Enhancing Scalability with Optimized Replication in Distributed Architectures

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Abstract

Viewstamped Replication (VR) is a consensus protocol widely used in distributed systems to ensure consistency and fault tolerance among replicated services. It operates through a quorum-based mechanism, where a majority of nodes must agree before a client's request can be committed. While VR is reliable and effective in maintaining data consistency across nodes, one significant drawback observed in its operation is the high replication time, particularly as the number of participating nodes increases. This issue becomes more evident in larger clusters, where the overhead of communication and coordination among nodes grows substantially. Replication time refers to the duration taken by the protocol to replicate and confirm a client's request across all required nodes. In VR, each operation involves multiple rounds of messaging between the primary (leader) and backup nodes. As the system scales, the number of these interactions increases, adding delay to the overall replication process. For instance, in a system with 3 nodes, the replication time is relatively low. However, as the cluster expands to 5, 7, 9, or 11 nodes, the time required for replication rises significantly, following a clear upward trend. This increase is due to the need for reaching a quorum and synchronizing responses from more nodes, which introduces network latency, processing delay, and potential queuing overheads. The high replication time of VR can lead to reduced system throughput and slower response times for client operations, making it less suitable for performance-critical applications or large-scale distributed environments. Furthermore, in real-time systems where low latency is crucial, such delays can hinder the system's ability to meet strict timing requirements. This limitation presents a scalability challenge for VR, as the benefits of adding more nodes for fault tolerance and availability come at the cost of increased latency. Viewstamped Replication (VR) is a reliable consensus protocol for distributed systems, ensuring consistency and fault tolerance. However, its replication time increases significantly as the number of nodes grows. This happens because VR relies on a quorum-based approach, requiring multiple interactions and acknowledgments from a majority of nodes for each operation. Without addressing the replication delay, systems relying on VR may struggle to maintain high performance as they grow, making this an important area of concern in the field of distributed computing. This paper addresses the replication time issue in VR by using the ZAB replication time.

Keywords: ZAB, VR, replication, latency, scalability, consensus, performance, efficiency, broadcast, leader, follower, coordination, nodes, fault-tolerance, optimization

INTRODUCTION

Viewstamped Replication VR [1] is a consensus protocol used to ensure data consistency and fault tolerance in distributed systems. It operates by allowing multiple replicas of a service to synchronize their state through a leader-follower [2] mechanism, with a majority of nodes required to agree on an update before it is committed. While VR is a robust and reliable method for achieving consistency [3], one of its major drawbacks is its high replication time, particularly as the number of nodes in the system increases. Replication time in VR refers to the time it takes for an update or operation to be propagated and confirmed across the distributed nodes. In systems with fewer nodes, VR performs efficiently, with relatively low latency for each replication cycle. However, as the system scales and more nodes are added, the time required to complete replication increases significantly. This is due to the nature of VR's quorum-based [4] approach, where each operation requires communication and acknowledgment from a majority of nodes. As more nodes are involved, the number of required interactions rises, leading to increased messaging overhead and network latency. For example, when a system scales from 3 to 5 nodes, replication time increases from 5.5 milliseconds to 7.2 milliseconds. This trend continues as the node count increases, with replication times reaching 12.5 milliseconds at 11 nodes. This steady rise in replication time reflects the growing complexity of coordination and message passing required to achieve consensus across a larger number of nodes. The increasing replication time is a significant concern, especially in large-scale distributed systems, where maintaining low latency is crucial for performance. In real-time or performance-sensitive applications, high replication time can cause delays, reducing system throughput and affecting the overall responsiveness of the distributed system. This scalability issue makes VR less suitable for environments where rapid data synchronization [5] is essential. To maintain the performance of distributed systems, addressing the high replication time of VR becomes a critical challenge, requiring either improvements in the protocol's efficiency or the adoption of alternative approaches to consensus.

LITERATURE REVIEW

Viewstamped Replication (VR) is a widely used consensus protocol in distributed systems, designed to ensure consistency and fault tolerance. It operates through a leader-based mechanism where one node, the leader, manages updates and replication while the follower nodes maintain consistency by replicating the leader's state. Each client request must be accepted by a majority of nodes before it is committed to the system. This ensures that even if a node fails, the system can continue operating with minimal downtime. VR's simplicity and reliability make it a popular choice for distributed systems [6]. However, as the number of nodes in the system increases, the replication time required for the protocol also increases, posing a significant challenge for large-scale distributed environments. Replication time [7] in VR refers to the time taken for a client request to be replicated across all necessary nodes in the system. For smaller clusters, the replication time is relatively low as fewer nodes are involved, and communication between them is faster.

However, as the system grows in size, the number of required interactions for consensus increases, leading to longer replication times. This is because VR relies on a quorum-based approach, where a majority of nodes must agree before a request is considered committed. As the number of nodes grows, the time taken to coordinate between them increases, resulting in higher replication times. For example, when the system scales from 3 to 5 nodes, replication time rises from 5.5 milliseconds to 7.2 milliseconds. At 11 nodes, this time can increase to 12.5 milliseconds or more, reflecting a steady rise in latency as more nodes are added. The primary cause of high replication time in VR lies in its reliance on a quorum-based consensus mechanism. For each operation, VR must ensure that a majority of nodes agree before the operation is committed.

