

Appendices

A Recovery Protocol and Algorithms

We explain how Nezha leverages the diskless crash recovery algorithm [1] from Viewstamped Replication in 3 steps. First, we explain how we adopt the recent concept of crash-vectors [2, 3] to fix the incorrectness in the crash recovery algorithm. Second, we explain how a replica rejoins Nezha following a crash. Third, we describe how the leader election works if the leader crashes.

A.1 Crash Vector

Like Viewstamped Replication, Speculative Paxos and NOPaxos, Nezha also adopts diskless recovery to improve performance. However, in contrast to them, Nezha avoids the effect of *stray messages* [4] (i.e., messages that are sent out but not delivered before replica crash, so that the relaunched replicas forget them) using the *crash-vector* [2, 3]. *crash-vector* is a vector containing $2f + 1$ integer counters corresponding to the $2f + 1$ replicas. Each replica maintains such a vector, with all counters initialized as 0s.

crash-vectors can be aggregated by taking the max operation element-wise to produce a new *crash-vector*. During the replica rejoin (§A.2) and leader change (§A.3) process, replicas send their *crash-vectors* to each other. Receivers can make their *crash-vectors* more up-to-date by aggregating their *crash-vector* with the *crash-vector* from the sender. Meanwhile, by comparing its local *crash-vector* and the sender’s *crash-vector*, the receiver can recognize whether or not the sender’s message is a potential *stray message* (refer to [3] for detailed description of *crash-vector*).

Nezha uses *crash-vectors* to avoid two types of *stray messages*, i.e. the *stray messages* during recovery and the *stray messages* (*fast-replies*) during quorum check.

(1) There can be *stray messages* during the recovery process. The stray messages cause replicas to elect a leader, whose state falls behind the others, and finally causes permanent loss of committed requests. Such error cases have been analyzed in [3] and we also illustrate it in §J.1 by taking NOPaxos as the example. The *crash-vector* prevents the *stray messages* effect because it enables the replicas to recognize potential *stray messages* by comparing a *crash-vector* received from a replica with the local *crash-vector*. During recovery, the RECOVERING replica first recovers its *crash-vector* by collecting and aggregating the *crash-vectors* from a majority of NORMAL replicas. Then, the replica increments its own counter (i.e. replica i increments the i th counter in the vector) and tags the new *crash-vector* to the messages sent afterwards. Once the update of *crash-vector* is exposed to the other replicas, they can recognize the *stray messages* sent by the replica before crash (i.e., those messages have a smaller value at the i th counter), and avoid processing those messages.

Thus, the recovery will not be affected by *stray messages*.

(2) Stray messages can also occur during the quorum check in the fast path: some replicas send *fast-replies* and crash after that. These *fast-replies* may become *stray messages* and participate into the quorum check, which makes the proxies/clients prematurely believe the request has been persisted to a super-majority of replicas, but actually not yet (i.e. the recovered replicas may not hold the requests after their recovery). Such error cases are illustrated in §J.2. The *crash-vector* prevents the effect of such *stray fast-replies*, because we include the information of *crash-vectors* in the *fast-replies* (§R.2). When a failed replica rejoins the system (Algorithm 1), it leads to the update of *crash-vectors* for the leader and other remaining followers, so these replicas will send *fast-replies* with different *hashes* from the *stray fast-replies* sent by the rejoined replica. Therefore, the stray *fast-replies* from the rejoined replica and the normal *fast-replies* from the other replicas cannot form the super-quorum together (refer to §J.2 for more details).

A.2 Replica Rejoin

Crashed replicas can rejoin the system as followers. After the replica crashes and is relaunched, it sets its *status* as RECOVERING. Before it can resume request processing, the replica needs to recover its replica state, including *crash-vector*, *view-id*, *log* and *sync-point*. With reference to Algorithm 1, we explain how the replica rejoin process works.

