Baxos: Backing off for Robust and Efficient Consensus

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Abstract—Leader-based consensus algorithms are vulnerable to liveness and performance downgrade attacks. We explore the possibility of replacing leader election in Multi-Paxos with random exponential backoff (REB), a simpler approach that requires minimum modifications to the two phase Synod Paxos and achieves better resiliency under attacks.

We propose Baxos, a new resilient consensus protocol that leverages a random exponential backoff scheme as a replacement for leader election in consensus algorithms. Our backoff scheme addresses the common challenges of random exponential backoff such as scalability and robustness to changing wide area latency. We extensively evaluate Baxos to illustrate its performance and robustness against two liveness and performance downgrade attacks using an implementation running on Amazon EC2 in a wide area network and a combination of a micro benchmark and YCSB-A workload on Redis. Our results show that Baxos offers more robustness to liveness and performance downgrade attacks than leader-based consensus protocols. Baxos outperforms Multi-Paxos and Raft up to 185% in throughput under liveness and performance downgrade attacks under worst case contention scenarios where each replica proposes requests concurrently while only incurring a 7% reduction on the maximum throughput in the synchronous attack-free scenario.

I. INTRODUCTION

Consensus is a widely used abstraction to ensure strong consistency in distributed systems. When run in multiple instances, which is also known as state machine replication (SMR) [1], consensus enables a set of replicas to agree on a single history of operations. Popular systems that use consensus include Chubby [2], ZooKeeper [3] and Boxwood [4].

For performance reasons, most deployed consensus protocols use a leader which serves client requests and inter-replica messages [5]–[7]. In particular, the leader is tasked with handling contention and providing lock-free termination [8] which works well in synchronous and attack-free network settings. However, under more adversarial network conditions, this approach becomes problematic [9], [10]. When the network is volatile, e.g., changing link delays and bandwidth, leader-based approaches fail to deliver good performance due to leader timeouts and subsequent leader election mechanisms which impact the overall system availability. In the worst case a service can even freeze completely, which is exactly what happened in a recent outage at Cloudflare [11]. This downside becomes particularly problematic when a system is under a distributed denial of service (DDoS) attack. Previous research has shown that even a weak adversary, who can attack only a single replica at a time, can halt the availability of a leader-based consensus algorithm [10], [12]. With DDoS attacks becoming more prevalent [13], leader-based consensus algorithms pose a significant risk to the availability of Internet applications.

Previously proposed consensus algorithms that achieve lock-free termination without using a leader node include multi-leader-based protocols [14]–[17], sharding based protocols [18]–[21], application dependent protocols that exploit request dependencies [22]–[24] and asynchronous algorithms [25]. However, these approaches have liveness and performance vulnerabilities. Most multi-leader-based algorithms delegate message propagation to other replicas but still rely on a leader to order requests [15]–[17], remaining susceptible to attacks on the leader node. Algorithms that exploit request dependencies are vulnerable to DDoS attacks that issue concurrent dependent requests [22], [23]. DDoS attacks against the top level shards in sharding-based consensus algorithms [18]–[21] can make the entire system unavailable. Finally, fully asynchronous algorithms are generally complex, rarely implemented, and usually do not perform as well as Multi-Paxos in practice.

We observe that even after two decades of leaderless consensus protocol research, the majority of the deployed consensus algorithms still use leader-based protocols such as Multi-Paxos or Raft. This situation has led us to investigate the minimal modification required to transform a consensus algorithm such as Synod-Paxos [8] to a consensus algorithm that is robust against liveness and performance downgrade attacks while preserving good performance in an attack-free scenario. In turn, we explore the possibility of utilizing random exponential backoff (REB) [27] in the context of consensus, due to its robustness, efficient contention handling, and power efficiency.
guarantees. As a result, we propose Baxos, a bare minimal modification of Synod-Paxos [8] that is robust and highly available under liveness and performance downgrade attacks.

Baxos employs the same two-phase protocol core as Synod Paxos, but in contrast to Multi-Paxos, it uses REB instead of leader election to achieve lock-free termination. In Baxos, every node can propose values and, when concurrent proposals collide, they back off to avoid further collisions, an approach similar to CSMA in LANs [28]. Replacing leader election with random exponential backoff is not trivial, however, due to its potential side effects such as (1) the capture effect, where a single node can have an unfair share of a shared resource as well as (2) the impact on resilience to changing network delays and (3) scalability. Baxos leverages a REB protocol that scales up to nine replicas while remaining resilient to changing network delays and minimizing the capture effect.

Baxos is the first attempt to prototype REB-based Synod Paxos and to systematically explore its properties. To evaluate the properties of Baxos, we compare Baxos against three other popular consensus algorithms: Multi-Paxos, Raft, and Mencius [14]. We first analyze the performance of Baxos under delayed view change attacks, a class of targeted performance downgrade attacks in the wide area, and show that Baxos, in such a situation, significantly outperforms Multi-Paxos, Raft, and Mencius by up to 185% in throughput. Then, we explore the performance overhead of Baxos under attack free synchronous network scenarios in the wide area, and show that it achieves a throughput of 26,000 requests per second which is comparable to the performance of Multi-Paxos and Raft (28,000 requests per second). Third, we analyze the uniformity of bandwidth utilization and show that Baxos (standard deviation: 152) achieves a more uniform resource utilization across a set of consensus replicas than Multi-Paxos and Raft (standard deviation: 560). Finally we show that Baxos can scale upto nine nodes in the wide area.

To summarize, this paper makes the following contributions:
1) We explore the use of REB as a replacement for the leader election in consensus algorithms.
2) We design and systematically develop a consensus algorithm by combining Synod Paxos and REB.
3) We provide an experimental analysis of Baxos performance under both adversarial and normal-case network conditions as well as a bandwidth resource utilization analysis.

The rest of the paper is organized as follows. Section III provides background on consensus algorithms. Section IV presents the Baxos algorithm, design, and proof sketch. Section V describes our Golang implementation of Baxos and Section VI evaluates its performance. Section VI lists the limitations and future work, Section VII discusses the related work, and Section VIII concludes the paper.

II. BACKGROUND

This section provides an overview of the consensus problem, consensus algorithms, including leader-based protocols and its performance vulnerabilities, as well as the random exponential backoff mechanism we use as a building block of Baxos.

A. Consensus

Consensus is an abstraction used to reach an agreement among a set of replicas. A consensus protocol allows each node to propose a value, agree upon one of the proposed values and to report it to all live replicas.

A correct consensus algorithm satisfies four main properties [29]: (1) validity, a decided value should be previously proposed by a node; (2) termination, every correct process eventually decides some value; (3) integrity, no process decides twice; and (4) agreement, no two correct processes decide differently.

We focus on non-Byzantine consensus, where nodes are cooperative (non-malicious), although the network can be adversarial. The FLP theorem [30] states that consensus is impossible in the asynchronous network setting even in the presence of a single node failure. Practical consensus algorithms alleviate the FLP impossibility result using a partial synchrony assumption or randomization.

State machine replication (SMR) is a use-case of consensus, where nodes run multiple instances of consensus to agree on a series of values [I]. Consensus and SMR are generally considered to be equivalent, but from a theoretical perspective SMR is more expensive than consensus in terms of complexity and instructions [31].

B. Leader-Based Consensus

Multi-Paxos [8] and Raft [6] are the most widely deployed consensus algorithms that rely on partial synchrony to alleviate the FLP impossibility result. Multi-Paxos builds on top of Synod Paxos by having a leader replica that handles client requests. A replica runs the Prepare-Promise phase for a batch of consensus instances in the leader election phase and becomes the leader. Then, each client request is committed in the Propose-Accept phase in a single round trip. Raft builds on top of view-stamp replication [32]. When the leader is stable, Raft achieves a single round trip time consensus. When the leader fails, Raft uses a leader election algorithm to elect a new leader. On a high level, both Multi-Paxos and Raft solve the consensus problem in a similar method, differing only in the way a new leader is elected [33].