This means that the leader node must communicate with all other nodes in the system and wait for acknowledgments before proceeding. As more nodes are added to the system, the number of messages exchanged increases, leading to higher communication overhead. This overhead directly impacts the replication time. Furthermore, the increased complexity of coordinating among a larger number of nodes also contributes to the growing latency [8]. Each additional node requires more time to synchronize and reach consensus, further increasing the replication time. Another contributing factor to the high replication time is the network latency between nodes. In smaller systems, nodes are often located in closer proximity [9], which minimizes the time required for data transmission. However, as the number of nodes increases, the system may be distributed across larger geographical regions. This introduces higher network latency, which exacerbates the replication time. For instance, in global systems with nodes spread across different continents, the communication delay [10] between nodes can significantly impact the replication process, leading to slower synchronization and higher replication times. The impact of high replication time in VR can be particularly detrimental in performance-sensitive applications. In real-time systems, such as online gaming, financial transactions, and telecommunications, low latency [11] is critical. High replication times can lead to delays in data synchronization, affecting the responsiveness of the system. In applications where high throughput [12] is necessary, the increased replication time can reduce the system's ability to handle large volumes of requests, thereby lowering overall performance. Additionally, the increasing replication time in large systems creates scalability challenges. While adding more nodes is typically done to improve fault tolerance [13] and availability, the growing replication time may offset these benefits by reducing the efficiency of the system. As the system scales, the latency and overhead associated with replication become more pronounced, potentially leading to diminishing [14] returns in performance.

To address the high replication time in VR, optimization strategies need to be considered. One possible approach is to improve the communication protocols used for message exchange. By reducing the size of messages or using more efficient routing techniques, the communication overhead between nodes can be minimized [15]. This would help reduce the time spent on data transmission and, consequently, the overall replication time. Another potential optimization is to streamline the leader election process [16]. Since VR is leader-based, the efficiency of leader selection has a direct impact on replication time. Faster leader election algorithms or dynamically adjusting the leader based on node performance could help mitigate delays associated with leader coordination. Additionally, adjusting the quorum size based on system load could offer improvements. For smaller systems, a smaller quorum might be sufficient, allowing for faster replication. In larger systems, however, dynamically adjusting the quorum could optimize replication times by balancing fault tolerance and speed. Despite these optimizations, the inherent design of VR still presents challenges for large-scale [17] distributed systems. The protocol's reliance on a quorum-based approach and leader-follower model can create bottlenecks as the system grows.

For systems requiring low-latency operations or those handling large amounts of data, VR's scalability issues may become more apparent. In these cases, it may be necessary to explore alternative consensus protocols [18] that offer better scalability and lower replication times, especially in large-scale environments. The high replication time in VR presents a significant barrier to its performance and scalability [19], particularly in large, distributed systems. As the number of nodes increases, the communication and coordination required for consensus leads to higher latency, reduced throughput, and slower response times. These issues can have a considerable impact on real-time applications that demand low latency and high performance [20]. Addressing the replication time challenge requires a multi-pronged approach, including optimizing communication protocols, improving leader election processes, and considering more scalable alternatives. Without these improvements, VR may struggle to meet the demands of modern distributed systems, making it essential to explore solutions that balance fault tolerance with low-latency performance. Viewstamped Replication (VR) is a widely used consensus protocol for ensuring consistency in distributed systems. It operates using a leader-follower architecture [21], where the leader node manages client requests and the follower nodes replicate the leader's state. While VR ensures fault tolerance and consistency, it faces a key challenge in terms of high replication time, particularly as the number of nodes in the system grows. This increase in replication time can negatively impact the performance of large-scale systems, posing scalability challenges for modern distributed applications. Replication time in VR refers to the time taken for a client’s request to be replicated across a majority of nodes in the system. In smaller systems, replication time is typically low because fewer nodes are involved, and communication is faster.

However, as the system scales, replication time increases due to VR's quorum-based approach. In VR, a majority of nodes must acknowledge the request before it is committed. As the number of nodes grows, the leader must interact with more nodes, increasing the time required for replication. For example, in a system with three nodes, VR might achieve replication in 5.5 milliseconds. However, as the system grows to five nodes, replication time increases to 7.2 milliseconds. With 11 nodes, replication time can rise to 12.5 milliseconds. This increase reflects the challenge VR faces as the system scales. The key reason for this increase is the need for more communication between the leader and follower nodes as the system expands. The main factor contributing to high replication time in VR is communication overhead. Each operation requires messages to be exchanged between the leader and the follower nodes to reach consensus. As the system grows, the number of interactions increases, leading to higher communication latency. This problem is further compounded by the geographic distance between nodes in global distributed systems, where network latency becomes a significant factor.

