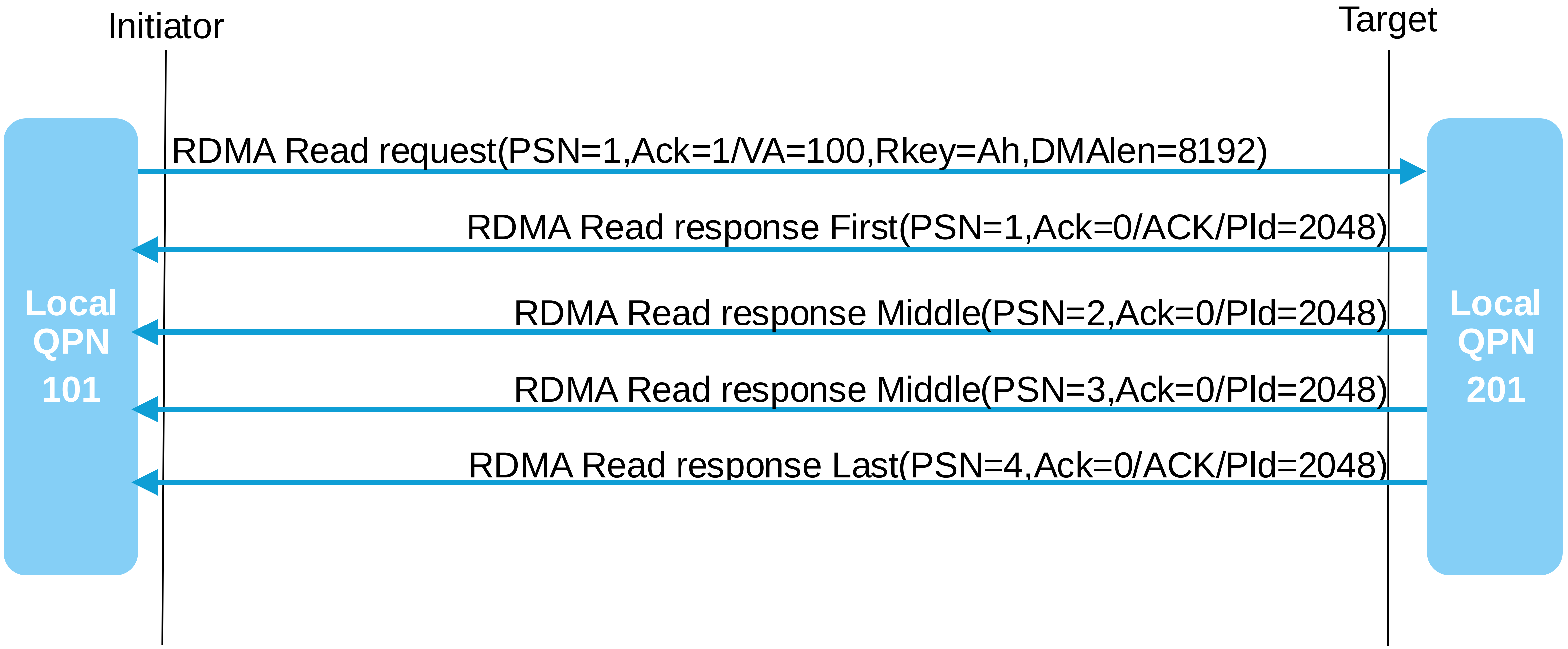
```
v InfiniBand
  v Base Transport Header
      Opcode: Reliable Connection (RC) - RDMA WRITE Middle (7)
      0... .... = Solicited Event: False
      .1.. .... = MigReq: True
      ..00 .... = Pad Count: 0
      .... 0000 = Header Version: 0
      Partition Key: 65535
      Reserved: 00
      Destination Queue Pair: 0x000065
      0... .... = Acknowledge Request: False
      .000 0000 = Reserved (7 bits): 0
      Packet Sequence Number: 8939303
    Invariant CRC: 0x4a966453
> Data (1024 bytes)
```

