ESCAPE to Precaution against Leader Failures

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Abstract—Leader-based consensus protocols must undergo a view-change phase to elect a new leader when the current leader fails. The new leader is often decided upon a candidate server that collects votes from a quorum of servers. However, votingbased election mechanisms intrinsically cause competition in leadership candidacy when each candidate collects only partial votes. This split-vote scenario can result in no leadership winner and prolong the undesired view-change period. In this paper, we investigate a case study of Raft's leader election mechanism and propose a new leader election protocol, called ESCAPE, that fundamentally solves split votes by prioritizing servers based on their log responsiveness. ESCAPE dynamically assigns servers with a configuration that offers different priorities through Raft's periodic heartbeat. In each assignment, ESCAPE keeps track of server log responsiveness and assigns configurations that are inclined to win an election to more up-to-date servers, thereby preparing a pool of prioritized candidates. Consequently, when the next election takes place, the candidate with the highest priority will defeat its counterparts and becomes the next leader without competition. The evaluation results show that ESCAPE progressively reduces the leader election time when the cluster scales up, and the improvement becomes more significant under message loss.

Index Terms—consensus algorithms, fault tolerance, leader election

I. INTRODUCTION

Leader-based consensus algorithms have been widely deployed in practical systems, such as HDFS [1], RAMCloud [2], Chubby [3], and ZooKeeper [4], and extensively studied in academia, such as Paxos [5], Viewstamped replication [6], and Raft [7]. Under normal operation, they utilize a designated server as a leader to efficiently conduct consensus that satisfies state machine replication properties. However, leader-based algorithms are vulnerable to single points of failures. When the leader fails, the consensus process cannot proceed, and the system must select a new leader server through a viewchange/leader election phase.

The view-change phase is undesired for providing high available services because no consensus can be reached without the coordination by the leader. Unfortunately, besides server crashes [8], [9], leader failures often take place because of various reasons, such as hardware failures [10], storage failures [11], and, most commonly, network failures [12]. These issues may result in frequent leadership changes in systems that use timeouts to detect leader failures [4], [7], [13]. Before a new leader is elected, the system becomes temporarily unavailable and endures an out-of-service (OTS) period. For large-scale online applications, even seconds of OTS time is detrimental to user experiences and the quality of service [14], [15]. Therefore, the completion time of leader election significantly affects the performance of consensus services.

Voting-based mechanisms have been often chosen to implement leader election by selecting a server that can collect votes from a quorum (e.g., simple majority). A typical example is Raft's leader election mechanism [7]. Under normal operation, Raft uses a strong leadership for log replication where its leader dominates the consensus process. The strong leadership forces servers (operating as *followers*) to only passively respond to the leader. Due to its modularity and simplicity, Raft quickly gained popularity and has been widely deployed [16]– [20]. However, Raft's leader election intrinsically creates competition among leadership candidates, which may result in split votes that needlessly prolong the leader election time.

In Raft, each follower starts a timer when joining the system and resets the timer upon receiving a heartbeat from the leader. To maintain its leadership, the leader sends periodic heartbeats to followers. If a follower triggers a timeout, it transitions to a *candidate* state and begins a leader election campaign to solicit votes. If the candidate successfully collects votes from a majority of servers, it becomes the new leader. However, Raft does not discriminate candidates as long as they are up-todate. When multiple candidates start their election campaigns simultaneously and each of them collects only partial votes, no candidate can be elected by collecting votes from a majority because votes are split. The system has to repeat the election process until a candidate collects sufficient votes and becomes the new leader.

A simple solution to mitigate split votes is to use randomized timeouts; the randomness can reduce the probability of concurrent candidates that simultaneously initiate new leader election campaigns. Raft's evaluation shows the reduction of competing candidates when adding randomness to timeouts in a 5-server cluster. However, this method does not fundamentally solve the problem of split votes and may become ineffective and inefficient when servers are not fully synchronized, especially at a large scale. To avoid concurrent election campaigns, the amount of randomness of election timeouts needs to be significantly increased when a system has more servers; the detection time of leader failures subsequently increases. In addition, stale servers (not fully synchronized) can interrupt election campaigns of up-to-date servers. When the timers of stale servers have a small initial timeout, they may often trigger timeouts before up-to-date servers, which may defer the appearance of a correct leader.

To address the above problem, in this paper, we propose a new leader election protocol, namely ESCAPE, that takes precautions against leader failures by preparing a pool of "future leaders" before potential election campaigns take place. When the current leader fails, ESCAPE is able to elect a new leader by one election campaign, escaping from leadership competition that causes split votes.

ESCAPE consists of two key components: the stochastic configuration assignment (SCA) and probing patrol function (PPF). Specifically, SCA assigns each server with a unique configuration that contains two paired parameters: a *priority* and an *election timeout*. The priority is an integer that determines the growth of a server's term (the logical time) while the election timeout defines the initial timeout of the server's timer. Initially, configurations are generated stochastically within a range (e.g., priorities are integers from [1, n] and election timeouts from [100, 200 ms]), where no two servers adopt the same configuration.

In addition to SCA, ESCAPE dynamically and atomically rearranges configurations among servers through the probing patrol function (PPF) and prepares a pool of prioritized candidates according to their log responsiveness. In principle, PPF arranges configurations that are inclined to win an election to servers that are up-to-date. To achieve this goal, first, PPF keeps track of each server's log index through the periodic leader-to-followers heartbeat. Then, it assigns higher-priority configurations to more up-to-date servers. Next, it distributes the new configurations in the following heartbeat. Finally, each server updates its priority and election timeout according to the received new configuration. Consequently, ESCAPE prepares a pool of candidates as "future leaders" with differently prioritized configurations. If the current leader crashes, a candidate with a higher priority is able to defeat a competitor with a lower priority. A new leader will be elected without suffering from unnecessary leadership competitions.

Although there is no one-size-fits-all leader election mechanism for all consensus protocols, ESCAPE can be adapted to support other election protocols, such as ZooKeeper [4], Redis cluster election [13] and Azure leader election [21]. It also maintains Raft's understandability and the proposed improvement is simple to implement. By applying ESCAPE, the system can always keep a pool of prioritized future leaders under normal operation, preventing potential conflicts before a new leader election takes place.