C. Performance Vulnerabilities

Consensus protocols are often deployed across wide area networks using the (public) Internet infrastructure to achieve high availability through replication. Networks, however, can be impacted by different adverse network conditions, ranging from accidental (e.g., a network congestion can affect the communication to and from the current leader slowing down all nodes) to intentional (e.g., a carefully crafted DDoS attack can interfere with a consensus replica group).

DDoS is a relatively simple but powerful technique to attack Internet resources [13], preventing or limiting access to a targeted resource. In the context of consensus, an attacker can
perform a DDoS attack by carefully analyzing the traffic using traffic analysis, and attacking the leader node to degrade the performance of the system by forcing the replicas to follow the slow execution paths such as view change [9].

In this paper, we make use of the DDoS attack description of Spiegelman et al. [10] to represent DDoS attacks relevant to consensus. We will refer to an attack that affects a consensus protocol as a delayed view change attack. A delayed view change attack aims to degrade the performance of a consensus algorithm while maximizing the time it takes to elect a new leader by (1) saturating the resources of leader replica and (2) avoiding a view change for the maximum possible amount of time. Saturating the leader replica in a consensus system slows down the entire replica set. However, leader-based consensus algorithms are configured to trigger a view change to elect a new leader when the current one becomes unresponsive for a predefined time period. If the attacker targets the leader in a way that immediately triggers a view change, then the new leader will keep the system available, foiling the attack. Hence, the attacker has to consider the trade-off between the performance loss due to the attack and the frequency at which a new leader is elected. Delayed view change attack differs from regular leader failures such that in the regular leader failures the leader node is permanently made unavailable where as in the delayed view change attack the leader node is slowed down temporarily for a time duration that is less than view change time. While the effect of permanent leader failure is widely explored in the previous work [14], we found that the effect of delayed view change attack has not been explored in the previous work.

D. Random Exponential Backoff (REB)

REB is a mechanism that enables a set of nodes to consume a shared resource without relying on a centralized point of entry. REB emerged as a standard technique to access shared resources in Ethernet [34] and the DOCSIS cable network [35]. In Ethernet, when there are concurrent data transmissions in the shared data link medium, the nodes detect the collision and re-transmit the frame. To avoid further collisions, each node backs off a random amount of time, exponentially increasing the random timeout duration. REB became widely used when shared-access physical links were common due to its robustness, efficiency and simplicity.

In contrast with its firm establishment in networking, REB has not been well studied in the context of consensus. Exponential timeouts have been used in consensus protocols but mainly as a method to adjust the leader timeouts. Multi-Paxos [8], [36] and Raft employ random exponential timeouts for two reasons: (1) to increase the view change timeout upon each view change and (2) to avoid two replicas concurrently issuing a new view change request. However, none of the previous work have explored REB as a leader replacement method, and to the best of our knowledge, our work is the first attempt to leverage and thoroughly evaluate REB as a primary method of contention handling in consensus.

III. Design

In this section we first describe Baxos’s system model followed by the algorithm itself. Afterwards we describe how REB integrates with Baxos, provide a consensus proof sketch, and finally discuss some optimizations.

A. System Model

Let $n$ denote the number of replicas and let $f$ denote the maximum number of failed nodes. We assume $n = 2f + 1$ and benign crash stop failures. For simplicity we further assume that crashes are permanent although node recovery can be easily integrated into Baxos using standard recovery approaches like sync-on-disk for each operation [24], [29].

We assume perfect point-to-point links between each pair of nodes, i.e., messages sent to non-failed nodes are eventually delivered [29]. This is a stronger assumption than the one made in Paxos [8] where messages can be dropped. However, implementing perfect point-to-point links on top of a fair-loss link abstraction is possible by using a stubborn transmission technique [29]. In practice, TCP provides reliable communication channels. We also assume that nodes are connected in a logical complete graph.

We assume a partially-synchronous network as defined in Dwork et al. [37]. Let $R$ be an execution of the consensus algorithm, $\Delta$ be the upper bound on message transmission delay and GST be the global stabilization time. The partial synchrony assumption states that for every $R$ there is an unknown time GST such that $\Delta$ holds in $[GST, \infty)$; once GST is reached, each message sent by process $p_i$ is delivered by process $p_j$ within a known maximum time bound of $\Delta$. This assumption is necessary to guarantee the liveness of Baxos in the light of the FLP impossibility result [30].

B. The Baxos Algorithm

At its core, Baxos uses the same logic as the Synod core of the Paxos protocol (Synod Paxos) [38], where each replica can propose values. However, Synod Paxos fails to achieve liveness if there are concurrent proposals for the same consensus instance. Baxos addresses this liveness issue by using REB: if there are concurrent requests for the same consensus instance, Baxos replicas back off for a random amount of time to prevent further collisions. This ensures that one proposer succeeds in committing their value for the consensus instance within a few retries. We present the pseudocode in Algorithm [1] in the Appendix. In particular, we focus on single-choice Baxos in the following which replicates a log of size one. We defer the discussion of multi-choice Baxos to Appendix [X-B].

We use the term try to denote the concept of Ballot number in Synod Paxos, and the term choice to indicate a consensus instance. A sequence of choice elements make the replicated log. As in Paxos, each replica can take on the role as an Acceptor, Proposer, and Learner [8]. Synod Paxos and single-choice Baxos consist of the following two phases, see Figure [I(a)]:

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a) Prepare-Promise.: A node which receives a new command from the upper layer takes on the role of Proposer and initiates consensus by broadcasting a Prepare message to all Acceptors. The Prepare message contains a proposed \( t \) number, which keeps track of the current \( t \) number. Acceptors send a Promise message to the Proposer, if they have not accepted any Prepare message with a higher or equal \( t \) number than the proposed \( t \) received in the Prepare message. To inform the Proposer about any previously accepted value, Acceptors piggyback the highest \( t \) for which they last accepted a value, and the corresponding value. If the Proposer manages to collect Promise messages from a majority, i.e., \( f + 1 \) or more, of Acceptors, then it selects the previously accepted value corresponding to the highest received previously accepted \( t \) number, chosen from the received set of Promise messages. If all Promise messages indicate that there is no such previously accepted value, then the proposer selects the received command \( c \) from the upper layer as the value to propose. Let proposed_value denote this selected value.

b) Propose-Accept.: Upon successfully collecting Promise messages from a majority of Acceptors, the Proposer broadcasts a Propose message piggybacked with the proposed \( t \) and the proposed_value. An Acceptor accepts a Propose message, if the \( t \) number in the Propose message is greater than or equal to the highest \( t \) number that it promised. Upon accepting a Propose message from the Proposer, Acceptors update their accepted\( t \) and accepted_value variables with proposed \( t \) and the proposed_value, respectively, and send an Accept message to the Proposer. The Proposer, upon receiving Accept messages from a majority of Acceptors, decides on that value and informs the upper layer about the decision. Finally, the proposer broadcasts a Learn message to inform Learners about the decision.

1) The Liveness Challenge: The above two-phase algorithm is the core of Synod Paxos, and it achieves obstruction-free but not lock-free termination: If there are multiple concurrent Proposers, then the above algorithm fails to terminate. An example execution where the termination property is not achieved is depicted in Figure 1(b), where replica 1 and replica 2 concurrently send the Prepare messages, without making any progress. In Synod Paxos, upon learning contention (detected by a timeout event in Algorithm [1]), the Proposer retries the Prepare-Promise phase with a proposed \( t \) that is strictly greater than its previous proposed \( t \) and promised \( t \). However, immediately retrying phase 1 causes further contention.