x6

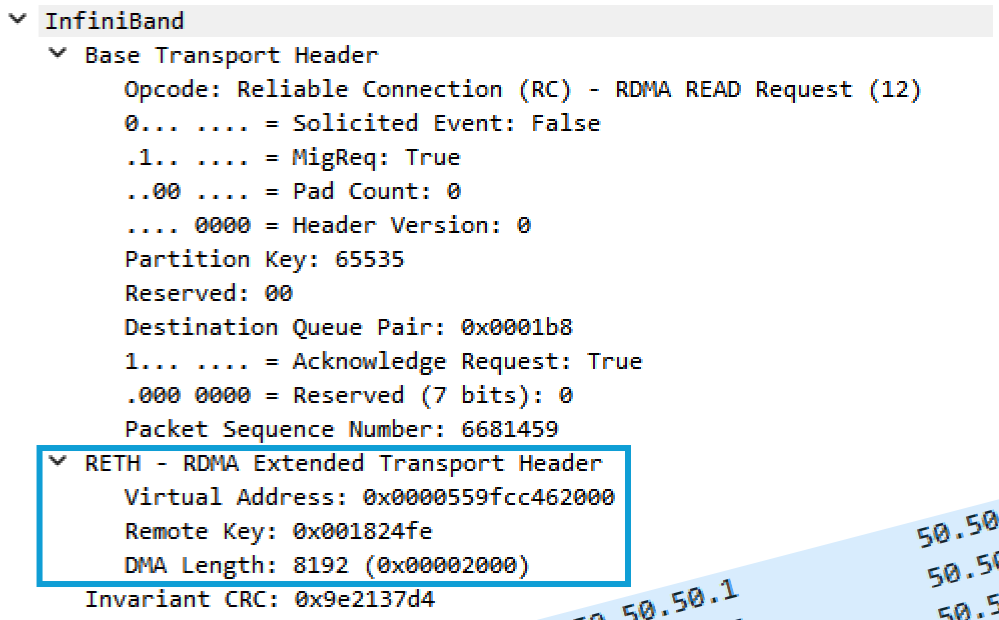


```
v InfiniBand
  v Base Transport Header
      Opcode: Reliable Connection (RC) - RDMA WRITE Last (8)
      0... .... = Solicited Event: False
      .1.. .... = MigReq: True
      ..00 .... = Pad Count: 0
      .... 0000 = Header Version: 0
      Partition Key: 65535
      Reserved: 00
      Destination Queue Pair: 0x000065
      1... .... = Acknowledge Request: True
      .000 0000 = Reserved (7 bits): 0
      Packet Sequence Number: 8939309
    Invariant CRC: 0xe68e300e
> Data (1024 bytes)
```

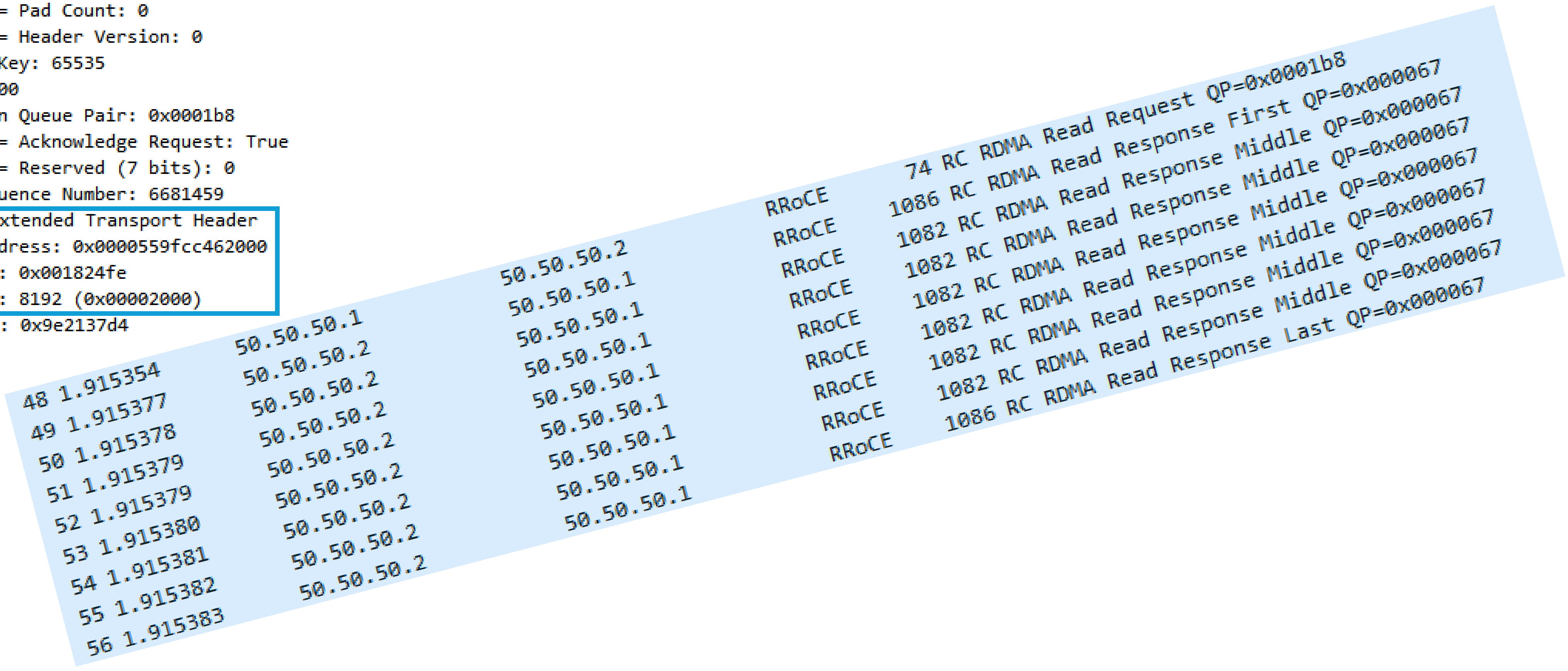
Example RDMA Read – 8k (MTU=2K)