In this paper, we make the following contributions:

- Raft leader election analysis. We analyzed the splitvote scenarios that prolong Raft's leader election. The analysis addresses the tradeoff by adding randomness to election timeouts to mitigate split votes through our evaluation of a Raft cluster.
- 2) The ESCAPE leader election protocol. We designed two major components for ESCAPE: stochastic configuration



Fig. 1: Server state transitions in Raft. Due to split votes, servers may stay in the candidate state for multiple elections.

assignments and the probing patrol function. Configurations are assigned with priorities and rearranged by the probing patrol function, solving candidacy competition by periodically prioritizing servers.

 Experimental comparisons of leader election time. We implemented ESCAPE and Raft and evaluated their performance of leader election under various fault scenarios at various scales. We distill the advantages of ESCAPE based on experimental results.

The remainder of the paper is organized as follows: Section II provides Raft basics; Section III states the problem of split votes and timer randomization; Section IV introduces the ESCAPE design in detail; Section V discusses correctness properties for ESCAPE; Section VI reports on the experimental evaluation of ESCAPE against Raft; and Section VII presents related work.

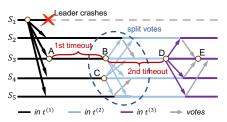
II. BACKGROUND

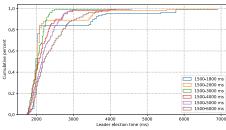
Designed for understandability, Raft relies on a leader to attain consensus under all non-Byzantine conditions. Consensus in Raft consists of two major phases: leader election and log replication. The system first elects a leader server by leader election, and then the leader conducts consensus in log replication. We now introduce some key concepts and limitations in Raft leader election.

A. Raft Basics

Raft deploys three servers states, and each server assumes one of the three states at any given time: leader, follower, and candidate. Under normal operation, there is only one leader and other servers assume a follower role. Followers only passively respond to requests, whereas the leader dominates the consensus by forcing followers to synchronize its log. Thus, the leader becomes the only bridge between internal servers and external clients. The leader receives entries from clients and issues AppendEntries RPCs to all the other servers. If the leader collects replies from a majority of servers, then the consensus for committing the entries is reached.

In Raft, the logical time is represented by *terms*. Terms are positive integers that increase monotonically. Each term begins with a leader election period and proceeds with a subsequent log replication period if a leader is elected. A server never reduces its term, which prevents the server from receding to a previous time point that could overwrite committed entries. In leader election, a new leader must have the highest term and log entries consistent with a majority of servers. This





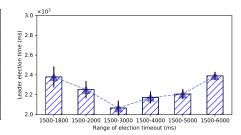


Fig. 2: Split votes with concurrent election campaigns. A new leader is elected after one of the competing candidates triggers a second timeout.

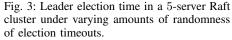


Fig. 4: Averaged leader election time with increasing amounts of randomness of election timeouts.

mechanism forces the system to always elect the most upto-date server as a leader.

If an incumbent leader crashes, the consensus service is suspended until a new leader is elected. Raft uses timeouts to detect leader failures. Initially, each server joins the system as a follower and starts a timer. A server resets its timer when receiving a heartbeat from the leader. If the leader crashes, a follower will trigger a timeout and transition to a candidate; it increments its term and initiates a leader election campaign by broadcasting RequestVotes RPCs to solicit votes. If it collects votes from a majority of servers (including itself), the candidate becomes the next leader (shown in Figure 1). However, if the candidate cannot collect enough votes within the election timeout nor receive a higher-termed message to transition back to a follower, the candidate initiates a new election campaign and repeats the above mentioned process. Other servers vote for a candidate if it satisfies the three following requirements: 1) the candidate's term is not less than the follower's term; 2) the follower has not voted yet in its term; 3) the candidate's log is at least as up-to-date as the follower's log.

B. Split Votes in Leader Election

The election regime may split votes in a given term. By following the three requirements, votes can be inopportunely split among candidates when concurrent election campaigns take place. Consequently, no candidate can collect votes from a majority of servers to be elected.

Figure 2 shows an example of split votes in a Raft cluster of 5 servers, in which terms are denoted by t. Assume server S_1 was the leader in $t^{(1)}$ (i.e., term=1) and crashed. Afterwards there was no communication between S_1 and the other servers. Consequently, timers of S_3 and S_4 expire and trigger new election campaigns at points B and C, respectively. Meanwhile, S_3 and S_4 increase their terms to $t^{(2)}$ and broadcast leader election requests. Then, S_2 receives an election request with $t^{(2)}$ from S_3 before it receives the one from S_4 . Since each follower only votes once per term, S_2 votes for S_3 and ignores the request from S_4 in $t^{(2)}$. On the contrary, S_5 votes for S_4 and denies the request from S_3 . At this time, since neither S_2 nor S_4 can collect three votes to win, the two candidates are trapped, and a split-votes scenario occurs.

The system has to wait for new elections initiated from servers whose timers expire. At point D, S_3 's timer expires again, and thus S_3 initiates a new election campaign while increasing its term to $t^{(3)}$. Fortunately, S_3 succeeds in collecting votes from a majority of servers without disruptions from the other servers. Then, S_3 is elected to be the new leader at point E and starts conducting log replication in $t^{(3)}$. After receiving heartbeats issued from the new leader, S_4 steps back to follower. From then on, the system recovers from the OTS condition and resumes to normal operation.

In addition, when different groups of servers have a lower internal (in-group) network latency but a higher external (between groups) network latency (e.g., geographically distributed servers), systems are more susceptible to split-vote scenarios. In this case, servers communicate faster within their "local" group than with the external servers. Thus, a candidate is more likely to succeed in collecting votes from its own group, and election requests from outside-group candidates will be repeatedly ignored if followers have voted for their "local" candidate. This problem also arises in distributed transient networks. Huang et al. [22] hinted that network split and message loss often cause multiple elections, which exacerbate the delay of the emergence of a new leader.