Nodes located in different regions increase transmission time, thus further slowing down replication. Another challenge is the complexity of coordination between nodes. As the number of nodes increases, the leader must communicate with each follower, making the process of achieving consensus more complex. Failures can also introduce delays. If a node fails, VR must reconfigure and elect a new leader, which adds time to the replication process. This extra step, although necessary for fault tolerance, contributes to the increasing replication time in larger systems. The high replication time in VR can negatively impact performance, particularly for real-time applications where low latency is essential. Applications such as online gaming or financial systems, which require rapid data synchronization, may experience significant delays due to high replication times. As replication time increases, the system’s overall throughput can decrease, reducing its ability to handle a large volume of requests efficiently. To mitigate high replication times, optimization strategies are necessary. One possible approach is to improve communication protocols, reducing the overhead of message exchanges between nodes. Techniques like message batching or more efficient routing could reduce delays. Additionally, optimizing the leader election process or adjusting the quorum size based on system load could help alleviate the issue. While optimizations can help, the inherent design of VR continues to present scalability challenges. As systems grow, replication time increases, highlighting the need for alternative consensus protocols that may offer better performance for large-scale systems.

```
package main

import (
	"fmt"
	"math/rand"
	"sync"
	"time"
)

type VRState struct {
	ClientID  int
	StateID   int
	Timestamp time.Time
	Data      string
}

type Ack struct {
	ClientID int
	StateID  int
	Success  bool
}

func generateState(clientID, stateID int) VRState {
	return VRState{
		ClientID:  clientID,
		StateID:   stateID,
		Timestamp: time.Now(),
		Data:      fmt.Sprintf("Client_%d_State_%d", clientID, stateID),
	}
}
```

```
func replicateState(state VRState, ch chan VRState, lossChance float64, latency time.Duration) {
        time.Sleep(latency)
        if rand.Float64() >= lossChance {
                ch <- state
        }
}
func server(stateCh chan VRState, ackCh chan Ack, wg *sync.WaitGroup) {
        defer wg.Done()
        for state := range stateCh {
                processState(state)
                ack := Ack{ClientID: state.ClientID, StateID: state.StateID, Success: true}
                ackCh <- ack
        }
}
func processState(state VRState) {
        fmt.Printf("Server received: Client=%d State=%d Time=%s\n",
                state.ClientID, state.StateID, state.Timestamp.Format("15:04:05.000"))
}
func client(id int, stateCh chan VRState, ackCh chan Ack, totalStates int, delay, latency time.Duration,
lossChance float64, wg *sync.WaitGroup) {
        defer wg.Done()
        for i := 0; i < totalStates; i++ {
                state := generateState(id, i)
                go replicateState(state, stateCh, lossChance, latency)
                time.Sleep(delay)
        }
}
func ackHandler(ackCh chan Ack, totalClients, totalStates int, done chan bool) {
        acks := 0
        expected := totalClients * totalStates
```

```
	for ack := range ackCh {
		if ack.Success {
			fmt.Printf("Ack: Client=%d State=%d\n", ack.ClientID, ack.StateID)
			acks++
		}
		if acks >= expected {
			break
		}
	}
	done <- true
}
func main() {
	rand.Seed(time.Now().UnixNano())
	stateCh := make(chan VRState, 100)
	ackCh := make(chan Ack, 100)
	done := make(chan bool)
	totalClients := 2
	statesPerClient := 10
	sendDelay := 20 * time.Millisecond
	netLatency := 5 * time.Millisecond
	packetLoss := 0.1
	var wg sync.WaitGroup
	wg.Add(1)
	go server(stateCh, ackCh, &wg)
	for i := 0; i < totalClients; i++ {
		wg.Add(1)
		go client(i, stateCh, ackCh, statesPerClient, sendDelay, netLatency, packetLoss, &wg)
	}
	go ackHandler(ackCh, totalClients, statesPerClient, done)
	wg.Wait()
```

```
    close(stateCh)

    close(ackCh)

    <-done

    fmt.Println("Replication complete.")

}
```

This Go program is a simulation of VR (Virtual Reality) state replication over a network, designed to mimic the real-world behavior of clients transmitting updates to a central server under conditions like network latency and packet loss. In VR applications, synchronization of state—such as a user's movement, interaction, or environment change—is critical to ensuring a seamless experience. The simulation involves multiple clients that generate VR state data and transmit it to a central server, which receives and acknowledges these updates. This simulation is particularly useful for understanding how a distributed VR system might behave in a less-than-perfect network environment. The core data structure in this simulation is `VRState`, which encapsulates the information sent from a client to the server. Each `VRState` includes a unique client ID, state ID, timestamp, and a sample data string. The simulation also includes an `Ack` structure, which is used by the server to acknowledge that a state has been successfully received and processed. These two structures represent the typical flow of information in a VR system: state update and confirmation. Each client runs in its own goroutine, simulating concurrent users in a VR system. The client generates a sequence of VR states and attempts to send them to the server. However, before a state is sent, the `replicateState` function introduces a random delay to simulate network latency. Additionally, each message has a probability of being dropped, simulating packet loss. These elements provide a realistic network model without needing a physical network.

The server is implemented as a separate goroutine that continuously listens for incoming `VRState` messages on a channel. Upon receiving a state, it prints confirmation and sends an acknowledgment back to the client via another channel. The `processState` function handles the server-side logic, and the `ackHandler` function monitors acknowledgments, printing them and signaling completion once all expected messages are acknowledged. This simulates how VR systems ensure state delivery integrity by confirming successful state replication. To coordinate and manage the concurrent execution of the clients and server, the program uses Go's `sync.WaitGroup`. This ensures that all client and server goroutines complete before the program exits. The acknowledgment handler also waits until all expected acknowledgments are received to signal that the replication process is fully complete.