Initiator
Target
Local QPN 101
Local QPN 201
RDMA Read request(PSN=1,Ack=1/VA=100,Rkey=Ah,DMAlen=8192)
RDMA Read response First(PSN=1,Ack=0/ACK/Pld=2048)
RDMA Read response Middle(PSN=2,Ack=0/Pld=2048)
RDMA Read response Middle(PSN=3,Ack=0/Pld=2048)
RDMA Read response Last(PSN=4,Ack=0/ACK/Pld=2048)

On the Wire Read (MTU=1K)



```
InfiniBand
  Base Transport Header
    Opcode: Reliable Connection (RC) - RDMA READ Request (12)
    0... .... = Solicited Event: False
    .1.. .... = MigReq: True
    ..00 .... = Pad Count: 0
    .... 0000 = Header Version: 0
    Partition Key: 65535
    Reserved: 00
    Destination Queue Pair: 0x0001b8
    1... .... = Acknowledge Request: True
    .000 0000 = Reserved (7 bits): 0
    Packet Sequence Number: 6681459
  RETH - RDMA Extended Transport Header
    Virtual Address: 0x0000559fcc462000
    Remote Key: 0x001824fe
    DMA Length: 8192 (0x00002000)
  Invariant CRC: 0x9e2137d4
```



```
48 1.915354   50.50.50.1   50.50.50.2   RRoCE     74 RC RDMA Read Request QP=0x0001b8
49 1.915377   50.50.50.2   50.50.50.1   RRoCE   1086 RC RDMA Read Response First QP=0x000067
50 1.915378   50.50.50.2   50.50.50.1   RRoCE   1082 RC RDMA Read Response Middle QP=0x000067
51 1.915379   50.50.50.2   50.50.50.1   RRoCE   1082 RC RDMA Read Response Middle QP=0x000067
52 1.915379   50.50.50.2   50.50.50.1   RRoCE   1082 RC RDMA Read Response Middle QP=0x000067
53 1.915380   50.50.50.2   50.50.50.1   RRoCE   1082 RC RDMA Read Response Middle QP=0x000067
54 1.915381   50.50.50.2   50.50.50.1   RRoCE   1082 RC RDMA Read Response Middle QP=0x000067
55 1.915382   50.50.50.2   50.50.50.1   RRoCE   1082 RC RDMA Read Response Middle QP=0x000067
56 1.915383   50.50.50.2   50.50.50.1   RRoCE   1086 RC RDMA Read Response Last QP=0x000067
```