Step 1: The replica sets its *status* as RECOVERING (line 2), and broadcasts the same CRASH-VECTOR-REQ to all replicas to request their *crash-vectors*. A *nonce* (line 4) is included in the message, which is a random string locally unique on this replica, i.e., this replica has never used this *nonce*¹.

Step 2: After receiving the CRASH-VECTOR-REQ, replicas with NORMAL status reply to the recovering replica with <CRASH-VECTOR-REP, *nonce*, *crash-vector*> (line 40-47).

Step 3: The recovering replica waits until it receives the corresponding replies (containing the same *nonce*) from a majority ($f + 1$) of replicas (line 23). Then it aggregates the $f + 1$ *crash-vectors* by taking the maximum in each dimension (line 7, line 100-105). After obtaining the aggregated crash vector cv , the replica increment its own dimension, i.e. $cv[replica-id] = cv[replica-id] + 1$ (line 8).

Step 4: The recovering replica broadcasts a recovery request to all replicas, which includes its *crash-vector*, i.e. <RECOVERY-REQ, cv > (line 11, line 26-30).

Step 5: After receiving the RECOVERY-REQ, replicas with NORMAL status update their own *crash-vectors* by aggregating with cv , obtained from the request in step 4. Then, these replicas send back a reply including their own *view-id* and

¹There are many options available to generate the locally unique *nonce* string [1, 3]. Nezha uses the universally unique identifier (UUID) (GENERATE-UUID in line 4), which have been widely supported by modern software systems.

Algorithm 1 Replica rejoin

Local State:
nonce, \triangleright A locally unique string on this replica
C, \triangleright Reply set of CRASH-VECTOR-REP
R, \triangleright Reply set of RECOVERY-REP
r, \triangleright short for *replica-id* (the message sender)
cv, \triangleright short for *crash-vector*
status, *view-id*, *last-normal-view*, *log*, *sync-point*