III. PROBLEM STATEMENT

Raft uses timer randomization to alleviate split votes. We implemented Raft and evaluated its leader election performance in a 5-server cluster. We measured 1000 runs for each of the six ranges of election timeouts. The network latency was set to 100-200 ms. Figure 3 presents the results in cumulative distribution of percentage, and Figure 4 shows the average election time. The results indicate that adding randomization can help the system to avoid split votes. A successful leader election campaign comprises two periods: the detection of the absence of leadership and election of a new leader. The former one is achieved by timer expiration with randomized election timeouts, and the latter one is accomplished by collecting votes from a majority of servers.

However, there exists a tradeoff between the durations of detection and election, which are associated with timer randomization. In particular, if the range of the randomization is extended, the positive effect is that it can shorten the election period but extends the detection period. A higher amount of randomness can alleviate split votes because the election timeouts of timers have a higher chance to differ from each other. This reduces the chance that multiple candidates simultaneously initiate election campaigns to solicit votes. While followers only passively respond to other servers, the negative effect is that it takes longer for servers to detect the absence of leadership, thereby increasing the leader election time. Conversely, if the amount of randomness shrinks, though it takes a shorter amount of time to detect a crashed leader, the probability of competing candidates increases. Servers are more likely to simultaneously initiate leader election campaigns, which inflict additional phases in leader election and prolong the emergence of a new leader.

For example, in Figure 3, with 300 ms of randomness from the range of 1500-1800 ms, due to split votes, approximately 18% of the election campaigns cannot converge in 3500 ms. The split-vote situation is mitigated with a larger amount of randomness. For example, with 500 ms of randomness from the range of 1500-2000 ms, less than 12% of the election campaigns experience split votes, and according to Figure 4, the average election time decreases. However, with increasing amount of randomness, the election time rises, in which the detection of the absence of leadership takes longer than the election of a new leader.

In clusters at large scales, we can set even larger amounts of randomness to avoid split votes, but this may not benefit to shorten the OTS time. If we could avoid split votes without sacrificing the duration of detection or election, the performance of leader election can be improved from both sides, thereby enhancing the reliability of services.

IV. ESCAPE LEADER ELECTION

In this section, we introduce ESCAPE, a leader election protocol that takes precautions against leader failures by preparing a pool of "potential leaders". These potential leaders are furnished with configurations that enable them to win in future election campaigns. A configuration contains a unique priority and an election timeout, and configurations are dynamically assigned to servers.

In general, ESCAPE enables fast leader election by always assigning a configuration that leads to an undefeated campaign to a server that has the most potential to become the next leader. To achieve this goal, ESCAPE assigns unique configurations to different servers via stochastic configuration assignment (SCA). In normal operation, ESCAPE dynamically rearranges and distributes these configurations through the probing patrol function (PPF).

A. Stochastic Configurations Assignment

The main idea of SCA is to enable differential growth rates of terms when multiple election campaigns take place. Let us first consider all candidates are qualified to assume future leadership; that is, they have the same up-to-date log states and are in the latest term (disqualified candidates will be considered in Section IV-B). By applying differential growth rates of terms, if followers trigger timeouts simultaneously, their election campaigns will take place in different terms and will not flock into a single term to form *flocked elections* that compete against each other as in Raft. The candidate with the highest-term campaign wins and becomes the next leader.

1) Stochastic configurations: To achieve stochastic configuration assignment, when joining the system, each server S_i assigns a unique priority, denoted by \mathcal{P}_i . The priority determines the term growth and election timeouts. A configuration is denoted by $\pi^{(\mathcal{P}_i)}$ where \mathcal{P}_i is the priority. To maintain simplicity, ESCAPE implements the priority by using server IDs. A server assigns a unique server ID, i, as its initial priority, where i is not assigned to any other server; that is, $\forall S_i, S_j \in \text{ESCAPE}, i \neq j$. A server's ID determines its priority such that $\mathcal{P}_i = i$.

2) *Election timeouts:* A server's priority initializes its election timeout as Eq. 1.

$$period_i = baseTime + k(n - \mathcal{P}_i) \tag{1}$$

In Eq. 1, baseTime is of constant value that should be set significantly larger than the network latency (e.g., if the network latency is 10ms, we can set baseTime=100ms). k is a constant value (ms) for adjusting the election timeout interval; a higher k promotes a larger gap among server election timeouts. n is the number of servers in the system. For example, in a 10-server cluster with a setting of baseTime=100 ms and k=10, server S_2 's initial priority $\mathcal{P}_2=2$, so its election timeout $period_2=180$ ms. For server S_{10} ($\mathcal{P}_{10}=10$), its initial election timeout is the base time (100 ms).

A configuration with a higher priority is paired with a shorter election timeout. Normally, with a shorter election timeout, a server often detects leader failures faster since its timer soon runs out of time. This regime provides an optimization that a higher-priority server will have a quicker response to leader failures.

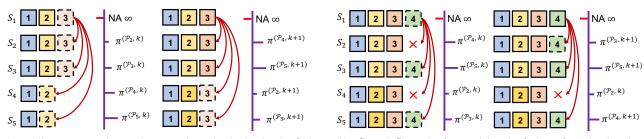
3) Term growth: A server's priority also determines its term growth. In ESCAPE, we denote a server S_i 's term as \mathcal{T}_{S_i} . If S_i initiates a new leader election campaign, S_i increases \mathcal{T}_{S_i} by Eq. 2:

$$\mathcal{T}_{S_i}^{(k+1)} \leftarrow \mathcal{T}_{S_i}^{(k)} + \mathcal{P}_i, \tag{2}$$

In addition, a server always updates its term when it receives messages with a higher term from other servers. The update is in accordance with Eq. 3.

$$\mathcal{T}_{S_i}^{(k+1)} \leftarrow max(\mathcal{T}_{S_i}^{(k)}, \mathcal{T}_{S_j, j \neq i}^{(k+1)}), \tag{3}$$

where $\mathcal{T}_{S_i}^{(k)}$ is the term of the latest update, and $\mathcal{T}_{S_j, j \neq i}^{(k+1)}$ is the received term from other servers. S_i always sets its term to the highest value regardless of the other arguments in a received message. For example, let us consider a server S_i with a priority $\mathcal{P}_i = 2$ working in term 3. If S_i 's timer expires, S_i initiates an election campaign and sets its term to 5 (Eq. 2). If S_i receives a message sent from a server S_j whose term is 4, S_i simply ignores the message. However, if S_j 's term is 6, S_i sets its term to 6, regardless of other information in the message (Eq. 3).



