CRAFT: An Erasure-coding-supported Version of Raft for Reducing Storage Cost and Network Cost

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Data replication: when server crashes...

- User data written to $N$ servers
- When any $F$ servers crashed, we still have other copies
Consensus between servers...

• Network may partition...
• Need consensus protocol!

• Observation: $N=2F$ servers not enough to tolerate $F$ crashes, can’t distinguish from partition
Raft: distributed consensus

• Use $N = 2F + 1$ servers to tolerate $F$ crashes
• A “leader” is elected by at least $F+1$ “followers”
  • Data is considered “committed” when stored $F+1$ copies
  
  \[ N=7, \ F=3 \]

• Leader crash: new election, reconciliation
  • New leader’s $F+1$ followers has at least 1 in common
Problem: data copied N times...

- Replication is costly
  - $N$ times network traffic!
  - $N$ times storage space!

- Can we do better?
Erasure Coding: Reed-Solomon Code

• \((k, m)\)-Reed Solomon code:
  • Data split into \((k+m)\) fragments, each \(1/k\) size
  • Any \(k\) fragments can recover original data

Data \{1GB\}

R-S Code \(k=3, m=2\)

Fragment #1

Fragment #2

Fragment #3

Fragment #4

Fragment #5

Each 1/3 GB

Data \{1GB\}
Combine erasure coding with crash tolerance?

• We already used $N=2F+1=5$ servers for fault tolerance.
• Correctness requires $F+1=3$ healthy servers.
• Why not just recover data from 3 out of 5 coded fragments?
Prior work: RS-Paxos

- Use \((k, m)\) Reed-Solomon code
  - Write is committed after written to \(Q_W\) servers
  - Read requires reading from \(Q_R\) servers for consensus
  - \(Q_W + Q_R - N \geq k\) (at least \(k\) in common, allows decoding)

\[
N = 7, \quad k = 3
\]
\[
Q_W = 4, \quad Q_R = 6
\]

- **Liveness** issue: when \(N = 2F + 1\), can’t tolerate \(F\) crashes!

*When Paxos meets erasure code: Reduce network and storage cost in state machine replication. Shuai Mu et. al., HPDC’14*
Pando: optimizing RS-Paxos

- Presented on Tuesday’s NSDI’20 session
- Shrink the quorum overlap from $k$ to 1 to reduce latency:
  - Faster in “normal” case, read from more if observed inconsistency
  - **Liveness** issue persists

$N=7, \ k=3$
$Q_W=4, \ Q_R=4$

*Near-Optimal Latency Versus Cost Tradeoffs in Geo-Distributed Storage. Muhammed Uluyol et. al., NSDI’20*
**CRaft: erasure coding + Raft**

- Use $N=2F+1$ servers to tolerate $F$ crashes.
- A “leader” is elected by at least $F+1$ “followers”.
- Leader replicates by sending coded fragments.
  - Use $(k,m)$ Reed-Solomon code, $k+m=N$ and $k \leq F+1$.
  - Data is committed when $(F+k)$ fragments are stored, i.e., next elected leader can see at least $k$ fragments.

For an example:

- $N=7$, $F=3$, $k=3$.
Challenge #1: liveness

• What if there’re fewer than \( F+k \) healthy servers?
  • Note: \( N=2F+1 \), need to tolerate \( F \) crashes
  • Worst case: only \( F+1 \) healthy servers!

• Solution: full replication when necessary
  • When \(<(F+k)\) healthy, send full copies (not fragments)
  • “Predict” if there’re \( \geq(F+k) \) healthy using heartbeats
Challenge #1: liveness

• In normal case, replicate coded fragments
• When \( <(F+k)\) servers are healthy, send full copies

\[ \text{Crash: } N=5, F=2, k=3 \]
\[ F+k=5 \]
Challenge #2: newly-elected leader

• The new leader has coded fragments, not full copies

• For committed entry’s fragments:
  • Any $F+1$ servers holds at least $k$ fragments for the entry, so the new leader can always recover full data by querying its followers

• For entries not yet committed:
  • In the worst case, cannot guarantee recovery...

• Solution: a post-election “LeaderPre” phase. Try recovery (collect fragments), or discard the entry!
Challenge #2: newly-elected leader

- Leader re-election follows normal Raft procedure (requires $F+1$ followers)
- In the LeaderPre phase, new leader tries recovery using data fragments
  - If recovery failed, delete later entries

$N=5$, $F=2$, $k=3$

$F+k=5$
CRaft: erasure coding + Raft

• **Efficient**: replicate coded fragments when possible, save network and storage ($\frac{1}{k}$ fraction)

• **Liveness**:
  • When there’re $<(F+k)$ healthy servers, send full copies
  • Newly-elected leader reads uncommitted fragments in the `LeaderPre` phase, trying to recover data from fragments

• **Correctness**: if recovery failed in `LeaderPre`, delete this entry and all following entries does not affect correctness
Comparing consensus protocols

<table>
<thead>
<tr>
<th></th>
<th>CRaft</th>
<th>Raft</th>
<th>RS-Paxos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disk Space &amp; I/O</td>
<td>$2F/k+1$</td>
<td>$2F+1$</td>
<td>$2F/k+1$</td>
</tr>
<tr>
<td>Network Throughput</td>
<td>$2F/k$</td>
<td>$2F$</td>
<td>$2F/k$</td>
</tr>
<tr>
<td>Liveness (max #crash)</td>
<td>$F$</td>
<td>$F$</td>
<td>$F-(k-1)/2$</td>
</tr>
</tbody>
</table>

Cannot tolerate $F$ crashes ($N=2F+1$)
Evaluation highlights

• Can CRAFT achieve higher throughput than vanilla Raft?
  • Yes! Thanks to the network/storage saving

• Can CRAFT achieve liveness upon F crashes?
  • Yes, CRAFT degrades into Raft in this case

• What about latency?
  • Write latency: improved (less network send per write)
  • Read latency: new leader’s recovery reads are slower
Evaluation setup

• We implement a Key-Value store application on top of Raft
• Tolerate $F=2$ or 3 crashes, using $N=5$ or 7 servers ($N=2F+1$)
• Using Reed-Solomon Code $k=3$, $m=2$ or 4 (satisfying $k+m=N$)

• Clients run on a separate machine, send read/write requests
• To compare against RS-Paxos, we implement “RS-Raft”, using very similar consensus procedure (read/write quorum $Q_R/Q_W$)
Evaluation: throughput

- CRaft and RS-Raft enjoy network/storage saving

N=5 servers

N=7 servers
Evaluation: liveness

- \( k = 3, F = 3, N = 2F + 1 = 7 \)
- RS-Raft: \( \max(Q_R, Q_W) \geq 5 \)
- CRaft:
  - Replicate coded fragment when healthy \( \geq F + k = 6 \)
  - Send full data when <6
Evaluation: read latency

• After leader crash and re-election, first read is slower (data recovery by collecting fragments)

• Subsequent reads have the same latency
Summary: CRaft

• Uses *erasure coding* to lower Raft’s overhead in network & storage
• Ensures correctness and *liveness* upon $F$ crashes (with $N=2F+1$)
• Boosts throughput significantly over original Raft