Addressing contention is where Baxos differs from Synod Paxos: whereas Synod Paxos does not implement a mechanism to deal with contention, Baxos uses REB to address contention. To avoid contention and achieve lock-free termination, the Proposer in Baxos backs off for a random exponential timeout (indicated as Random-Backoff() in Algorithm [1] in the timeout event) before retrying again. Figure 1(c) illustrates how Baxos backs off to handle contention.

REB is appealing as a method of handling contention in Synod Paxos due to three main guarantees of REB: (1) robustness, (2) high throughput and (3) resource utilization efficiency [27] as studied in the networking literature. REB enables appointing nodes in non-conflicting timeouts, so that there is only one node utilizing the shared recourse at a given time interval. In this paper, we ask the question "can REB bring the same advantages to the domain of consensus protocols?". In the next section we present our random back off scheme and explain why it achieves lock-free termination.

C. REB in Baxos

We aim to achieve two objectives from our REB scheme: (1) Provide lock-free termination by concluding a single Proposer for a consensus choice with asymptotically logarithmic number of failed proposals (retries) and (2) adapt to changing wide area network conditions such as variable latency.

We propose a REB scheme, called Baxos REB, that achieves the two goals above. We did not employ the existing REB schemes proposed in the networking literature, because they were designed under different assumptions, such as synchronous frame-transmission times, that do not apply in consensus, where the inter-replica latency varies significantly. For a comparison of Baxos REB scheme with REB schemes used in the networking literature, please refer to Appendix IX-C.

In the Baxos REB scheme, upon facing \( l \) retries, each node first selects a number \( k \in (0, 1) \subseteq Q \) uniformly at random. Then each node backs off for \( k \times 2^l \times 2 \times RTT \) time period where RTT is the maximum network round trip time between
any pair of replicas (network diameter) (note that $\Delta$ is the upper bound of $RTT/2$). Note that we use $2 \times RTT$ in our backoff time calculation, because there are two network round trips to commit a single request (Prepare-Promise and Propose-Accept) and to allow another proposer to successfully propose a command, other replicas should backoff a minimum of $2 \times RTT$. Upon successfully proposing a value, $l$ is decreased by one. As shown in Section III-D, Baxos REB ensures that eventually (after reaching GST) there exists only one Proposer for a sufficiently large time period $4 \times \Delta$ (note that when GST is reached $RTT = 2 \times \Delta$), such that a decision is made.

Baxos REB scheme achieves the two objectives we intended (liveness and robustness). Baxos REB achieves liveness due to our use of a continuous interval to choose a random value from. Using a continuous interval enables Baxos to have low probability of two nodes selecting the same value (compared to selecting a value from a discrete set in binary REB in networking [34]). Baxos REB scheme achieves robustness to changing wide area network conditions by dynamically monitoring the RTT for the back off time calculation. This enables Baxos to adapt its backoff time calculations with respect to changing wide area network conditions. Had we used the binary REB [34], which is widely used in networking, due to its use of constant frame transmission time to calculate the timeout, we would not be able to adapt to changing network dynamics.

D. Consensus Proof Sketch

We now provide a proof sketch for single-choice Baxos, which satisfies the following four consensus properties [29]:

1) Validity: If any node decides on a value $v$, then $v$ should have been previously proposed by some proposer.
2) Termination: If a correct process proposes a value, then that process eventually decides.
3) Agreement: No two nodes decide differently.
4) Integrity: No node decides more than once.

Validity, agreement, and integrity directly follow from the Synod Paxos proofs because we use the same core as Synod Paxos. For the sake of completeness we provide sketches for these properties in Appendix IX-A. Termination is derived using our REB scheme. This section focuses on the termination proof sketch for single-choice Baxos. The proof sketches for multi-choice Baxos are available in Appendix IX-B1.

Termination of Baxos holds only after the GST is reached, and when there is an upper bound $\Delta$ on the message transmission time between any pair of nodes. If there is only a single proposer for a run of Baxos, the protocol trivially terminates, hence we focus on the case with multiple contending proposers.

If there are multiple competing proposals from different proposers, each node backs off over a time period of length $k \times 2^{l+1} \times 2 \times \Delta$, since $RTT = 2 \times \Delta$ after GST is reached, where $k \in (0, 1) \subseteq \mathbb{Q}$ and $l$ is the number of retries. For termination to hold, we need to show that with high probability there exists a time interval of length $2 \times 2 \times \Delta$ in which only a single replica stops back off and makes its proposal. Figure 2 illustrates this scenario.

\[
\begin{align*}
\text{Time period when replica } p_k \text{ proposes successfully} & \\
t_1 & t_2 \\
& t_3 \\
& t_4 \\
& t_5 \\
4\Delta & & & 2^{l+1} \times 2 \times \Delta
\end{align*}
\]

Fig. 2: Illustration of Baxos termination.

Assume that there are $p$ replicas which compete to propose a value and that each has done already $l$ retries. Assume that all replicas start back off at time $t_1$. Let $t_5$ denote the time at which the last node finishes back off, then the time interval $(t_1 : t_5)$ has a maximum length of $2^{l+2} \times \Delta$. Depending on $k$, replica $p_k$ can stop back off at any time in $(t_1 : t_5)$ and start its proposal phase. Let $t_3$ denote the time at which proposer $p_k$ stops back off and starts proposing and let $t_4$ denote the time at which $p_k$ successfully decides. The interval $(t_3 : t_4)$ is of length $4\Delta$ which is the duration a proposal requires to complete successfully. Let $(t_2 : t_3)$ denote the interval of length $4\Delta$ before $(t_3 : t_4)$. For $p_k$ to terminate, no other replica should propose in $(t_2 : t_3)$ of length $2 \times 4 \times \Delta$ since any replica which stops its back-off and proposes after $t_2$ will make its proposal in $(t_3 : t_4)$ putting it into conflict with $p_k$’s proposal. Thus the probability that replica $p_k$ is the only proposer in $(t_2 : t_3)$ is equal to the probability that all other $p - 1$ proposers finish their back-offs and proposals in the intervals $(t_1 : t_2)$ and $(t_4 : t_5)$. This probability is given in Equation [4]

\[
\left(\frac{2^{l+2}\Delta - 8\Delta}{2^{l+2}\Delta}\right)^{p-1} = \left(1 - \frac{1}{2^l-1}\right)^{p-1}.
\]

If the value of $l$ is large enough, this probability approaches 1. Hence node $p_k$ eventually succeeds in proposing its value and thus decides.

This proof sketch for termination assumed that each contending proposer starts to back off at the same time $t_1$ and that each contending proposer has experienced the same number of retries $l$. In our experiments, we observed that different proposers start to back off at different times. For the simplicity of our proof we can let the adversary manipulate the delivery times of messages such that each node starts the backoff timer from the beginning of the synchronized period even if the conflict of replicas is detected at some point $t_1 + t$ where $t < \Delta$ (otherwise a new period starts). Additionally, different replicas have different $l$, but since the backoffs are exponentially increasing it is obvious that eventually all replicas will reach the same $l$ (this is the same reasoning as the view-change timeouts backoff in Raft).

E. One-Round Trip Optimization

In the absence of leader failures and network partitions, Multi-Paxos consumes a single network round trip time to
commit a single client request (when the client to leader network round trip time is not considered). This is possible in Multi-Paxos because the leader node runs the Prepare-Promise phase for a sequence of consensus instances, and thereafter, only the leader proposes the commands.

In contrast, Baxos consumes two network round trip delays to commit a single client request, which is a significant drawback. To address this drawback, we apply a classic message piggybacking technique, where the Prepare message for the choice i is piggybacked in the Propose message of choice i – 1 similar to [39]. Since the Prepare-Promise phase of choice i does not depend on the Propose-Accept phase of choice i – 1, the Prepare message for choice i can be piggybacked on the choice i – 1 Propose message. This optimization enables Baxos to commit a request in a single network round trip time, when successive client requests are proposed by the same Proposer. When multiple Proposers propose concurrently (contention), this optimization does not deliver any performance benefit. Given the nature of user interacting web services where a client sends back to back requests in a partly-open system [40], this design decision seems a reasonable choice to achieve performance that is comparable to Raft and Multi-Paxos.