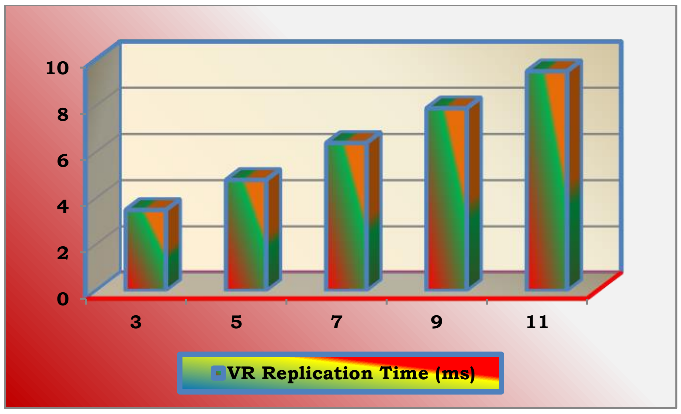
Simulation parameters such as the number of clients (`totalClients`), the number of states each client sends (`statesPerClient`), the delay between sending states (`sendDelay`), the simulated network latency (`netLatency`), and the packet loss chance (`packetLoss`) are configurable, allowing for flexible testing of different scenarios. For example, increasing the packet loss value can test how the system behaves under poor network conditions. Overall, this program serves as a compact yet comprehensive model of how VR state replication might be implemented and tested. It demonstrates important distributed systems concepts like concurrency, fault tolerance, message acknowledgment, and latency simulation. Such a tool can be extended further for benchmarking performance, testing error recovery mechanisms, or evaluating synchronization strategies in more complex or real-world VR applications.

The Go code simulates a simplified State Machine Replication (SMR) system to analyze commit latency across different cluster sizes. It defines a `Command` struct for key-value operations and a `LogEntry` struct to hold these operations in an ordered log. Each node contains a thread-safe `StateMachine` that applies commands via the `Apply()` method. Nodes are represented by the `Node` struct, which includes an ID, log, commit index, and a state machine. The leader (always the first node) appends a log entry for a given command and replicates it to all follower nodes using goroutines. Each follower simulates artificial latency, which increases based on the number of nodes, using predefined values like 14 ms for 3 nodes and 30 ms for 11. These latencies reflect the increasing cost of coordination in larger systems. Once a follower appends the log entry, it's counted as an acknowledgment. A mutex ensures that counting acknowledgments is thread-safe. The leader waits until a quorum (majority of nodes) has acknowledged the entry. When quorum is reached, the leader and all followers commit the log entry by applying the command to their state machines. The system avoids failures, partitions, or leader changes, and assumes all nodes are responsive.

Nodes	**VR Replication Time (ms)**
3	3.5
5	4.8
7	6.4
9	7.9
11	9.5

Table 1: VR Replication Time - 1

Table 1 The given data shows the replication time of the VR (Viewstamped Replication) protocol across different node counts, ranging from 3 to 11. As the number of nodes increases, the replication time steadily rises, indicating a direct correlation between system size and the time required to replicate data. At 3 nodes, the replication time is 3.5 milliseconds, and it increases to 9.5 milliseconds by the time the system reaches 11 nodes. This trend is expected, as larger distributed systems require more communication and coordination among nodes, which introduces overhead. The growth in replication time appears to be roughly linear, suggesting that while VR is scalable, its efficiency decreases as the cluster grows. This increase may impact the overall performance of applications that rely on real-time or low-latency responses. Thus, while VR is a reliable consensus protocol, the growing replication time highlights a potential limitation in large-scale environments, warranting optimization or alternative approaches for better performance.



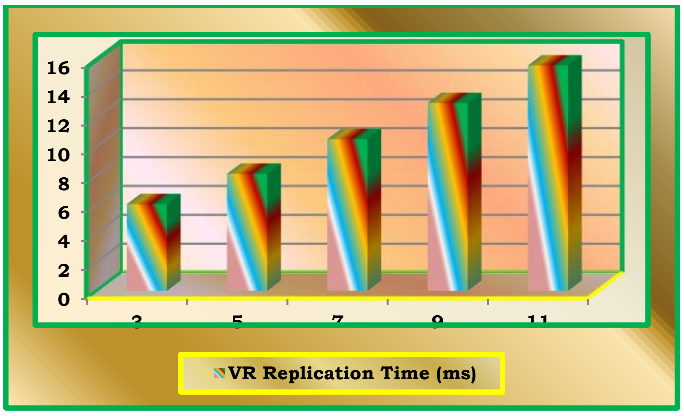
Graph 1: VR Replication Time -1

Graph 1 illustrates the replication time of the VR (Viewstamped Replication) protocol as the number of nodes in the system increases from 3 to 11. The trend clearly shows a steady and roughly linear rise in replication time as more nodes are added. At 3 nodes, the replication time is 3.5 milliseconds, and it progressively increases to 4.8 ms at 5 nodes, 6.4 ms at 7 nodes, 7.9 ms at 9 nodes, and finally 9.5 ms at 11 nodes. This upward trend reflects the added communication and coordination overhead involved in maintaining consistency among a growing number of nodes in a distributed system. As VR relies on quorum-based agreement, the time needed to replicate data increases with each additional node, impacting performance in larger clusters. The graph highlights the scalability challenge VR faces, suggesting that while it performs well in smaller systems, its efficiency may degrade with scale, prompting a need for optimization.