(a) All servers synchronously respond to the leader in the k-th configuration heartbeat, but S_4 and S_5 fall behind in log replication. Then, the higher-priority configurations previously possessed by S_4 and S_5 are rearranged to more up-to-date servers (S_2 and S_3).

(b) S_2 and S_4 crash after receiving the k-th configuration heartbeat. Then, S_2 recovers in the k+1-th heartbeat, but S_3 is still crashed. After the rearrangement, since S_4 cannot receive the newly issued configuration, S_4 will have a stale configuration after recovery.

Fig. 5: Examples for the probing patrol function in a 5-server ESCAPE system.

In contrast to Raft, the increment of logical time in ESCAPE is no longer consecutive: simultaneously initiated election campaigns are scattered into different terms. This avoids flocked elections and split votes before a leader appears. Similar approaches have been adapted by some state-of-the-art systems, such as Redis LE [13] and Zookeeper [23]. However, SCA alone does not always lead the system to the desired condition since the network may change unpredictably. Current up-to-date servers may fall behind in the next round, whereas slower servers may catch up. Therefore, a mechanism that rearranges configurations based on server log responsiveness is necessary to keep the election scheme efficient.

B. Atomic Configuration Rearrangement

A new leader is the candidate that has successfully collected votes from a majority of servers in the highest term. Yet, server configurations are not related to log responsiveness (i.e., log replication status). A tricky scenario may occur: if the candidate that has the highest term does not have an up-todate log, its election campaign cannot succeed because upto-date servers never vote for it; other servers resume their election campaigns after updating their terms to the highest one. Therefore, the configuration that empowers a high term growth is "wasted" if the candidate is not an up-to-date server, which undermines the purpose of applying SCA.

To tackle this challenge, ESCAPE reassigns configurations that are inclined to win a future election to servers that have up-to-date logs through the probing patrol function (PPF). First, PPF keeps track of servers' log index, which indicates a server's log responsiveness, via the periodical heartbeat sent from the leader (Listing 1). Then, the leader collects replies and rearranges configurations to each server. Next, it broadcasts new configurations in the following heartbeat. Finally, servers update to the newly assigned configuration if the received one is different.

PPF assists the redistribution of configurations based on log responsiveness, yet the process is not atomic because configurations are not atomically rearranged. For instance, if server S_i with configuration $\pi^{(\mathcal{P}_i)}$ crashes, the leader may assign $\pi^{(\mathcal{P}_i)}$ to another server (say S_j). When S_i recovers, S_i restores its stale priority $(\pi^{(\mathcal{P}_i)})$; at this time, if the leader crashes, S_i and S_j may trigger election campaigns simultaneously and split votes.

Listing 1: Parameters in ESCAPE compared with Raft

Listing 1. Larameters in ESCAPE compared with Ka	
type AppendEnt	rs of AppendEntries RPCs riesArgs struct{
term	int64
leaderId	string
prevLogInd	
prevLogTer	m int64
entries[]	
leaderComm	
newConfig	Configurations //newly added
}	
<pre>type Configurations struct{ timerPeriod time.Duration priority int64 confClock int64 }</pre>	
//the reply messages	
type AEReplyAr	-
	int64
success	
	configStatus //newly added
}	
tune configSta	tue et rugt (
type configStatus struct{ LogIndex int64	

LogIndex int64 timerPeriod time.Duration }

To prevent stale configurations from interfering with leader election, ESCAPE adds a hyperparameter, configuration clock (denoted by confClock in Listing 1), that shows the freshness of configurations. The configuration clock is the logical clock of configuration rearrangements. In a configuration $\pi^{(\mathcal{P}_i,k)}$, k denotes the configuration clock of this configuration, π . In normal operation, the configuration clock increments monotonically with the number of heartbeats. In leader election, *servers never vote for candidates whose configuration clock is stale*. That is, a candidate's configuration clock should not be less than a voter's configuration clock. As for deciding a new leader, ESCAPE adopts all the rules of Raft.

Figure 5 shows two examples of configuration rearrangements in a 5-server cluster. In Figure 5a, initially, server configurations are assigned in accordance with Eq. 1. Since PPF rearranges configurations according to log responsiveness,

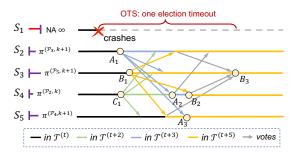


Fig. 6: Concurrent election campaigns, initiated simultaneously, always have a discrepancy in terms; ESCAPE leads to faster convergence by electing a higher termed leader.

if higher-priority servers fall behind in log replication, servers with the same log as the leader (most up-to-date logs) are assigned with higher-priority configurations.

When a server recovers (e.g., from a crash or network issues), its configuration may become stale because the server is unable to sync up with the leader. For example, in Figure 5b, S_2 and S_4 crash and do not respond to the leader after they receive the k-th configuration heartbeat. Then, S_2 recovers in the next heartbeat, but S_4 does not. S_2 's high-priority configuration is assigned to S_5 , though S_5 still has a fresh configuration. Unfortunately, S_4 's configuration becomes stale. After S_4 recovers, S_4 's confClock is k, but the system already operates in a higher configuration clock. S_4 needs to synchronize with the leader to refresh its configuration.

The probing patrol function enables a resilient configuration distribution and promotes the efficiency of leader election since it avoids that a higher-priority configuration is assigned to a losing candidate (i.e., a server without the most up-to-date log). Therefore, when the current leader crashes, the server with the highest-priority configuration has the maximum potential to detect the leader failure and initiate a new election campaign before any other servers.

C. Declining Competing Candidates

The combination of SCA and PPF enables fast leader election that avoids split votes. When candidates start new elections simultaneously, the election with the highest term always defeats other elections. After followers synchronize to the highest term, they will refuse to respond to lower-term requests; thus, votes in a given term aggregate at one server, terminating the election in a single election campaign.