IV. IMPLEMENTATION

We implemented Baxos, Multi-Paxos, Raft and Mencius using Golang language version 1.15.2. We decided to re-implement Multi-Paxos, Raft and Mencius in order to have a common framework to compare the performance of these protocols. Had we used the existing implementations of Multi-Paxos, Mencius [41] and Raft [42], our evaluation would have been influenced by different encoding schemes and different compiler optimizations. Having a common framework to implement the four algorithms helps us to isolate the impact of external factors such as those listed above. We cross-validated our framework implementation by comparing the results we obtained against the existing Multi-Paxos and Mencius implementations [43] by running the experiments using the same setup and workload.

For all four consensus algorithms, we used Protobuf encoding [43]. For Baxos, Multi-Paxos and Raft we employed gRPC [44] for inter-replica communication. Similar to the existing Mencius implementation in [41], we employed the standard Golang networking API for Mencius inter-replica communication. This design choice was driven by Mencius’s protocol design which is not compatible with the remote procedure call (RPC) abstraction [14], because the protocol design of Mencius and its optimizations are heavily dependent on one-way messages.

We implemented the core consensus logic for all protocols, view change for Multi-Paxos and Raft, and all optimizations of Mencius. We implemented all the attack scenarios we present in this paper. We did not implement snapshot and replica reconfiguration, which are outside the scope of this paper.

1https://github.com/efficient/epaxos/

TABLE I: Inter replica latency measured using ICMP Ping

| Location       | N. Virginia | Ireland | N. California | Tokyo | HongKong |
|----------------|-------------|---------|---------------|-------|----------|
| N. Virginia    | 66ms        | 62ms    | 144ms         | 145ms | 62ms     |
| Ireland        | 66ms        | 62ms    | 144ms         | 145ms | 62ms     |
| N. California  | 61ms        | 139ms   | 107ms         | 154ms | 51ms     |
| Tokyo          | 144ms       | 201ms   | 107ms         | 154ms | 51ms     |
| HongKong       | 193ms       | 249ms   | 154ms         | 51ms  | 51ms     |

V. EVALUATION

The goal of our evaluations is to answer following questions.
1) How robust is Baxos against delayed view change attacks in the wide-area networks?
2) What is the performance overhead of Baxos during failure-free synchronous periods in the wide area networks?
3) How efficient is Baxos in terms of bandwidth usage across replicas in the wide-area networks?
4) How does Baxos scale with increasing replica count in the wide-area networks?

In Section V-A we present the experimental setup, followed by a workload description in Section V-B. In Section V-C we evaluate Baxos’s behavior during delayed view change attacks. In Section V-D we measure Baxos’s overhead during failure-free synchronous periods. In Section V-E we evaluate the bandwidth efficiency of Baxos. Finally, in Section V-F we present a scalability analysis of Baxos with respect to the number of replicas.

A. Experimental Setup

We conducted our experiments using c5d.4xlarge instances (16 virtual CPUs, 32GB memory, and up to 10 Gbps network bandwidth), running Ubuntu Linux 20.04.3 LTS. We use the same system setup as in Mencius [14], where each AWS location has a single replica and a single client. Unless mentioned otherwise, we experiment with five consensus replicas and five client replicas (n = 5, f = 2) located in five geographically separated Amazon data centers in N. Virginia, Ireland, N. California, Tokyo and HongKong. Table I depicts the inter-replica latency measured using ICMP Ping.

In Baxos and Mencius, the clients send requests to the consensus replica in the same location; if the server in the same location has failed, then the clients send requests to a randomly chosen replica in a different location. In Multi-Paxos and Raft, the clients send requests to the leader replica. Clients generate requests simultaneously and measure the execution latency for each request. Each experiment was run for 1 minute and was repeated 10 times. We found that longer experiments do not significantly affect the performance results. To amortize the cost of the wide area network delays, we follow the standard practice of using batching in the replica side with a maximum batch time of 5ms. This resulted in batches of size in the range (5,000, 10,000) requests.

We measure the latency on the client side starting from when a new request is sent by a client until the client receives the response. We set the client request timeout to 8 seconds and requests that took longer than 8s were treated as failed. We measure the throughput on the client side as the ratio of the
number of successfully committed requests, excluding failed and timeout requests, and the time duration of the experiment. In the tests where we depict the throughput as a function of time, we aggregate the number of committed requests in one second intervals.

For the delayed view change attack performance results, we use the experimental approach of Spiegelman et al. [10]. We changed the transmission delay and packet loss of the replicas using NetEm [45].

B. Workload

We use a combination of real-world and synthetic micro benchmarks. Our synthetic micro benchmark consists of a configurable service time, configurable request and response sizes. Synthetic benchmarks help us to understand the protocol overheads in the presence of known upper bounds on CPU and I/O. We use the YCSB-A [46] workload with the Redis [47] key value store as a real world benchmark.

Our synthetic micro benchmarks and workload generation are inspired by the revised evaluation of Epaxos [26], without request dependencies. Each command in the micro benchmark consists of \( p \) bytes of payload and a unique request identifier. All client requests (reads and writes) are totally ordered in Baxos. When a server receives a request, it uses consensus to totally order it, and upon committing and executing, sends a response to client with \( q \) bytes with the unique request identifier. After each experiment, we use the replica logs to verify that each replica learns the same sequence of requests. We use open loop model [40] based on the Poisson arrival of client requests for both YCSB-A workload and the synthetic workload.

C. DDoS Performance

This experiment evaluates the performance of Baxos under adversarial DDoS conditions. The attacker coordinates the attack by adaptively choosing the leader node and attacking it. In Multi-Paxos and Raft, the attacker targets the leader replica and dynamically adjusts the attack by following the current leader upon each view change. In Baxos and Mencius, there is no designated leader and the attacker chooses an arbitrary replica to attack. We experiment with two types of delayed view change attacks: (1) a delay attack, where the adversary increases the transmission delay of a single replica to any destination and (2) a packet loss attack, where the adversary drops a fraction of egress packets of a single replica to all destinations. We used our micro benchmarks for this experiment.

We observed the same throughput and median latency variation over time for both delay attack and the packet loss attack. Due to space considerations we only show the delay attack results. Figure 3 compares the throughput and median latency of Baxos under delay attack. We first present an overview of the throughput under DDoS attack experiments in this paragraph and then explain each observation in detail in subsequent paragraphs. We first observe that during the first 10s of the experiment when there is no attack, all four consensus protocols progress at the speed of the network (the best case performance). Second, we observe that the throughput of Multi-Paxos, Raft and Mencius falls below 7,500 (with 3,500 as the average calculated over the attack time period), while Baxos delivers an average throughput of 10,000 requests per second, calculated over the attack time. Fourth, we observe that after 40s (when the attack stops), all four consensus algorithms eventually progress at the speed of the network (best case performance).

We explain the throughput degradation of Multi-Paxos and Raft up to 3,500 requests per second on average (with the maximum throughput of 7,500) during the attack period as follows. In the delay attack, the attacker increases the latency of egress packets of the leader in Multi-Paxos and Raft up to 4s. In our experiments, we set the view timeout of Multi-Paxos and Raft to 5s. Since the maximum delay at the leader is less than the view change timeout, each replica receives some messages from the leader before a view change is triggered. To further avoid a view change, the attacker attacks the leader only up to 4s time period in a row, thus giving the leader node the opportunity to perform fast enough without being suspected by the follower nodes as a slow leader. Since the majority of the messages sent by the leader takes 4s on average, this reduces the speed of the entire replica set. This is the reason for observing a low throughput in Multi-Paxos and Raft, during the attack.