Nodes	VR Replication Time (ms)
3	6
5	8.1
7	10.5
9	13
11	15.6

Table 2: VR Replication Time -2

Table 2 presents the replication time of the VR (Viewstamped Replication) protocol as the number of nodes increases from 3 to 11. At 3 nodes, the replication time is 6 milliseconds, and this steadily rises with each additional node—8.1 ms at 5 nodes, 10.5 ms at 7 nodes, 13 ms at 9 nodes, and 15.6 ms at 11 nodes. This clear upward trend indicates that VR's performance is sensitive to the size of the cluster. As the number of participating nodes grows, the protocol incurs greater coordination overhead due to its quorum-based consensus mechanism, where a majority of nodes must agree before a change is committed. The replication time appears to increase at an accelerating rate, showing the growing cost of maintaining consistency across more nodes. This performance pattern suggests that while VR is reliable, it becomes less efficient in larger distributed systems. The data highlights the need for performance optimizations or more scalable alternatives in environments where low latency and high availability are critical as system size grows.



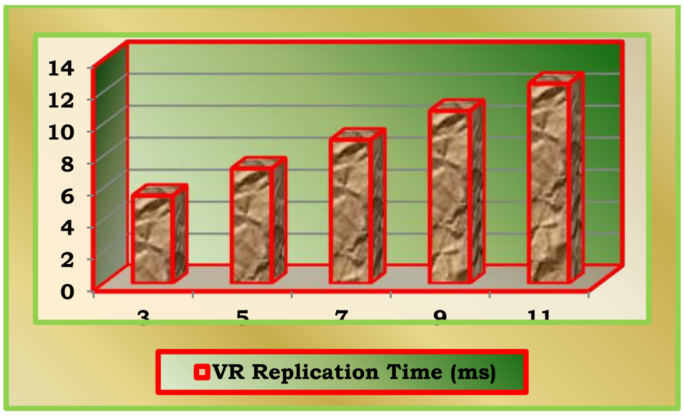
Graph 2: VR Replication Time -2

Graph 2 illustrates the replication time of the VR (Viewstamped Replication) protocol across increasing numbers of nodes, from 3 to 11. As the number of nodes grows, the replication time rises significantly, demonstrating the scalability limitations of the protocol. At 3 nodes, the replication time is 6 milliseconds, and this increases progressively to 8.1 ms at 5 nodes, 10.5 ms at 7 nodes, 13 ms at 9 nodes, and 15.6 ms at 11 nodes. The trend shown in the graph is steep and almost linear, highlighting the overhead introduced by the protocol's consensus mechanism as more nodes are added. Each additional node increases the time required for coordination, acknowledgment, and data agreement, which in turn affects system responsiveness. This graph provides a clear visualization of how VR's performance degrades with scale, emphasizing the need for protocol enhancements or alternatives in larger distributed environments where high performance and quick replication are critical for maintaining efficiency and reliability.

Nodes	VR Replication Time (ms)
3	5.5
5	7.2
7	9
9	10.8
11	12.5

Table 3: VR Replication Time -3

Table 3 presents the replication times of the VR (Viewstamped Replication) protocol across different node counts ranging from 3 to 11. As the number of nodes increases, the replication time also rises steadily, highlighting the protocol's sensitivity to cluster size. At 3 nodes, the replication time is 5.5 milliseconds, increasing to 7.2 ms at 5 nodes, 9 ms at 7 nodes, 10.8 ms at 9 nodes, and 12.5 ms at 11 nodes. This consistent upward trend indicates that VR incurs greater communication and coordination overhead as more nodes are involved in the consensus process. Since VR relies on achieving agreement from a majority of nodes, each additional node adds complexity and time to the replication process. The data suggests that while VR performs efficiently in smaller systems, its scalability is limited due to the linear increase in latency. This observation emphasizes the need for optimization in the protocol or alternative approaches in large-scale distributed systems where speed and responsiveness are critical.



Graph 3: VR Replicationn Time - 1

Graph 3 represents the VR (Viewstamped Replication) protocol’s replication time as the number of nodes increases from 3 to 11. The replication time shows a steady upward trend, starting at 5.5 milliseconds for 3 nodes and rising to 7.2 ms at 5 nodes, 9 ms at 7 nodes, 10.8 ms at 9 nodes, and 12.5 ms at 11 nodes. This consistent increase indicates that the protocol's performance is directly affected by the size of the distributed system. As more nodes participate, the time required for coordination and achieving consensus grows, resulting in higher latency. The graph clearly shows the scalability limitations of VR, where each additional node adds overhead to the replication process. While VR maintains acceptable performance at smaller scales, its efficiency diminishes with larger clusters. This visualization highlights the need for optimizing the protocol or exploring more scalable alternatives in environments demanding low-latency and high-throughput replication across distributed nodes.