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1: upon RECOVER do
2:   status = RECOVERING
3:   C =  $\emptyset$ 
4:   nonce = GENERATE-UUID
5:   READ-CRASH-VECTOR
6:   cv-set =  $\{m.cv \mid m \in C\}$ 
7:   cv = AGGREGATE(cv-set  $\cup$   $\{cv\}$ )
8:   cv[r] = cv[r] + 1  $\triangleright$  Increment its own counter
9:   do
10:    R =  $\emptyset$ 
11:    READ-RECOVERY-INFO
12:    highest-view =  $\max\{m.v \mid m \in R\}$ 
13:    leader-id = highest-view % ( $2f + 1$ )
14:    while (leader-id = r)
15:      Pick  $m \in R$ :  $m.v = \text{highest-view}$ 
16:      STATE-TRANSFER(leader-id)
17: function READ-CRASH-VECTOR
18:   m.type = CRASH-VECTOR-REQ
19:   m.r = r
20:   m.nonce = nonce
21:    $\triangleright$  Broadcast CRASH-VECTOR-REQ to all replicas
22:   for  $i \leftarrow 0$  to  $2f$  do
23:     SEND-MESSAGE(m, i)  $\triangleright$  Send message m to the replica i
24:   Wait until  $|C| \geq f + 1$   $\triangleright$  C is initialized as  $\emptyset$  by the caller
25:   return
26: function READ-RECOVERY-INFO
27:   m.type = RECOVERY-REQ
28:   m.r = r
29:   m.cv = cv
30:    $\triangleright$  Broadcast RECOVERY-REQ to all replicas
31:   for  $i \leftarrow 0$  to  $2f$  do
32:     SEND-MESSAGE(m, i)
33:   Wait until  $|R| \geq f + 1$   $\triangleright$  R is initialized as  $\emptyset$  by the caller
34:   return
35: function STATE-TRANSFER(i)
36:   m.type = STATE-TRANSFER-REQ
37:   m.r = r
38:   m.cv = cv
39:   SEND-MESSAGE(m, i)
40:   Wait until status = NORMAL
41:   return
42: upon receiving CRASH-VECTOR-REQ, m do
43:   if status  $\neq$  NORMAL then
44:     return
45:   m'.type = CRASH-VECTOR-REP
46:   m'.r = r
47:   m'.nonce = m.nonce
48:   m'.cv = cv
49:   SEND-MESSAGE(m', m.r)
50:   return
51:   if nonce  $\neq$  m.nonce then
52:     return
53:   C = C  $\cup$   $\{m\}$ 
54: upon receiving RECOVERY-REQ, m do
55:   if status  $\neq$  NORMAL then
56:     return
57:   cv = AGGREGATE(cv, m.cv)
58:   m'.type = RECOVERY-REP
59:   m'.r = r
60:   m'.v = view-id
61:   m'.cv = cv
62:   m'.log = log
63:   SEND-MESSAGE(m', m.r)
64: upon receiving RECOVERY-REP, m do
65:   if status  $\neq$  RECOVERING then
66:     return
67:   if CHECK-CRASH-VECTOR(m, cv) = false then
68:     Resend RECOVERY-REQ to m.r
69:   else  $\triangleright$  Remove stray messages and add the fresh one
70:     R' =  $\{m' \in R \mid m'.cv[m'.r] < cv[m'.r]\}$ 
71:     R = R  $\cup$   $\{m\}$  - R'
72:      $\forall m' \in R'$ , resend RECOVERY-REQ to m'.r
73: upon receiving STATE-TRANSFER-REQ, m do
74:   if status  $\neq$  NORMAL then
75:     return
76:   if CHECK-CRASH-VECTOR(m, cv) = false then
77:     return
78:   m'.type = STATE-TRANSFER-REP
79:   m'.log = log
80:   m'.v = view-id
81:   m'.sp = sync-point
82:   m'.cv = cv
83:   SEND-MESSAGE(m', m.r)
84: upon receiving STATE-TRANSFER-REP, m do
85:   if status  $\neq$  RECOVERING then
86:     return
87:   if CHECK-CRASH-VECTOR(m, cv) = false then
88:     return
89:   log = m.log
90:   last-normal-view = view-id = m.v
91:   log = m.log
92:   sync-point = m.sp
93:   status = NORMAL  $\triangleright$  Rejoin as a NORMAL follower
94:   function CHECK-CRASH-VECTOR(m, cv)
95:     if m.cv[m.r] < cv[m.r] then  $\triangleright$  A potential stray message
96:       return false
97:     else
98:       cv = AGGREGATE( $\{cv, m.cv\}$ )  $\triangleright$  Update local cv
99:       return true
100:   function AGGREGATE(cv-set)
101:     ret =  $\underbrace{[0 \dots 0]}_{2f+1}$ 
102:     for  $c \in cv\text{-set}$  do
103:       for  $i \leftarrow 0$  to  $2f$  do
104:         ret[i] = max(ret[i], c[i])
105:     return ret

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crash-vector, i.e. $\langle \text{RECOVERY-REP}, \text{view-id}, \text{crash-vector} \rangle$ (line 54-63).

Step 6: The recovering replica waits until it receives the recovery replies from $f + 1$ replicas (line 31). If the RECOVERY-REP is not a *stray message*, it updates its own *crash-vector* by aggregating it with the *crash-vectors* included in these replies (line 67); otherwise, it resends RECOVERY-REQ to that replica, asking for a fresh message (line 68). Because the *crash-vectors* may have been updated (line 67), those RECOVERY-REP which have been received can also become *stray messages* because their *crash-vectors* are no longer fresh enough. Therefore, we also remove them (R' in line 70) from the reply set R (line 71), and resend requests to the related replicas for fresher replies (line 72).