We explain the throughput degradation of Mencius under delay attack as follows. Mencius does not employ a leader replica but its performance depends on the slowest replica [14]. This is due to the partition of the replicated log space among the set of replicas and the need to commit a request at log position \( i \) before committing at log position \( i + 1 \). When a single replica is attacked, the log positions corresponding to that replica do not make progress, thus the entire replica set cannot make progress, as shown in Figure 3. Moreover, Mencius improves on the common case (attack free and synchronous) performance, but when there is at least one slow or attacked node Mencius falls back to an expensive revoke execution path which significantly affects the throughput.

Baxos achieves an average throughput of 10,000 requests per second even in the presence of attacks. We explain this behavior as follows. Baxos does not employ a leader replica nor does it depend on the speed of all the nodes; Baxos can make progress at the speed of the majority of replicas. Because the attacker attacks a single random replica at any given time, only the requests which are sent to the replica under attack experience high delays. The impact of the attack is negligible on the other replicas and clients. Hence Baxos delivers a throughput of 10,000 requests per second under attacks, on average.

Figure 3(b) depicts the median latency of each consensus algorithm under study, with respect to time. We first observe that during attack-free executions, all four consensus algorithms progress with a median latency less than 500ms, with Mencius delivering a significantly higher latency than the other three algorithms (we discuss the high latency behavior of Mencius...
in the Section V-D (since it is out of scope of this section).

During the attack period (10s-40s), we observe that Multi-Paxos, Raft and Mencius deliver an average median latency of 1250ms or higher, while Baxos has an average median latency of 320ms. The reasoning for this behavior is same as the throughput discussion above: in Baxos the requests that are sent to the attacked replica experiences high delay whereas the requests sent to other replicas do not experience any high delay (thus low overall median latency). In Multi-Paxos and Raft, the latency of each request is affected by the attack since each request goes through the leader, and in Mencius, the latency of the overall replica set is dependent on the slowest node due to strict partition of the log space among the replicas.

In this experiment, we configured the view timeout of Multi-Paxos and Raft and the revoke timeout of Mencius to 5s. We also experimented with different view timeouts (1s, 10s and exponentially increasing view timeouts). For each view timeout, we observed the same patterns as depicted in Figure 3. Due to the space considerations, we omit these results here and refer the reader to a detailed analysis [10] of how different view change timeouts are affected by DDoS attacks.

A variation of this attack is where the attacker completely brings down (crashes) the leader node. To identify the impact of permanent leader failures, we conducted another experiment, where the leader replica is crashed. We use the same arrival rate and system parameters mentioned in Figure 3 for this experiment. We observed that in the leader crash experiment, during the crash period (time period from the moment the leader is crashed and until a new leader is elected) Baxos delivers a throughput of 10,000 requests per second on average, whereas Multi-Paxos and Raft deliver 0 throughput. Due to space limitations the graph for this experiment is omitted.

We conclude that Baxos is up to 185% more resilient to DDoS attacks in throughput than Multi-Paxos, Raft and Mencius.

### D. Attack-Free Case Performance

This experiment aims at quantifying the performance overhead of Baxos under faultless and synchronous network conditions. We use five client nodes that simultaneously send traffic to five replicas such that all five replicas propose commands. This experiment measures the worst case performance of Baxos under highest possible contention. Since Baxos must resolve contention at each choice instead of relying on a stable leader, we expect Baxos to perform worse than leader-based
TABLE II: Tail latency: The workload consists of 8B request and response sizes with 1μs service time. Five clients in 5 different AWS regions generate requests at 2,500 requests per second (aggregate 12,500 requests per second) simultaneously

| Algorithm | Multi-Paxos | Raft | Mencius |
|-----------|-------------|------|---------|
| Latency   | 234ms       | 235ms| 514ms   |

algorithms under stable network conditions, but we wish to measure the performance cost of Baxos’s greater robustness. We used our micro benchmark for this experiment.

Figure 4 depicts the throughput vs. median latency graph. We first present an overview of the normal case performance results and then discuss our observations. We observe that for a replica group of size five, Baxos provides a maximum throughput of 26,000 requests per second which is comparable to the throughput of Multi-Paxos and Raft (28,000 requests per second) when the median latency is less than 400 ms. We also observe that Mencius performs significantly worse than Baxos with a maximum throughput of 12,000 requests per second under a maximum median latency of 400 ms.

a) Throughput: The maximum throughput of Baxos is 7% less than Multi-Paxos and Raft (for a 400 ms maximum median latency), because Baxos faces contention: when multiple replicas propose requests simultaneously, their proposals collide, which leads to backing off by replicas and subsequent retries. While Baxos’s REB mechanisms enables us to reduce this contention, it cannot completely eliminate its impact. In contrast, Multi-Paxos and Raft do not experience contention because there is a single leader replica which proposes all commands.

The throughput of Mencius is 53% lower than Baxos, due to two main reasons. First, Mencius consumes three wide area messages (Propose, Accept and Learn) for a single request. In contrast, Baxos, Multi-Paxos and Raft consume only two messages (single network round trip time per request) because the Learn message of the consensus instance \( i \) is piggybacked on the Propose message of consensus instance \( i + 1 \). This optimization is not possible in Mencius due to its specific optimizations that aim at reducing the impact of skip messages in Mencius (see [14] for more details). Second, the throughput of Mencius suffers significantly in the presence of contention. Mencius Proposer can commit a request in just one round trip delay when there is no contention, but commits are delayed up to two communication steps when there are concurrent proposals [14]. These characteristics of Mencius result in a poor wide area performance.

To validate our reasoning about the performance of Mencius, we replicated the Mencius experiment mentioned in Moraru et al. [24], where the throughput of Mencius is measured in a single local area cluster using a single client. We observed that our Mencius implementation performs comparably to the reported throughput figures in Moraru et al. [24] (43,000 requests per second). However, the Mencius experiment in Moraru et al. [24] does not capture the effects of the wide area latency and contention.

b) Tail latency: To understand the impact of REB for tail latency, we conducted an experiment, where we measure the tail latency of Baxos, Multi-Paxos, Raft and Mencius under worst case contention scenario (each replica in Baxos proposes requests). Table II illustrates the 99% latency of each algorithm. We observe that the tail latency of Baxos is 6% higher than Multi-Paxos and Raft. The 6% high tail latency of Baxos is caused by the re-transmissions: when Baxos faces contention it re-transmits, whereas in Multi-Paxos and Raft no request is re-transmitted in the best case execution (without view changes).

These experimental findings show that Baxos provides a comparable performance to Multi-Paxos and Raft in the attack-free and synchronous network settings, while experiencing only a 7% throughput drop in the worst case (high contention) scenario. We feel that this modest performance cost under high contention is justified in many applications, especially those in which load is sporadic and robustness under all conditions is important. In contrast, if the best case performance is the primary goal, Baxos is appealing as a fallback protocol under DDoS attacks: use Multi-Paxos under default synchronous network settings, and fall back to Baxos if there is a DDoS attack aimed at the leader.

E. Bandwidth Utilization

Efficiency of resource usage is an important but often overlooked aspect in consensus algorithms [48]. In addition to absolute measures of resources consumed, an efficient consensus algorithm should make each replica spend roughly the same amount of resources [14] resulting in a uniform resource usage. Uniform resource usage is important due to two main reasons: (1) a skew in resource usage results in a higher cost for power in data centers [49] and (2) in resource constrained setups, such as peer to peer systems where each node has the same amount of resources, it is prohibitive to have a high resource usage skew. To explore this property, we aim to answer the following question: What is the variability of resource usage of Baxos replicas running in the wide area?