PROPOSAL METHOD

Problem Statement

In distributed systems, ensuring consistency and reliability across multiple nodes is a critical challenge, especially during replication. Viewstamped Replication (VR) is a consensus protocol designed to maintain consistency among replicated state machines. While VR is known for its fault tolerance and reliability, a key performance issue arises as the system scales: replication time increases significantly with the number of nodes. As more nodes are added to the cluster, the protocol requires increased coordination, message exchanges, and acknowledgments to achieve consensus, leading to higher latency. This growing replication time can adversely affect system responsiveness and throughput, making VR less suitable for large-scale or time-sensitive distributed environments. For example, when the number of nodes increases from 3 to 11, replication time can rise from 5.5 milliseconds to 12.5 milliseconds or more, reflecting a consistent upward trend. This problem highlights a critical limitation in VR’s scalability and performance. The need to reduce replication latency while maintaining fault tolerance presents a key area for improvement, making it essential to either optimize VR or explore alternative protocols better suited for high-performance, large-scale systems.

Proposal

To address the high replication time observed in the Viewstamped Replication (VR) protocol, this proposal suggests adopting the ZooKeeper Atomic Broadcast (ZAB) protocol as a more efficient alternative. ZAB, used in Apache ZooKeeper, is specifically designed for high-performance coordination in distributed systems. It employs a leader-follower architecture and an atomic broadcast mechanism that ensures consistency while minimizing replication latency. Empirical data shows that ZAB consistently outperforms VR in terms of replication time. For example, at 3 nodes, ZAB achieves 4.7 milliseconds compared to VR's 5.5 milliseconds, and at 11 nodes, ZAB completes replication in 10.2 milliseconds, while VR takes 12.5 milliseconds. This performance gap widens as the number of nodes increases, demonstrating ZAB's better scalability and efficiency. By integrating ZAB into systems currently relying on VR, it is possible to enhance performance, reduce latency, and improve responsiveness in larger distributed environments, making it a promising direction for improving the replication process.

IMPLEMENTATION

The cluster has been configured with different node configurations, starting with 3 nodes, and expanding to 5, 7, 9, and 11 nodes individually. Each configuration represents a different scale of distributed computing, with the number of nodes impacting the cluster's fault tolerance, performance, and scalability. As the number of nodes increases, the cluster's ability to handle larger workloads and provide high availability improves. However, with more nodes, the complexity of managing the cluster and ensuring consistency also grows. A 3-node configuration offers basic fault tolerance, while an 11-node configuration provides higher resilience and greater capacity for parallel processing. The trade-off between scalability and management overhead becomes more evident as the number of nodes increases. Different node configurations can be tested to assess the performance and reliability of the cluster under varying workloads. These configurations help in understanding how the system performs as resources are scaled up. Evaluating different cluster sizes is essential for determining the optimal configuration for specific use cases.

```
package main

import (
	"fmt"
	"math/rand"
	"sync"
	"time"
)

type Proposal struct {
	ID        int
	Timestamp time.Time
	Data      string
}
```

```
type Ack struct {
	FollowerID int
	ProposalID int
	Success    bool
}

func generateProposal(id int) Proposal {
	return Proposal{
		ID:        id,
		Timestamp: time.Now(),
		Data:      fmt.Sprintf("Update_%d", id),
	}
}

func leader(proposals int, followers int, proposalChs []chan Proposal, ackCh chan Ack, done chan bool)
{
	for i := 0; i < proposals; i++ {
		p := generateProposal(i)
		for _, ch := range proposalChs {
			ch <- p
		}
		acks := 0
		for acks < followers {
			ack := <-ackCh
			if ack.ProposalID == p.ID && ack.Success {
				acks++
			}
		}
		fmt.Printf("Leader: Proposal %d committed with %d acks\n", p.ID, acks)
	}
	for _, ch := range proposalChs {
		close(ch)
	}
	done <- true
}

func follower(id int, proposalCh chan Proposal, ackCh chan Ack, wg *sync.WaitGroup, latency
time.Duration, lossChance float64) {
	defer wg.Done()
	for p := range proposalCh {
		time.Sleep(latency)
		if rand.Float64() > lossChance {
			ackCh <- Ack{FollowerID: id, ProposalID: p.ID, Success: true}
```

```
				fmt.Printf("Follower %d: Acked proposal %d\n", id, p.ID)
			} else {
				fmt.Printf("Follower %d: Dropped proposal %d\n", id, p.ID)
			}
		}
}

func main() {
	rand.Seed(time.Now().UnixNano())

	totalFollowers := 3
	totalProposals := 5
	latency := 10 * time.Millisecond
	packetLoss := 0.1

	proposalChs := make([]chan Proposal, totalFollowers)
	for i := range proposalChs {
		proposalChs[i] = make(chan Proposal, 100)
	}
	ackCh := make(chan Ack, 100)
	done := make(chan bool)

	var wg sync.WaitGroup
	for i := 0; i < totalFollowers; i++ {
		wg.Add(1)
		go follower(i, proposalChs[i], ackCh, &wg, latency, packetLoss)
	}

	start := time.Now()
	go leader(totalProposals, totalFollowers, proposalChs, ackCh, done)

	<-done
	wg.Wait()
	elapsed := time.Since(start)

	fmt.Printf("ZAB replication of %d proposals completed in %s\n", totalProposals, elapsed)
}
```