Step 7: The RECOVERING replica picks the highest *view-id* among the $f + 1$ replies (line 12). From the highest *view-id*, it knows the corresponding leader of this view (line 13). If the RECOVERING replica happens to be the leader of this view, it keeps broadcasting the recovery request (line 9-14), until the majority elects a new leader among themselves. Otherwise, the RECOVERING replica fetches the *log*, *sync-point*, *view-id* from the leader via a state transfer (line 16, line 33-39). After that, the replica set its *status* to NORMAL and can continue to process the incoming requests.

Specially, the RECOVERING replica(s) do not participate in the view change process (§A.3). When the majority of replicas are conducting a view change (possibly due to leader failure), the RECOVERING replica(s) just wait until the majority completes the view change and elects the new leader.

A.3 Leader Change

When the follower(s) suspect that the leader has failed, they stop processing new client requests. Instead, they perform the view change protocol to elect a new leader and resume request processing. With reference to Algorithm 2, we explain the details of the view change process.

Step 1: When a replica fails to receive the heartbeat (i.e., *sync* message) from the leader for a threshold of time, it suspects the leader has failed. Then, it sets its *status* as VIEWCHANGE, increments its *view-id*, and broadcasts a view change request to all replicas including its *crash-vector*, i.e. $\langle \text{VIEW-CHANGE-REQ}, \text{view-id}, \text{replica-id}, \text{cv} \rangle$ (line 6-10)². The replica switches its *status* from NORMAL to VIEWCHANGE, and enters the view change process.

Step 2: After receiving a VIEW-CHANGE-REQ message, the recipient checks the *cv* and *replica-id* with its own *crash-vector* (line 32). If this message is a potential *stray message*, then the recipient ignores it. Otherwise, the recipient updates its *crash-vector* by aggregation. After that, the recipient also

participates in the view change (line 35) if its *view-id* is lower than that included in the VIEW-CHANGE-REQ message.

Step 3: All replicas under view change send a message $\langle \text{VIEW-CHANGE}, \text{view-id}, \text{log}, \text{sync-point}, \text{last-normal-view} \rangle$ to the leader of the new view ($\text{replica-id} = \text{view-id} \% (2f + 1)$) (line 11). Here *last-normal-view* indicates the last view in which the replica's *status* was NORMAL.

Step 4: After the new leader receives the VIEW-CHANGE messages from f followers with matching *view-ids*, it can recover the system state by merging the *logs* from the $f + 1$ replicas including itself (line 67). The new leader only merges the *logs* with the highest *last-normal-view*, because a smaller *last-normal-view* indicates the replica has lagged behind for several view changes, thus its *sync-point* cannot be larger than the other replicas with higher *last-normal-view* values. Therefore, it makes no contribution to the recovery and does not need to join.

Step 5: The new leader initializes an empty log list (denoted as *new-log*) (line 74). Among the VIEW-CHANGE messages with the highest *last-normal-view*, it picks the one with the largest *sync-point* (line 75-77). Then it directly copies the log entries from that message up to the *sync-point* (line 78-82).

Step 6: Afterwards, the new leader checks the remaining entries with larger *deadlines* than *sync-point* (line 83-88). If the same entry (2 entries are the same iff they have the same $\langle \text{deadline}, \text{client-id}, \text{request-id} \rangle$) exists in at least $\lceil f/2 \rceil + 1$ out of the $f + 1$ *logs*, then leader appends the entry to *new-log*.

Step 7: After *new-log* is built, the new leader broadcasts $\langle \text{START-VIEW}, \text{cv}, \text{view-id}, \text{new-log} \rangle$ to all replicas (line 68-70).

Step 8: After receiving the START-VIEW message with a *view-id* greater than or equal to its *view-id*, the replica updates its *view-id* and *last-normal-view* (line 97), and replaces its *log* with *new-log* (line 98). Besides, it updates *sync-point* as the last entry in the new *log* (line 98), because all the entries are consistent with the leader. Finally, replicas set their *statuses* to NORMAL (line 100), and the system state is fully recovered.