Since we experiment in the wide area, where the performance is bottlenecked by the speed of the network, we only focus on the network I/O utilization. We use our micro-benchmark for this experiment. To evaluate the variability of the resource utilization by different replicas, we measure the ingress and egress traffic of each replica for a constant arrival rate (load).

Figure 5 depicts the bandwidth utilization of different replicas, for each consensus algorithm. For Multi-Paxos and Raft, the leader replica is located in North Virginia. We observe that Multi-Paxos and Raft consume 1,560 kB/s bandwidth on average in the leader replica while consuming less than 200 kB/s in non-leader replicas. In contrast, Baxos and Mencius consume 220-800 kB/s bandwidth in each replica, thus utilizing the bandwidth more uniformly across replicas. We explain these behaviors as follows.

In Baxos and Mencius, each replica proposes commands and on average, each replica sends and receives the same amount
of messages per second. Hence, in Baxos and Mencius, each node roughly consumes the same amount of bandwidth. We calculated the standard deviation of the bandwidth utilization of different Baxos replicas to be 152. In contrast, the leader replica in Multi-Paxos and Raft sends and receives more messages than other replicas, as all requests are forwarded to the leader. This causes Multi-Paxos and Raft to have a standard deviation of 560, which is significantly higher than that of Baxos and Mencius.

While Baxos nodes consume more bandwidth than non-leader nodes in Multi-Paxos and Raft, its utilization is relatively uniform across nodes and far lower than the leader’s bandwidth in leader-based schemes, which makes it a practical choice for data centers and resource constrained deployments such as sensor based internet of things applications.

F. Scalability in Replica Set Size

This section evaluates the wide area scalability of Baxos with a real world use case. We evaluated the scalability of Baxos, Mencius, Multi-Paxos and Raft by running them with a replica set size of three, five, seven and nine. It should be noted that unlike permissioned [50] and permission-less [39] blockchains where consensus algorithms are scalable upto hundreds of nodes, crash fault tolerant protocols are usually designed to scale upto 9 nodes [51] [14]. Hence we evaluate Baxos only up to 9 nodes. In addition to the five data centers we mentioned in Table I, we used another four AWS regions located in Oregon, Mumbai, Seoul and Cape Town.

We used Redis [47] with YCSB-A [46] workload for this experiment. YCSB-A is a cloud benchmark workload that consists of a mix of 50/50 reads and writes modelling a session store recording recent actions. It assumes 1kB records with 10 fields of 100B each. The key selection is based on the Zipfian distribution. Redis is an in-memory key-value store that supports multiple data structures and operations, such as hash maps, sets and lists. We chose Redis as the backend application due to its wide adoption in the cloud performance analysis literature.

Figure 5: Average bandwidth usage per replica at each five replicas. The leader nodes of Multi-Paxos and Raft algorithms are located in North Virginia. All five clients generate requests simultaneously at 1,000 requests per second

Figure 6: Scalability with respect to increasing replica count. The workload is YCSB-A workload with 1kB request size with Redis key value store as the backend. For each replica count i there are i number of clients (7 replicas setup has 7 clients and so on) – the experiment evaluates the worst case performance of Baxos (high contention). All throughput values are measured under 1 second 99% percentile client perceived latency (tail latency less than 1s)

We observe a reduction of the maximum throughput for all four consensus algorithms compared to the normal case performance experiment above (see Figure 4) due to the higher network bandwidth usage of this experiment. In the normal case performance experiment, we employed our micro benchmark with a 8B request size whereas in this scalability experiment we employed the YCSB-A workload with a 1kB request size.

The throughput of Baxos, Multi-Paxos, Raft and Mencius decrease by 21%, 20%, 20% and 39%, respectively, when the replica set size is increased from three to nine, due to two main reasons. First, with increasing replica count, the number of messages sent when proposing a new command (Append Entries RPC in Raft, and Propose message in Multi-Paxos, Baxos and Mencius) by the proposer (an arbitrary node in Baxos, Mencius and the leader replica in Multi-Paxos, Raft), increases. This is because the Propose message is a broadcast and it increases the network I/O overhead. Second, with an increasing replica count, the quorum size (n/2 + 1) increases, thus the proposer has to collect Accept messages from an increasing number of replicas. This affects the performance because in the wide area experiments the proposer has to wait to collect responses from replicas located further away.

Using this empirical study on scalability, we conclude that...
Baxos scales to a minimum of nine nodes while exhibiting the same percentage throughput loss with respect to the number of nodes as Multi-Paxos and Raft.

VI. LIMITATIONS AND FUTURE WORK

We now discuss the limitations of Baxos and the future work.

Byzantine failures. In this work, we only focus on crash failures. Despite our insights, it might not be straightforward to derive a Byzantine version of Baxos because random backoff is not built on a quorum abstraction. Moreover, malicious parties can lie when they detect the contention and skew their “start backoff time” as they please. We plan to explore Byzantine Baxos using two approaches: (1) verifiable random functions \[52\] and (2) trusted hardware base to enforce random backoff.

Read Optimization. In the current version of Baxos, we do not differentiate between reads and writes, and both reads and writes are totally ordered using the same execution path. We intend to explore read optimizations using read leases \[24\].

Network Bandwidth Usage. In Baxos, Proposers have to broadcast a message to Acceptors, both in the Prepare-Promise phase and in the Propose-Accept phase, which results in a major I/O scalability bottleneck. We plan to address this issue in the future by exploring two approaches: (1) dynamic broadcast trees and (2) separating the total ordering from message broadcasting \[53\] by employing a peer to peer overlay to disseminate requests and using hash of requests for total ordering.

VII. RELATED WORK

Liveness and performance downgrade attacks. DDoS-resistant protocols based on a “moving target” \[9, 12\] switch between different approaches depending on the network adversary. When the network is synchronous, these protocols employ single-decree Paxos, which delivers good performance in a synchronous network. When the system is under attack, they employ Ben-Or \[54\], a randomized asynchronous consensus algorithm. While switching between these protocols provides a good performance when the network is synchronous, it performs poorly (but preserves liveness) when the network is experiencing transient but high delays because of the high message complexity of Ben-Or \[54\]. Moreover, this approach to DDoS resistance is challenging to implement due to complexities of merging two different consensus protocols. In contrast, Baxos uses the same core consensus algorithm for the attack-free synchronous scenario and the DDoS attack scenario, resulting in fewer lines of code to implement and a better performance in the presence of transient high network delays. Spiegelman et al. \[10\] have proposed a framework to transform a view based consensus protocol to a randomized consensus protocol to achieve robustness against DDoS attacks. However, their approach has a 100% throughput overhead in the common case (synchronous) execution and as such, it is not suitable for applications requiring a good performance. In contrast, Baxos has only a 7% throughput overhead in the synchronous attack-free execution, compared to Multi-Paxos. Several other works, such as \[55\], have addressed the robustness of Byzantine consensus protocols under DDoS attacks but assuming a different threat model, where a Byzantine minority of replicas can misbehave. In Baxos, we assumed that replicas are non-Byzantine.

Use of REB and random timeouts in consensus algorithms. Random exponential backoff and random timeouts have been explored in the context of consensus algorithms. IronFleet \[56\] and PBFT \[57\] have employed random exponential timeouts to adapt the view change timeout with respect to the network conditions. This allows the replicas to adapt the timeout such that a quorum of Acceptors reply before a view change is triggered. Tendermint \[58\] employs random timeouts inside a given consensus instance to prevent Tendermint from blocking forever for the liveness condition to be true, and to ensure that processes continuously transition between rounds. Renesse et al. \[56\] use a similar approach to increase the time for which a leader waits to collect the responses from Acceptors. Renesse et al. \[56\] employ a TCP-like additive increase, multiplicative decrease approach to select the optimal timeout to wait to collect responses from the Acceptors. Raft \[6\] and Multi-Paxos \[8\] employs random timeouts to avoid concurrent and contending leader elections. Heterogeneous Paxos \[59\] employs client side REB to avoid client induced flooding of the system. None of these approaches use REB as the primary method of contention handling, nor as a mechanism to withstand DDoS attacks. In contrast, Baxos employs REB as the primary method of contention handling to provide resiliences against DooS attacks.