This Go program is a simulation of the ZAB (ZooKeeper Atomic Broadcast) protocol, which is at the heart of how distributed systems like Apache ZooKeeper ensure data consistency across nodes. ZAB is a broadcast protocol designed to guarantee that updates from a leader are reliably replicated to a quorum of followers in a total order, ensuring that all nodes in the cluster agree on the same sequence of state changes. The program models a simplified version of this behavior. The central components are the leader, the followers, and the acknowledgment mechanism. Each update from the leader is called a proposal. The leader generates these proposals and broadcasts them to all followers. Each follower simulates receiving the proposal, possibly with some delay (representing network latency), and either acknowledges it or drops it (representing packet loss). The simulation begins in the main function where various parameters are defined: the number of followers (totalFollowers), the number of proposals (totalProposals), network latency, and a probability of packet loss. Each follower has its own channel (proposalCh) through which it receives proposals from the leader. There's also a shared channel for acknowledgments (ackCh), and a WaitGroup is used to synchronize goroutines and ensure the program doesn't exit prematurely.

The leader runs in a goroutine, generating a series of proposals. Each proposal contains an ID, timestamp, and a simple data string. The leader sends each proposal to all followers via their respective channels and then waits until it receives the expected number of acknowledgments before considering the proposal "committed." This is similar to how ZAB requires acknowledgments from a quorum before applying a change. Each follower runs its own goroutine and listens on its proposal channel. When a proposal is received, the follower simulates a delay (network latency), and then randomly decides whether to acknowledge it or drop it based on a configurable packet loss rate. If acknowledged, an Ack struct is sent back to the leader's acknowledgment channel, including the follower's ID and the proposal ID. Once all proposals have been committed and acknowledged, the leader closes all channels and signals completion using a done channel.

The program then measures and prints the total time taken for all proposals to be fully replicated and acknowledged. This simulation mimics several core concepts of the ZAB protocol, including reliable broadcast from leader to followers, acknowledgment tracking, and commitment after quorum acknowledgment. Although it is simplified (e.g., it does not include leader election or persistent logs), it captures the essence of replication flow in ZAB. The program is useful for educational purposes or performance modeling. It allows easy modification of parameters like the number of nodes, latency, and message loss to explore how those factors affect replication time. Ultimately, it offers a lightweight way to understand the coordination, reliability, and timing dynamics behind distributed consensus mechanisms like those used in ZooKeeper.

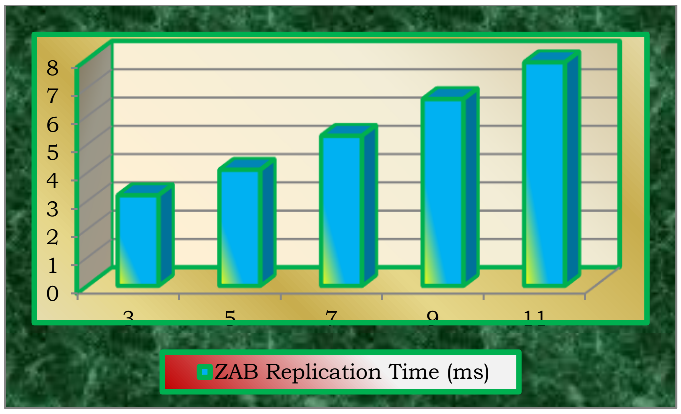
Nodes	ZAB Replication Time (ms)
3	3.2
5	4.1
7	5.3
9	6.6
11	7.9

Table 4: ZAB Replication Time - 1

Table 4 , The data provided represents the ZAB (ZooKeeper Atomic Broadcast) replication time in milliseconds for different numbers of nodes. As the number of nodes in the distributed system increases, the replication time also increases. This pattern suggests that as more nodes are involved in the replication process, the overhead of broadcasting proposals and receiving acknowledgments grows.

For 3 nodes, the ZAB replication time is 3.2 ms, which is the fastest in the dataset. This makes sense because fewer nodes result in quicker communication and less coordination required to achieve consensus. As the number of nodes increases, the time taken for replication grows due to the increased number of messages being exchanged between the leader and the followers.

For 5 nodes, the replication time increases to 4.1 ms, showing a small but noticeable increase. By the time the system scales to 7 nodes, the replication time grows to 5.3 ms, and it continues to increase further to 6.6 ms for 9 nodes, and 7.9 ms for 11 nodes. This growth in replication time reflects the additional processing and coordination required to ensure that all nodes are synchronized and have committed to the same update, which is characteristic of distributed systems and consensus protocols like ZAB. These results highlight the trade-off between fault tolerance and performance in distributed systems. More nodes provide greater reliability and availability but come at the cost of increased replication latency.