Step 9: After the system is fully recovered, the replicas can continue to process the incoming requests. Recall in §R.3 that the incoming request is allowed to enter the *early-buffer* if its deadline is larger than *the last released request* which is not commutative. To ensure uniform ordering, the eligibility check is still required for the incoming request even if it is the first one arriving at the replica after recovery. The replica considers the entries (requests) in the recovered *log*, which are not commutative to the incoming request, and chooses the one as *the last released request* with the largest deadline among them. The incoming request can enter the *early-buffer* if its deadline than *the last released request*, otherwise, it is put into the *late-buffer*.

Note that the view change protocol chooses the leader in a round-robin way ($\text{view-id} \% (2f + 1)$). Specially, a view change process may not succeed because the new leader also

²The view change request will be rebroadcast if the replica times out but is still waiting for the view change process to complete. The same is also true for the view change message described in the next step.

Algorithm 2 Leader change

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Local State:
V,                                ▷ Reply set of VIEW-CHANGE
r,                                ▷ short for replica-id (the message sender)
cv,                                ▷ short for crash-vector
last-normal-view,                 ▷ The most recent view
                                ▷ in which the replica's status is NORMAL
status, view-id, log, sync-point

1: upon SUSPECT LEADER FAILURE do
2:   do
3:     INITIATE-VIEW-CHANGE(view-id + 1)
4:   while (status  $\neq$  NORMAL)
5: function INITIATE-VIEW-CHANGE(v)
6:   status = VIEWCHANGE
7:   view-id = v
8:   V =  $\emptyset$ 
9:   ▷ Broadcast VIEW-CHANGE-REQ to all replicas
10:  for i  $\leftarrow$  0 to 2f do
11:    SEND-VIEW-CHANGE-REQ(i)
12:    ▷ Send VIEW-CHANGE to the new leader
13:  SEND-VIEW-CHANGE(v%(2f + 1))
14:  Wait until status = NORMAL or TIMEOUT
15:  return
16: function SEND-VIEW-CHANGE-REQ(i)
17:   m.type = VIEW-CHANGE-REQ
18:   m.v = view-id
19:   m.cv = cv
20:   SEND-MESSAGE(m, i)
21:   return
22: function SEND-VIEW-CHANGE(i)
23:   m.type = VIEW-CHANGE
24:   m.v = view-id
25:   m.cv = cv
26:   m.log = log
27:   m.sp = sync-point
28:   m.lnv = last-normal-view
29:   SEND-MESSAGE(m, i)
30:   return
31: upon receiving VIEW-CHANGE-REQ, m do
32:   if status = RECOVERING then
33:     return
34:   if CHECK-CRASH-VECTOR(m, cv)=false then
35:     return
36:   if m.v > view-id then
37:     INITIATE-VIEW-CHANGE(m.v)
38:   else
39:     if status = NORMAL then
40:       SEND-START-VIEW(m.r)
41:     else ▷ The leader is asking for fresher VIEW-CHANGE
42:       SEND-VIEW-CHANGE(m.r)
43: function SEND-START-VIEW(i)
44:   m.type = START-VIEW
45:   m.v = view-id
46:   m.cv = cv
47:   m.log = log
48:   SEND-MESSAGE(m, i)
49:   return
50: upon receiving VIEW-CHANGE, m do
51:   if status = RECOVERING then
52:     return
53:   if CHECK-CRASH-VECTOR(m, cv)=false then
54:     return
55:   if m.v > view-id then
56:     INITIATE-VIEW-CHANGE(m.v)
57:   else ▷ The sender lags behind
58:     SEND-START-VIEW(m.r)
59:   else if status = VIEWCHANGE then
60:     if m.v > view-id then
61:       INITIATE-VIEW-CHANGE(m.v)
62:     else if m.v < view-id then ▷ The sender lags behind
63:       SEND-VIEW-CHANGE-REQ(m.r)
64:     else ▷ Remove stray messages and add the fresh one
65:       V' = {m'  $\in$  V | m'.cv[m'.r] < cv[m'.r]}
66:       V = V  $\cup$  {m} - V'
67:        $\forall m' \in V'$ , resend VIEW-CHANGE-REQ to m'.r
68:       if |V|  $\geq$  f + 1 then
69:         log = MERGE-LOG(V)
70:         for i  $\leftarrow$  0 to 2f do
71:           SEND-START-VIEW(i)
72:         last-normal-view = view-id
73:         status = NORMAL ▷ Leader becomes NORMAL
74: function MERGE-LOG(V)
75:   new-log =  $\emptyset$ 
76:   largest-normal-view = max{m.lnv | m  $\in$  V}
77:   largest-sync-point = max{m.sp | m  $\in$  V}
78:   and m.lnv = largest-normal-view
79:   Pick m  $\in$  V:
80:     m.lnv = largest-normal-view and
81:     m.sp = largest-sync-point
82:   ▷ Directly copy entries up to sync-point
83:   for e  $\in$  m.log do ▷ m.log is already sorted by deadlines
84:     if e.deadline  $\leq$  largest-sync-point.deadline then
85:       new-log.append(e)
86:     else
87:       break
88:   ▷ Add other committed entries beyond sync-point
89:   entries = {e | e  $\in$  m.log
90:             and e.deadline > largest-sync-point.deadline
91:             and m.lnv = largest-normal-view}
92:   for e  $\in$  entries do
93:     ▷ Check how many replicas contain e
94:     S = {m | m  $\in$  V and e  $\in$  m.log}
95:     if |S|  $\geq$   $\lceil f/2 \rceil + 1$  then
96:       log.append(e)
97:   Sort new-log by entries' deadlines
98:   return new-log
99: upon receiving START-VIEW, m do
100:  if status = RECOVERING then
101:    return
102:  if CHECK-CRASH-VECTOR(m, cv)=false then
103:    return
104:  if m.v < view-id then
105:    return
106:  last-normal-view = view-id = m.v
107:  log = m.log
108:  sync-point = log.last()
109:  status = NORMAL ▷ Followers become NORMAL