Suppose the leader in Figure 5b crashes in term t, and we show an extreme case (Figure 6) to illustrate how ESCAPE elects a leader without competition when three concurrent leader election campaigns materialize. After S_2 , S_3 , and S_4 's timers expire, three election campaigns are initiated simultaneously at point A_1 , B_1 , and C_1 , respectively. In this case, no server votes for S_4 since S_4 's configuration is stale. On the contrary, S_2 and S_3 are up-to-date servers, but S_3 's election campaign has a higher term (t+5) than S_2 (in term t+3). Thus, S_4 synchronizes to term t+3 at point A_2 and to term t+5 at point B_2 , while S_5 synchronizes directly to term t+5 and then

rejects S_2 's request at point A_3 . S_3 's election campaign takes over the other campaigns, and S_3 is elected at point B_3 , when votes from a majority of servers are collected. Overall, leader election converges in one election campaign, and the system recovers after S_3 becomes the leader.

ESCAPE maintains the understandability of Raft and can also be easily deployed. If the system is fully synchronous, the configuration rearrangement can be implemented by a separate heartbeat at a low interval rate. The separation can reduce the messaging cost. The leader in ESCAPE needs to sort and assign configurations, a task with linear time complexity, imposing a slight computational cost.

The idea of ESCAPE differs from the optimization that Raft intended to apply to solve split votes. The authors of Raft argued that they tried to rank candidates in the same term to solve split-vote scenarios and implied that this measure would cause corner cases that undermine safety [7]. Figure 7 shows an intuitive comparison of the ideas behind Raft and ESCAPE where three candidates initiate election campaigns. Term surfaces represent the logical times a system currently accrues. If we draw a term surface for candidates (not considering followers), Raft leader election campaigns are more likely to lie in the same surface (left in Figure 7). Raft's authors intended to rank candidates in the same surface to intensify the competition among candidates in a given term, thereby the additional mechanisms may cause corner cases that put log safety in peril. However, due to the discrepant term growth enabled by prioritized configurations in ESCAPE, simultaneously initiated election campaigns escape from competing on the same surface but reside on their own term surfaces, and the system leaps to the highest surface with a new leader. Therefore, concurrent campaigns are in a cube (3D vs. 2D)consisting of varying term surfaces, and the candidate on the top surface defeats the other campaigns, leading the system to the highest term.

In addition to the use in Raft, ESCAPE can also be adapted to other consensus protocols. Since the correctness of leaderbased consensus protocols relies on the combination of leader election (view-change) and log replication phases, there is no one-size-fits-all leader election mechanism that stands alone to be directly applicable in every consensus protocol. However, the concept of ESCAPE can be adopted to optimize leader-based consensus protocols in terms of preparing "future leaders" in advance, before the next leader election takes place. For example, the slave election and promotion in Redis [13] ranks slave servers with SLAVE RANK, which determines the delay for a slave server to get elected in a given configEpoch. This approach has similar issues as Raft's competing candidates discussed in Section II. Slave servers may simultaneously initiate elections and reside in the same configEpoch. Applying ESCAPE can avoid potential competitions and boost the election process. The time spent on leader election is something that leader-based systems want to avoid but have to endure; similar cases such as [21] and [4] can also apply ESCAPE to enable fast leader election, paving the way to avoid potential future conflicts.

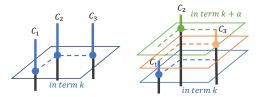


Fig. 7: Raft intended to rank competing candidates whose campaigns are in the same term (left), while ESCAPE involves priority-based configuration assignments to distribute concurrent campaigns into different terms (right).

V. CORRECTNESS ARGUMENTS

While accelerating the completion of leader election by avoiding split votes, ESCAPE maintains Raft's safety and liveness properties. ESCAPE also exhibits a stronger liveness than Raft. We discuss these points in detail in the remainder of this section.

Lemma 1. An ESCAPE leader election is able to be translated to Raft leader elections.

Proof. An ESCAPE leader election can be implemented by multiple consecutive Raft leader elections depending on a server's priority. We denote an ESCAPE leader election initiated by a server with a priority \mathcal{P} as $E_{\mathcal{P}}$. We assume the system is in term t (i.e., $\mathcal{T}^{(t)}$) before the election takes place. Consequently, the system will be in term $t + \mathcal{P}$ after the server wins the election and becomes the new leader. We show that $E_{\mathcal{P}}$ can be implemented by \mathcal{P} consecutive Raft leader elections whose term increases from t to $t + \mathcal{P}$, denoted by $\mathcal{R}_{t \to t + \mathcal{P}}$; that is,

$$\mathcal{R}_{t \to t + \mathcal{P}} \Longrightarrow E_{\mathcal{P}}, \text{ where } |\mathcal{R}_{t \to t + \mathcal{P}}| = \mathcal{P}$$

Suppose a server S operating in term t in Raft triggers a timeout and becomes a candidate. S then increases its term to t+1. At this time, if S loses its connection to other servers, S will time out again and increase its term to t+2. We denote this period of disconnection as a *blackout window*. Raft allows a sufficiently large blackout window because it tolerates all non-Byzantine (benign) failures. Thus, a server's leader election with a priority \mathcal{P} in ESCAPE is implemented by \mathcal{P} leader elections in Raft that take place in a blackout window.

Figure 8 illustrates an example of Lemma 1. S_i and S_j are two ESCAPE servers. Before their elections, S_i and S_j are in term $\mathcal{T}^{(t)}$ with configurations of $\pi^{(P_3)}$ and $\pi^{(P_2)}$, respectively. After initiating their election campaign, S_i 's term increases directly to $\mathcal{T}^{(t+3)}$ (at A_3) while S_j 's term increases to $\mathcal{T}^{(t+2)}$ (at B_2). These two election campaigns can be implemented by Raft leader elections, where S_i has a blackout window of three consecutive timeouts (at A_1 , A_2 , and A_3), and S_j has that of two consecutive timeouts (at B_1 and B_2).