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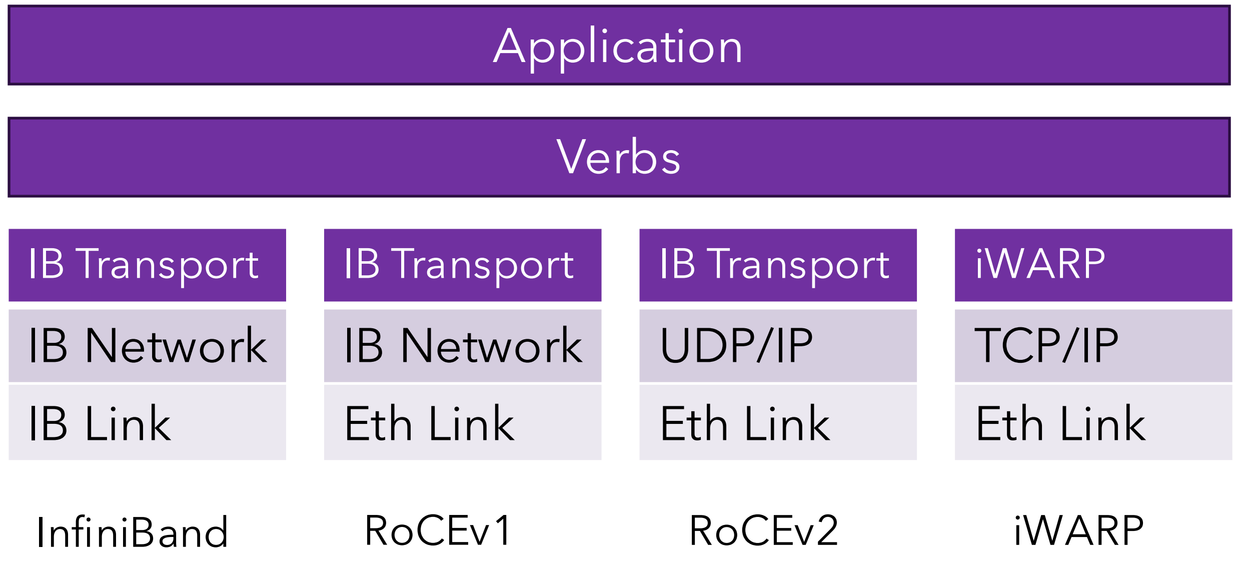
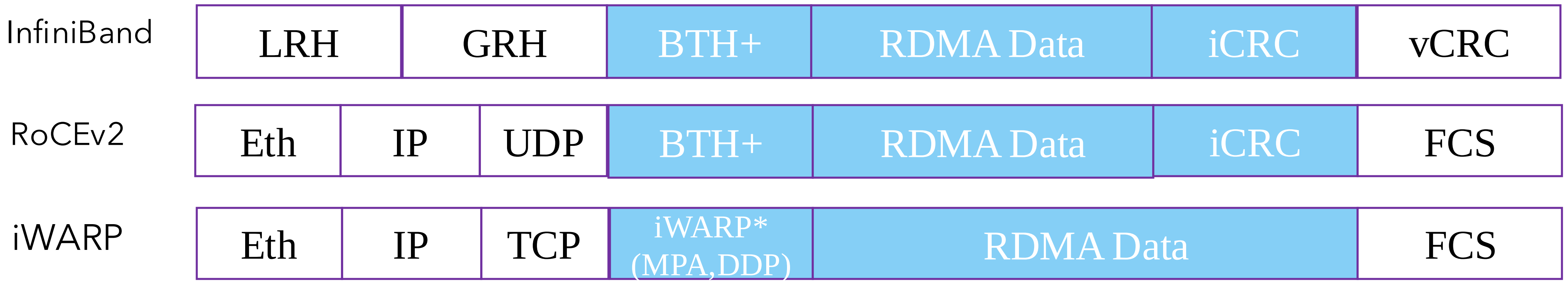
Transports and Congestion Control

RDMA Transports





RoCE – RDMA over Converged Ethernet

Upper layers are the same as in Infiniband	link and physical layers are replaced with Ethernet. EtherType indicates RoCE (0x8915).
RoCE versions	RoCEv1 doesn't contain an IP header, therefore it is not routable. RoCEv2 over UDP (a.k.a "routable RoCE")
Ethernet subnet management means are used.	Uses the ARP (Address Resolution Protocol) to get remote MAC address. Requires a network interface on the same port.
Requires lossless operation – i.e. PAUSE / PFC.	Same as InfiniBand, but disadvantage comparing to iWARP.

Congestion Control

PFC (Priority Flow Control) pause frames are used to signal congestion to the source and throttle.

DCQCN (Data Center Quantized Congestion Notification) employs ECN (Explicit Congestion Notification) for signaling congestion feedback. Preferred for Storage workloads.

RoCC (Robust Congestion Control) utilizes switch queue size for fair data rate signaling.

Shaped-Quota is receiver-driven, optimizing bandwidth allocation. It abandons use of PFC.

RTTCC (Round Trip Time Congestion Control) uses RTT as a feedback signal in hardware for congestion control. Preferred for HPC and AI workloads.