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fails (as mentioned in [1]). In this case (i.e. after followers have spent a threshold of time without completing the view change), followers will continue to increment their *view-ids* to initiate a further view change, with yet another leader.

After the replica rejoin or leader change process, replicas' *crash-vectors* will be updated. Due to packet drop, some replicas may fail to receive the update of *crash-vectors* during the recovery, thus they cannot contribute to the quorum check of the fast path in the following request processing, because their *crash-vectors* are still old and cannot generate the consistent hash with the leader's hash. To enable every replica to obtain the fresh information of *crash-vectors* rapidly, the leader can piggyback the fresh *crash-vectors* in the *sync* messages, so that replicas can check and update their *crash-vectors* as soon as possible.

A.4 Evaluation of Recovery

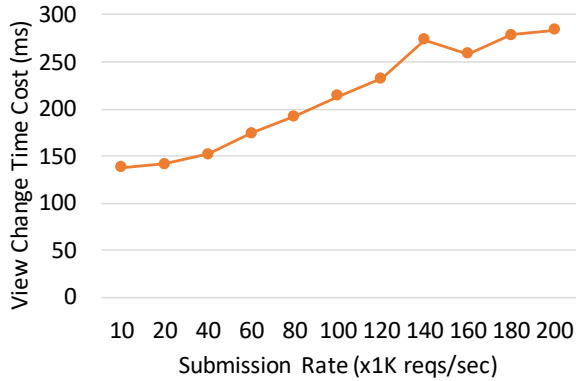


Figure 1: Time cost of view change

We evaluate the failure recovery as shown in Figure 1 and Figure 2. Since follower's crash and recovery do not affect the availability of Nezha, we mainly focus on the evaluation of the leader's crash and recovery. We study two aspects: (1) How long does it take for the remaining replicas to complete a view change with the new leader elected? (2) How long does it take to recover the throughput to the same level before crash?