Theorem 1 (Validity). *If all the servers have the same input, then any value decided upon must be that common input.*

Proof. The validity property holds in Raft [7], where a committed value must have been logged by a majority of

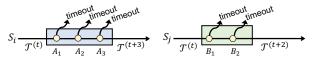


Fig. 8: An ESCAPE leader election can be translated into multiple consecutive Raft leader elections.

servers. With Lemma 1, since ESCAPE leader election can be implemented by Raft leader elections, the improvement made by ESCAPE is isolated from log replication in Raft. Thus, ESCAPE maintains the validity property.

Lemma 2. An ESCAPE election campaign and a Raft election campaign initialized by the same server is indistinguishable on other servers.

Proof. Suppose a cluster runs Raft and ESCAPE simultaneously where a server, say S_i , initiates an ESCAPE leader election campaign and sends a request to another server, say S_j . We show that S_j cannot distinguish if this request is from a Raft election campaign, denoted by R_{S_i} or an ESCAPE election campaign, denoted by E_{S_i} . That is,

$$\forall S_i \in \text{Raft} \land \text{ESCAPE}, E_{S_i} \overset{S_j}{\sim} R_{S_i}$$

ESCAPE does not change the rules or the parameters of election requests for electing a new leader in Raft. From Lemma 1, an ESCAPE election can be implemented by multiple Raft elections, and S_j is not aware of the length of the blackout window on S_i . Therefore, when S_j receives the ESCAPE election campaign request from S_i, S_j is unable to distinguish if the request from an ESCAPE election or a Raft election at the end of the blackout window, i.e., for $S_j, E_{S_i} \sim R_{S_i}$.

Theorem 2 (Safety). Nonfaulty servers do not decide on conflicting values.

Proof (Sketch). The safety property also holds in Raft [7]. ESCAPE leader election is isolated from the log replication phase. Thus, under normal operation, ESCAPE maintains the safety property. In addition, during a view-change/leader election phase, from Lemma 2, ESCAPE and Raft election campaigns are indistinguishable, and servers follow the same rule to determine a new leader. Thus, a new leader elected by ESCAPE must be able to be elected by Raft with a specific initial configuration. A leader in ESCAPE maintains its correctness and no committed values can be overwritten. Therefore, ESCAPE maintains Raft's safety property.

Lemma 3. If any two servers are in the same configuration clock, they must possess different configurations.

Proof. Initially, SCA assigns each server a unique configuration based on the server ID. Under normal operation, PPF atomically rearranges configurations, based on server log responsiveness, at any given configuration clock. If the leader fails, the assignment task may become incomplete, but it never assigns two servers with the same configuration.

Lemma 4. If any two servers possess same configuration, they must be in different configuration clocks.

Proof. We prove this lemma by contradiction. We claim that servers assigned with the same configuration have the same confClock, say k. Then, at configuration clock k, a leader must have assigned the same configuration to more than one server, which contradicts Lemma 3.

Since ESCAPE tolerates f benign faults, from Lemma 4, there are at most f servers that are in different configuration clocks while possessing the same configuration. Suppose in clock k, a server S_1 has a configuration $\pi^{(\mathcal{P}_*,k)}$. In clock k+1, server S_1 crashes, and $\pi^{(\mathcal{P}_*)}$ is assigned to S_2 ; thus, S_2 's configuration is $\pi^{(\mathcal{P}_*,k+1)}$. Then, S_2 crashes and $\pi^{(\mathcal{P}_*)}$ is assigned to S_3 . In this way, since ESCAPE tolerates f failures, $\pi^{(\mathcal{P}_*)}$ can be iteratively assigned to S_i in clock k+i-1 where $i \leq f$.

Theorem 3 (Configuration uniqueness). *No two nonfaulty* servers possess the same prioritized configuration.

Proof. Lemma 3 guarantees that, at any given time, candidates are prioritized by configurations. From Lemma 4, configurations are prioritized by their logical clocks. Since configuration clocks grow monotonically along with physical time, the rearrangement of configurations always atomically scatters servers into different priorities.

Due to the problem of competing candidates, Raft ensures liveness if the system ultimately elects a leader. That is, *every nonfaulty server eventually decides a value*. However, with bounded messaging delay, Raft cannot guarantee a lower bound of the eventuality; competing candidates may often occur if timer timeouts are not ideally chosen. In contrast, equipped with SCA and PPF, ESCAPE ensures that a new leader can be elected by at most f + 1 leader elections in the worst case. If the highest-priority candidate does not fail, it will become the new leader and terminates leader election in one election campaign.

Lemma 5. ESCAPE terminates a leader election phase in one campaign with nonfaulty candidates.

Proof. With Theorem 3, in the phase of leader election, no two candidates possess the same prioritized configurations. Thus, at most one legit election campaign takes place in a given term. With nonfaulty candidates, the candidate that increases its term to the highest will be elected, which subsequently terminates the leader election. \Box

Theorem 4 (Strong liveness). Every nonfaulty server decides a value after at most f + 1 leader elections.

Proof. ESCAPE and Raft both tolerate f non-Byzantine failures with a total of 2f + 1 servers. With a correct leader, nonfaulty servers decide a value in two rounds of heartbeats under normal operation. When the leader fails, normal operation resumes after a new leader is elected. In ESCAPE, if f failures occur on every candidate that has the highest-priority

among nonfaulty ones, ESCAPE must wait for f + 1 election campaigns before a correct candidate appears. With Lemma 5, ESCAPE elects a new leader in one leader election campaign when candidates are nonfaulty. Therefore, normal operation resumes after at most f + 1 leader elections.

Theorem 5 (Complexity). ESCAPE leader election has a message transmission complexity of $\mathcal{O}(n^2)$.

Proof. Upon leader failures, every server is able to start an election campaign after its timer expires and subsequently broadcasts a request to all the other servers. If a candidate is qualified for the next leadership, other servers send a vote to the candidate. Therefore, during the election, the message transmission complexity is $O(n^2)$.

Additionally, the best case, where only one election campaign is initiated, has a message transmission complexity of $\mathcal{O}(n)$. Compared with Raft, ESCAPE has a higher probability to achieve the best case. The highest priority and the shortest election timeout is assigned to the most up-to-date candidate, who presumably will firstly detect leader failure and become the next leader.