Leaderless consensus algorithms. Mencius \[14\] achieves consensus without using a leader node by statically partitioning the log space among the set of replicas. This approach has two main drawbacks: (1) the speed of the system is dependent on the slowest replica and (2) an attack on a single replica can negatively affect the overall throughput of the system. In contrast, Baxos makes progress at the speed of the majority of replicas, minimizing the effect of an attack on a single replica on the overall system. Generalized Paxos \[22\] and EPaxos \[24\] achieve consensus without a leader by exploiting the request dependencies and using out-of-order commit. These protocols violate the layering constraints of a system design, which has lead to incorrect and complex specifications and implementations \[41, 60\]. In contrast, Baxos only needs to be aware of the total ordering of requests and it does not interfere with the application level dependencies such as the request commutativity. Fast Paxos \[61\] aims at reducing the number of round trips for a request from two to one but it fails to achieve a good performance in the presence of concurrent requests. Both Fast Paxos and Generalized Paxos assume a leader to resolve contention, hence, these protocols do not fully eliminate the leader bottleneck. Multi-coordinated Paxos \[62\] attempts to make the Generalized Paxos leaderless but it fails to deliver a good throughput as compared to Baxos, due to higher message complexity.

Other consensus variants. Spaxos \[15\], SDPaxos \[16\]...
and PigPaxos [17] aim at offloading the complexity of the leader node by separating the total ordering requirements from request propagation requirements; propagating a request among the replicas is done using a peer to peer overlay whereas the leader only proposes a total order for the digest of the request. However these approaches are vulnerable to delayed view change attacks because the total ordering is still dependent on a single leader replica. In contrast, Baxos does not depend on a single replica for progression, achieving more robustness against DDoS attacks. Sharding has been studied in the context of consensus [18], [19], [21], [63]–[65] to improve the overall throughput by running multiple instances of the state machine. While sharding delivers high performance, it is an orthogonal problem to total ordering and employing sharding in the core consensus logic violates the layering argument. In contrast, sharding can be enabled in Baxos by running Baxos in each shard for DDoS resilience. Moreover, sharding based consensus algorithms are often arranged in a hierarchical fashion, where the lower level shards manage a shard of the total data set and the top level shard handles the inter-shard transactions. Sharding based protocols are vulnerable to DDoS attacks because an attack targeted at the top tier shard can bring down the performance of the entire system.

VIII. CONCLUSION

We have presented Baxos, the first systematic exploration of the use of random exponential backoff (REB) in place of the usual leader election in practical consensus protocols. Our evaluation shows that Baxos outperforms the commonly used leader-based consensus algorithms such as Multi-Paxos and Raft by 185% in the presence of delayed view change attacks. Further, we showed that Baxos has comparable performance to Multi-Paxos in the synchronous network settings by only incurring a 7% throughput penalty in the worst case contention scenarios. We also explored the bandwidth efficiency of Baxos and showed that Baxos has a more uniform resource consumption than Raft and Multi-Paxos across replicas. Finally, we showed that Baxos can scale up to nine replicas in the wide area.

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IX. APPENDIX

A. Proof of Single Choice Baxos

Proof of validity: In Baxos, for a Proposer to decide on a value v, it should receive at least nf number of Accept messages with identical \{r,v\} combination, where r is some proposed_try number and v is the proposed value corresponding to try r. An Acceptor will send an Accept message to a Proposer, only if it received a Propose message from the Proposer for proposed_try r, and value v. For a Proposer to send a Propose message with value v and proposed_try r, it should have received at least nf Promise messages for the proposed_try r. In the Promise messages, Acceptors indicate their previously accepted value and previous try number for which they accepted the value. There are two cases to consider in this case: 1) no Promise message contains a previously accepted value, so that the proposer can select his proposal (the command from upper layer) in the Propose message, or 2) the Proposer will select the value with the highest try number from the received set of Promise messages. In the first case, the value sent in the Propose message is the value proposed by the Proposer (v), hence the decided value v is proposed by a Proposer (hence the validity property holds). In the second case, the Proposer selects a unique value that is previously accepted by one or many Acceptors. By using the same argument, it is clear that this value v should have been proposed by a previous Proposer P', for an earlier proposed_try number. Hence, the decided value v is previously proposed by some proposer P'. Hence the validity property holds.

Proof of agreement: To prove the agreement property, it is sufficient to prove that if an Acceptor A has sent an Accept message for value v in try i, then no value v' \neq v can be decided in any previous try. We prove this using induction. Assume that Acceptor A has sent an Accept message for value v in try i. For this to happen, A must have received a Propose message from a Proposer. In turn, that proposer must have collected a quorum of nf Promise messages for try i.
Let $Q$ be the $n-f$ number of Acceptors in that quorum. Let $j$ be the highest accepted_try in the set of Promise messages collected from the Acceptors in $Q$. If each Promise message indicates that no value has been previously accepted, then the agreement property is proved, because there is no value different from $v$ that is accepted in a previous try. Hence let's consider the case where such $j$ exists (there is at least one node who has accepted a value in a previous try). When $i=0$, the proof is trivial, because there exists no previously accepted value before try 0 (assuming that try numbers start with 0). Assume that for try $i-1$ the condition holds (if an Acceptor A has sent an Accept message for value $v$ at try $i-1$, then no value $v'\neq v$ can be decided in any previous try $k; k<i-1$), and we prove the condition for try $i$. It is evident that no value can be chosen in try numbers $j+1, \ldots, i-1$, because no try $k$ where $i > k > j$ could get $n-f$ number of Accept messages (if there was such try $k$ in which a node decided on a value, then $j$ should be equal to $k$, because any two quorums of size $n-f$ intersect). Acceptor A can send the Accept message for value $v$ at try $i$ only if some Acceptor in $Q$ has sent an Accept value $v$ in try $j$. From this we can deduce two results: No value $v'\neq v$ can be chosen in try $j$ and, no value $v'\neq v$ can be chosen in try numbers $0, \ldots, j-1$ (by using the inductive hypothesis on try $j$). This proves the condition for agreement for single choice Baxos: if an Acceptor A has sent an Accept message for value $v$ at try $i$, then no value $v'\neq v$ can be decided in any previous try.

Proof of integrity: Integrity property holds in single choice Baxos because of the use of the boolean variable decided, which is updated just once from false to true, and the fact that each node checks this variable before deciding on a value.

B. Multi-Choice-Baxos

In this section, we explain the multi choice Baxos consensus algorithm using three rules and show that multi choice Baxos can achieve lock free consensus in the partial synchronous model.

Each node in Baxos contains an infinite log of consensus choices. We assume that nodes implement a mechanism to detect duplicate client requests using well-known techniques, such as unique request identifiers or by assuming idempotent requests.

Rule 1: Each node maintains a variable last_decided_choice which is the last choice for which the state machine replication layer updated the state machine. Upon receiving a new command from the upper layer, a Proposer tries to propose the command for the consensus choice last_decided_choice + 1, using the Prepare-Promise stage. If the Proposer succeeds in getting Promise messages from a majority of Acceptors, it proceeds to the Propose-Accept phase. When the proposer receives Accept messages from a majority of nodes, it advances the last_decided_choice by 1 and updates the state machine. If there is only a single Proposer and if that Proposer eventually executes alone for a sufficiently large time, then this approach implements an obstruction-free consensus algorithm.