We maintain 3 replicas and 10 open-loop clients, and vary the client submission rate from 1K reqs/sec to 20K reqs/sec, so the total submission rate varies from 10K reqs/sec to 200K reqs/sec. Under different submission rates, we kill the leader and measure the time cost of view change, as shown in Figure 1. To mitigate the noise effect, we also run each case for 5 times and average them as the reported value. We can see from Figure 1, the time cost of view change grows as the submission rate increases, because there is an increasing amount of state (log) transfer to complete the view change. In general, the view change takes about 150 ms-300 ms.

The time cost to recover the same throughput level is larger

than the time cost of view change, because there are other necessary works to do after the replicas enter the new view. For example, replicas need to relaunch the working threads and reinitialize the contexts; replicas need to notify proxies and further the clients to continue submitting requests; replicas need to handle clients' retried requests, which fail to be responded before crash; followers may need additional state transfer due to lagging too far behind, etc.

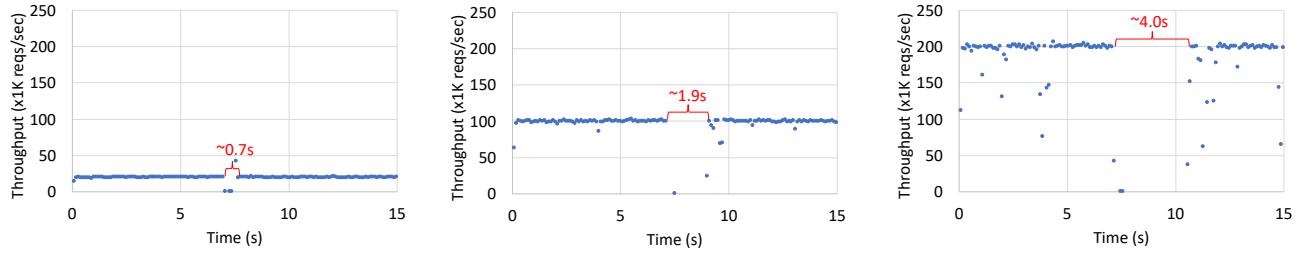
In Figure 2, we plot three recovery cases with different throughput levels. Based on the measured trace, we calculate the throughput every 10 ms, and plot the data points in Figure 2. Figure 2 implies that the recovery time is related to the throughput level to recover. A lower throughput level takes a shorter time to recover, and vice versa. Figure 2 shows three different throughput levels: it takes approximately 0.7 s, 1.9 s, 4.0 s, to recover to the same throughput level under the load of 20K reqs/sec, 100K reqs/sec, 200K reqs/sec, respectively. As a reference to compare, Figure 3.20 in [5] evaluates the recovery time for an industrial Raft implementation [6], which takes about 6 seconds to recover to 18K reqs/sec.

A.5 Reconfiguration

Just like Speculative Paxos and NOPaxos, Nezha can also use the standard reconfiguration protocol from Viewstamped Replication [1] (with its incorrectness fixed by *crash-vector* [2,3]) to change the membership of the replica group, such as replacing the failed replicas with the new ones that have a new disk, increasing/decreasing the number of replicas in the system, etc. However, Nezha is free from reconfiguring the network, whereas Speculative Paxos and NOPaxos require to modify their network (e.g., updating the forwarding rules of the Openflow controller, initializing a new session number at the sequencer, etc.) for every reconfiguration, which adds non-trivial complexity in a real deployment.

References

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(a) Total submission rate of 20K reqs/sec (b) Total submission rate of 100K reqs/sec (c) Total submission rate of 200K reqs/sec

Figure 2: Recover to the same throughput level under different load

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