VI. EVALUATION

In this section, we show experimental comparisons majorly between ESCAPE and Raft. ESCAPE aims to avoid split votes and reduce the leader election time, so the comparison was conducted for leader election under various scenarios including crash and omission failures.

A. Experimental Setup

We implemented ESCAPE and Raft prototypes using the Golang programming language and deployed the prototypes on 4, 8, 16, 32, 64 and 128 VM instances on Compute Canada Cloud. Instances are located in the same data center; the raw network latency between two VMs is less than 2 ms, and the network bandwidth is around 400 Megabytes/second. We simulated a geo-distributed setup by using NetEm to implement a higher network latency that uniformly distributes from 100 to 200 ms. Each instance includes a machine with two 2.40 GHz Intel Core processors (Skylake) with a cache size of 16 MB, 8 GB of RAM, and 20 GB of disk space running on Ubuntu 18.04.1 LTS.

B. Election Time under Leader Failures

We first compared the leader election time for ESCAPE and Raft under leader failures. In this case, we repeatedly crashed the leader of a cluster of 8, 16, 32, 64, and 128 servers for 1000 runs of leader election at each scale. In the Raft cluster, election timeouts were set to 1500-3000 ms, which is the value range recommended by Raft for our network latency [7]. In ESCAPE clusters, the *baseTime* of election timeouts for servers was set to 1500 ms with k=500 for Equation 1. In practice, to avoid simultaneous timeouts among servers, k can be set $\times 2$ higher than the network latency. Thus, ESCAPE allows the "potential leader" to complete its election before other servers trigger timeouts. This setting assists the

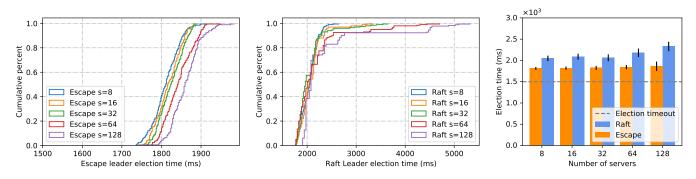


Fig. 9: Leader election (LE) time comparison of ESCAPE and Raft at increasing scales. The first two figures indicate the cumulative percent of distribution of LE time for 1000 runs of each scale, and the last figure compares the average LE time of both protocols.

occurrence of the best case in leader election (discussed after Theorem 5). The leader election time is recorded including the detection of the leader crash and the election of a new leader. In each run, candidates need to collect votes from a majority of servers in their terms to claim leadership. For example, in an 8-server cluster, the quorum size is 5; after the leader crashes, a new leader is the candidate that has collected 4 votes from the remaining servers (candidates vote only for themselves).

Figure 9 shows the evaluation result for ESCAPE and Raft operating in clusters at increasing scales (denoted by s). The cumulative percent of the leader election time distribution for both protocols are presented in the first two figures. In ESCAPE, all the election campaigns were completed within 2000 ms, with no occurrence of split votes; in contrast, when $s \ge 32$, less than 40% of Raft's election campaigns were completed within 2000 ms. In the 128-server cluster, more than 17% of election campaigns experienced split votes, and their election time exceed 4500 ms. The last figure shows the comparison of averaged election times. Compared with Raft, ESCAPE shortens the leader election time by 11.6% and 21.3% at sizes of 8 and 128 servers, respectively.

C. Election Time in Multiple Phases

From Section VI-B, the evaluation result shows that ES-CAPE outperforms Raft in leader election under single leader failures. Because ESCAPE does not encounter split votes in a given term, it reduces the leader election on average. In order to observe the performance for both protocols when configurations lead to multiple phases with competing candidates, we evaluated the leader election time where five clusters of various scales elect a new leader in zero, one, two, and three phases with competing candidates (shown in Figure 10).

Raft witnesses a surge in leader election time when split votes repeat. Both protocols exhibit similar performance without competing candidates: election converges in 1812 ms (ESCAPE s=8) to 1976 ms (Raft s=128) for clusters at different scales. However, Raft suffers from a provisional livelock when competing candidates emerge. Although Raft and ESCAPE take similar time to detect leader failures, competing candidates impede Raft from completing the current election. The livelock lasts for approximately the number of phases with competing candidates \times the election timeout. With three phases of competing candidates, Raft takes approximately 6535 ms to elect a leader in a cluster of 8 servers, and 7473 ms in a cluster of 128 servers, nearly four times as long as ESCAPE (1924 ms at s=128).

On the contrary, ESCAPE completes all election campaigns within 2000 ms throughout different evaluations, regardless of the number of phases with competing candidates. ESCAPE no longer elects a leader based on the success that a candidate collects votes faster than its opponents and forms a majority. The highest-termed candidate finally supersedes the other election campaigns and becomes the new leader. In a 128-server cluster, compared with Raft, ESCAPE reduces the election time by 44.9%, 64.2%, and 74.3% under one, two, and three phases with competing candidates, respectively.

D. Election Time under Message Loss

In addition to multiple phases with competing candidates, we evaluated the leader election performance under message loss, a scenario that frequently occurs in practice. ESCAPE and Raft depend on a majority of servers participating in the consensus, so we chose to evaluate leader election under message loss rates (Δ) of 0%, 20%, 30%, 40%. At each rate, a broadcast only reaches 1– Δ servers. For example, in a cluster of 10 servers and Δ =20%, a sender (leader or candidate) randomly omits two servers in each broadcast, whereas if Δ =0%, no message loss materializes.

Zookeeper [4] implemented a leader election mechanism [23] using unique server IDs to set priorities, which is similar to ESCAPE's SCA method without PPF. However, if applying this approach to Raft, the priority assignment is not atomic. We applied Zookeeper's leader election approach in Raft and refer to it as Z-Raft. To compare the performance of ESCAPE, Raft, and Z-Raft at various scales under varying rates of message loss, we chose to perform the experiment in clusters of 10, 50, and 100 servers.