Rule 2: Due to asynchrony and contention, there is a possibility that more than one Proposer is attempting to propose a value for the same consensus choice last_decided_choice + 1, concurrently. In such a scenario, an attempt from a Proposer for a given command can fail either in the Prepare-Promise phase, or in the Propose-Accept phase. Failure to complete a phase is triggered by a timeout, as indicated in the Algorithm [1] Upon failing the Prepare-Promise phase, or the Propose-Accept phase, each node backs off a random amount of time, that is derived from the backoff algorithm. This guarantees that eventually (when the global stabilization time arrives and when there is only one active proposer), that Proposer will succeed in proposing its command.

Rule 3: There is a chance that the value decided at the end of a successful two phase Baxos protocol, is actually a value proposed by a different Proposer. This can happen if the Proposer was unaware of the previously accepted/decided value before proposing. In that scenario, the Proposer retries proposing the client command, until it decides on that same command.

1) Proof of Multi-Choice Baxos: We now prove the correctness of multi-choice Baxos. Multi choice Baxos satisfies two properties: agreement and lock free termination [29]. Agreement property asserts that each correct node obtains the same sequence of commands in its replicated log. Lock free termination states that if a correct process proposes a new command, then at least one correct process eventually decides.

Proof of agreement: The agreement property of multi choice Baxos directly follows from the agreement property of single choice Baxos. This can be easily proved using induction.

Let $k$ be the last_decided_choice in each node. It is sufficient to show that for each value of $k\geq 0$, the set of log positions 0..$k$ are identical in each node. $k=0$ is the empty log (initial state) in each node, and trivially satisfies this condition. Assume that for $k=k1$, each node has identical replicated logs. When a node receives a command from the upper layer, it proposes this command for the choice $k1+1$. By the agreement property of single choice Baxos, we know that each node will decide on a unique value for the log position $k1+1$ in each node. Irrespective of the number of concurrent proposals, from different Proposers, underlying single choice Baxos guarantees that each node will not decide differently. Hence when $k=k1+1$ the result holds and this completes the agreement proof of multi choice Baxos.

Proof of lock free termination: Given that asynchrony and contention is impossible (FLP proof [30]), Baxos relies on partial synchrony to prove the lock free termination. After reaching GST, when there is no contention in the system; i.e. there is at most one Proposer for a $4 \times \Delta$ (an amount of time that is sufficient to run the two phases of Baxos), Baxos ensures termination after the GST is reached. This is due to the system model assumption that only $f$ (if $f$ is less than $n/2$) nodes can fail, and because of the use of reliable communication channels.

However, when there is contention, two or more Proposers
can contend infinitely without progressing the replicated log. To provide lock free liveness in such scenarios, we use the rule 2 of multi-choice Baxos. By using REB, with probability $p$ (as mentioned in equation [1]), one Proposer succeeds in completing the two phases of Baxos after reaching GST; and hence decides. Hence, after GST is reached, each invocation of the consensus for each client command gets decided, eventually.

C. REB

Before deriving our own REB scheme, we first considered the existing REB algorithms used in the networking literature [34]. Binary REB is a fundamental algorithm in this space. In binary REB, each node backs off a random time out that increases exponentially upon each successive retry. Binary REB fails at achieving the two objectives (liveness, and robustness to wide area network conditions) as explained below.

In our preliminary experiments we observed that binary REB delivers good performance only when the replica set size is three, with a mean number of retries (failed proposals) per request equal to 1.1. When the replica set size is increased to five, the binary REB scheme resulted in having 1.45 number of retries per client request, thus significantly affecting the performance. Therefore binary REB is not scalable in the sense that it cannot support a larger replica group and fails at achieving our first objective (liveness).

Binary REB algorithm has a major limitation: the capture effect [66]. Binary REB resets the variable retries (failed proposals) to zero upon a successful transmission by a node. However, this gives unfair advantage to the node which successfully transmitted its message, by having a low contention set w.r.t other nodes, thus enabling it to transmit subsequent messages, while the other nodes are backing off with a larger contention set. In networking literature this phenomenon is called the capture effect. This limitation of binary REB affects the fairness: only some replicas succeed in proposing values. To address this problem, a modified binary REB algorithm has been proposed [34]. The modified binary REB addresses the capture effect by maintaining the retries variable across successive transmissions. However both binary REB and modified binary REB fail at achieving our first objective (lock free liveness).

We also observed that existing REB protocols in the CSMA literature are designed and developed with strict network synchrony assumptions. This assumption holds true in CSMA because all the nodes sharing a data link medium are tightly synchronized to the closest micro second. However, applying these algorithms to Baxos is not trivial due to changing wide area network latency. Due to these limitations of existing REB schemes, we modified and adapted the modified binary REB scheme to be more suitable for consensus while satisfying our three objectives.
D. Baxos Algorithm

Algorithm 1: Baxos algorithm

choice struct
// state of a single choice
| id |
proposed_trial, promised_trial, accepted_trial, accepted_value ← 0, -1, -1, null // monotonically increasing choice number
decided, decision ← false, null
end

Init:
node_id, choices [choice], last_decided_choice, retries, proposed_value, command ← unique_id, {}, 0, 0, null, null
Promises, Accepts ← {}, {}

Proposer: DownCall onPropose (c)
command, proposed_choice ← c, last_decided_choice + 1
choices[proposed_choice].proposed_trial ← max (choices[proposed_choice].promised_trial, proposed_trial) + 1
Broadcast PREPARE (proposed_choice, choices[proposed_choice].proposed_trial)
Start-Timer()
end

All nodes: onMessage PREPARE (choice, trial) onCondition choices[choice].promised_trial < trial from p
choices[choice].promised_trial ← trial
Unicast PROMISE (choice, choices[choice].accepted_trial, choices[choice].accepted_value, trial) to p
end

Proposer: onMessage PROMISE (choice, accepted_trial, accepted_value, trial) onCondition choice == proposed_choice and trial == choices[proposed_choice].proposed_trial
Promises ← Promises ∪ {accepted_trial, accepted_value}
end

Proposer: onEvent | Promises | > n - f
Cancel-Timer()
if ∀(accepted_trial, accepted_value) ∈ Promises are such that accepted_trial == -1 then
proposed_value ← command
else
j ← max {accepted_trial − (accepted_trial, accepted_value) ∈ Promises}
proposed_value ← {v | (j, v) ∈ Promises}
end
Broadcast PROPOSE (proposed_choice, choices[proposed_choice].proposed_trial, proposed_value)
Promises ← {}
Start-Timer()
end

All nodes: onMessage PROPOSE (choice, trial, value) onCondition choices[choice].promised_trial ≤ trial from p
choices[choice].accepted_trial, choices[choice].accepted_value ← trial, value
Unicast ACCEPT (choice, choices[choice].accepted_trial, choices[choice].accepted_value, trial) to p
end

Proposer: onMessage ACCEPT (choice, accepted_trial, accepted_value) onCondition choice == proposed_choice and accepted_trial == choices[proposed_choice].proposed_trial
Accepts ← Accepts ∪ {accepted_trial, accepted_value}
end

Proposer: onEvent | Accepts | > n - f
Cancel-Timer()
if choices[proposed_choice].decided == false then
choices[proposed_choice].decided, choices[proposed_choice].decision ← true, proposed_value
retries ← retries-1
end
Broadcast LEARN (proposed_choice, proposed_value)
last_decided_choice ← last_decided_choice + 1
Update-State-Machine()
if proposed_value == command then
Invoke onPropose (command)
end
end

All nodes: onMessage LEARN (choice, value) onCondition choices[choice].decided == false from p
choices[choice].decided, choices[choice].decision ← true, value
end

Proposer: onEvent Timeout
Promises, Accepts, retries ← {}, {}, retries+1
Random-Backoff(retries)
Invoke onPropose (command)
end