Figure 11 shows the evaluation results averaged over 1000 runs. Without message loss (Δ =0%), the election time of Raft is slightly higher than that of ESCAPE and Z-Raft. However, message loss severely exacerbates split votes in Raft, especially at large scales. When Δ =40% in the Raft

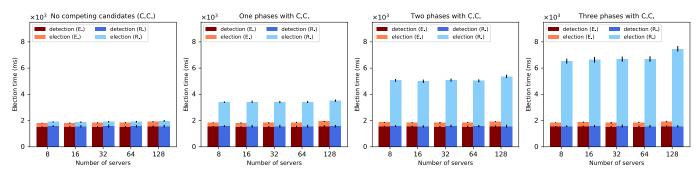


Fig. 10: Leader election time performance in zero, one, two, and three phases with competing candidates (C.C.) at five varying scales. The detection period is recorded between when a leader crashes and a candidate appears. The election period is recorded between when a candidate starts an election campaign and a new leader is elected. ESCAPE benefits from its dynamic configuration assignments and performs leader election in a single campaign regardless of the number of competing candidates.

cluster, 40% of servers become unqualified candidates since they do not have up-to-date logs. Election campaigns triggered by unqualified candidates are in the same term and stranded in their election campaigns until a qualified candidate with a higher term wins the competition.

The results of Z-Raft and ESCAPE exhibit similarity when the rate of message loss is relatively small. Since Z-Raft does not atomically arrange configurations, a low rate of message loss does not significantly jeopardize the effectiveness of fixed priorities. However, when message loss rates increase, without dynamically rearranging priorities, servers that are initially assigned with higher priorities are more likely to become stale servers whose logs are no longer up-to-date. This situation defeats the purpose of using priorities to rank candidates. Thus, when Δ increases, the gap of election times among Raft, Z-Raft, and ESCAPE expands.

In contrast, ESCAPE assigns the "best" configuration (the highest priority and shortest election timeout) to the most upto-date server through SCA and PPF. With message loss in the network, if the most up-to-date server changes, the "best" configuration is dynamically rearranged to the qualified server. Because the configuration rearrangement is atomic, candidates are differentiated in real time based on log responsiveness through periodic heartbeats. When the leader crashes, the

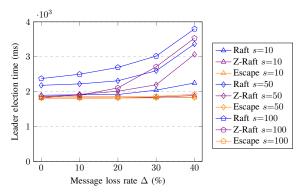


Fig. 11: Leader election comparisons under message loss. When $\Delta = 40\%$, in each broadcast, 40% of the servers were not able to receive messages sent by a leader or candidates.

server firstly triggers an election campaign and completes the campaign in one phase (all the other servers will vote for this server), escaping from potential competitions.

The evaluation results show the quantitative comparison among three protocols. In a cluster size of 10 servers, compared with Raft, when $\Delta=10\%$ and $\Delta=40\%$, Z-Raft reduces election time by 9.8% and 14.3%, respectively, while ESCAPE reduces election time by 9.6% and 19%, respectively. The reduction in election time is more significant at large scales for ESCAPE, especially at a high rate of message loss. In a cluster of 100 servers, ESCAPE reduces the leader election time by 21.4% and 49.3%, when $\Delta=10\%$ and $\Delta=40\%$, respectively.

VII. RELATED WORK

Consensus algorithms coordinate servers to agree on proposed values in distributed systems. To efficiently achieve agreement among servers, numerous consensus algorithms use a designated leader to coordinate the process for committing values. These algorithms are called leader-based consensus algorithms and contain election protocols to choose a unique server to play a particular role.

With an assumption of no server failures and an asynchronous network, the Chang and Roberts algorithm arranges an array of servers as a logical ring [24], where a server communicates with its descendant in a clock-wise manner, and a single process that has the largest identifier is elected as the leader. In addition, the Bully algorithm [25] addresses fault tolerance by relying on communication among servers; it assumes a synchronous network and uses timeouts to detect server failures. The server with the highest server ID will be elected as the leader.

More recently, the celebrated Paxos algorithm [5], [26] implicitly utilize a global leader for reaching consensus; every server that assumes a proposer role is allowed to broadcast proposals to be accepted. Nonetheless, the concept of leadership hides behind the consensus process that refuses values carrying a smaller proposal number [7]. To avoid conflicts and optimize performance, approaches using explicit leader roles have been developed [3], [27]–[29]. In addition, Viewstamped Replication (VR) [6], [30] provides an alternative way to

achieve consensus using a leader-based approach. Although Raft shares similarities with Paxos and VR, Raft uses strong leadership where the messages flow only from the leader to other servers; all other servers passively synchronize states from the leader, resolving conflicts by obeying the leader's commands. Utilizing strong leadership reduces the types of messages and thus improves Raft's understandability, making Raft widely deployed in practical large-scale distributed systems such as Baidu File System [16], SDN designs [17], and HyperLedger Kafka [18]. Thus, the leader election mechanism is crucial because a Raft system fails without a leader. However, Raft's leader election may result in competing election campaigns that needlessly prolong the election time. The performance evaluation of Raft in [22] hinted at this problem, especially when the network splits and drops message.

Although Zookeeper [4] ushered a way to prioritize servers using server IDs as identifiers [23], this approach does not atomically rearrange priorities based on server log responsiveness. Consequently, the highest-priority server is guaranteed as the most up-to-date. In this case, highest-priority servers can be defeated in leader election campaigns and can not be elected as the new leader, especially under problematic networks (e.g., packet loss). In contrast, ESCAPE does not only use server identifiers to assign priorities, but also periodically rearranges priorities and election timeouts in the cluster. Through the proposed election mechanism, ESCAPE prepares and manages a pool of prioritized candidates, resolving potential conflicts before the next election takes place. Furthermore, ESCAPE shares Raft's safety and liveness properties and maintains understandability and modularity as well.

VIII. CONCLUSIONS

In this paper, we develop a new consensus protocol called ESCAPE that enables fast leader election. ESCAPE assigns stochastic configurations to prioritize servers. Higher-priority configurations are dynamically distributed to more up-to-date servers via the probing patrol function, forming a pool of prioritized candidates. The top candidate, with the highest priority configuration, in the pool is groomed as a "future leader". Thus, leader election completes without suffering from split votes, taking precautions against leader failures before the next election takes place. ESCAPE can also be adapted in other election protocols to resolve potential competition in advance. The evaluation results show improvements of leader failures, especially under message loss.

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