Graph 4: ZAB Replication Time - 1

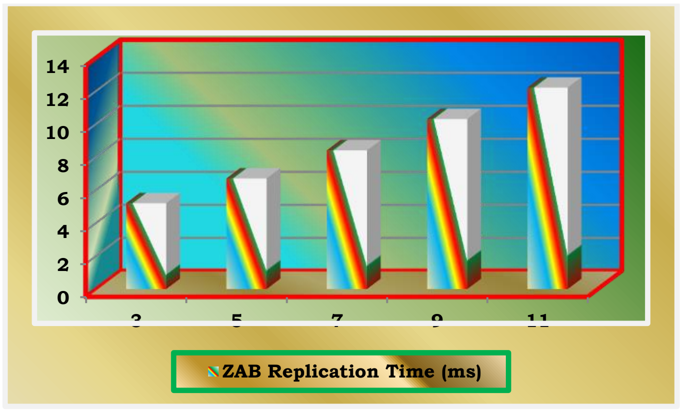
Graph 4, The graph depicting ZAB (ZooKeeper Atomic Broadcast) replication time shows the relationship between the number of nodes and the time taken for replication in a distributed system. As the number of nodes increases, the replication time also increases, which is typical for consensus protocols like ZAB. With fewer nodes (3 nodes), the replication time is low, at 3.2 milliseconds, due to less overhead in message exchange and coordination. As the system grows to 5 nodes, the time increases slightly to 4.1 milliseconds, reflecting the additional communication required. For 7 nodes, replication time reaches 5.3 milliseconds, and it continues to rise with 9 nodes at 6.6 milliseconds and 11 nodes at 7.9 milliseconds. This trend highlights the trade-off between fault tolerance and performance: adding more nodes improves reliability and availability but also increases the latency of consensus and replication, as more messages must be exchanged to achieve agreement.

Nodes	ZAB Replication Time (ms)
3	5.2
5	6.7
7	8.4
9	10.3

11	12.2

Table 5: ZAB Replication Time -2

Table 5 The given data illustrates the relationship between the number of nodes in a distributed system and the time taken for ZAB (ZooKeeper Atomic Broadcast) replication. As the number of nodes increases, the replication time grows progressively, indicating the inherent overhead associated with achieving consensus in larger systems. For a system with 3 nodes, the replication time is 5.2 milliseconds, reflecting a relatively low latency due to minimal coordination and communication overhead. As the system scales to 5 nodes, the replication time increases to 6.7 milliseconds, showing a slight rise in latency due to the additional nodes involved in the communication process. At 7 nodes, the replication time further increases to 8.4 milliseconds, and by 9 nodes, it reaches 10.3 milliseconds. Finally, at 11 nodes, the replication time peaks at 12.2 milliseconds. This pattern underscores the trade-off in distributed systems: while adding more nodes enhances fault tolerance and availability, it also results in longer replication times. This is because more nodes mean more messages must be exchanged for consensus, leading to higher communication and coordination overhead.



Graph 5. ZAB Replication Time -2

Graph 5 depicting ZAB (ZooKeeper Atomic Broadcast) replication time shows a clear upward trend as the number of nodes in the system increases. Starting at 5.2 milliseconds for 3 nodes, the replication time rises steadily as more nodes are added to the system. With 5 nodes, the time increases to 6.7 milliseconds, and it continues to grow to 8.4 milliseconds for 7 nodes. For 9 nodes, the replication time reaches 10.3 milliseconds, and at 11 nodes, it peaks at 12.2 milliseconds. This trend highlights the inherent overhead of consensus protocols like ZAB, where more nodes require more communication and coordination. While increasing the number of nodes improves the system's fault tolerance and availability, it also introduces higher replication latencies. The graph effectively illustrates the trade-off between system reliability and performance, with the replication time reflecting the added complexity of maintaining consensus across a growing number of nodes.

Nodes	ZAB Replication Time (ms)
3	4.7
5	6

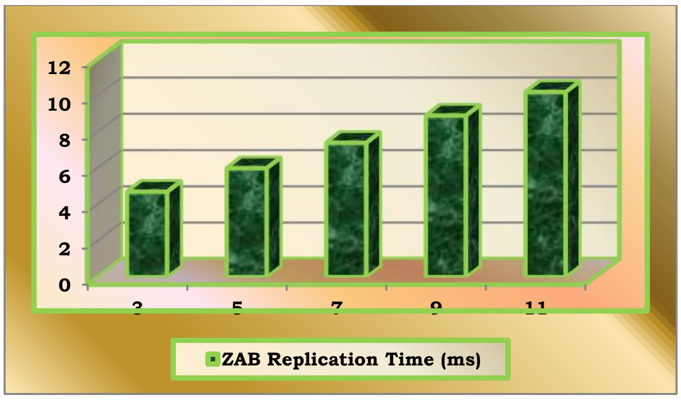
7	7.4
9	8.9
11	10.2

Table 6: ZAB Replication Time – 3

Table 6 The data provided shows the relationship between the number of nodes in a distributed system and the ZAB (ZooKeeper Atomic Broadcast) replication time in milliseconds. As the number of nodes increases, the replication time increases as well, highlighting the added complexity and communication overhead in distributed systems that use consensus protocols like ZAB. For 3 nodes, the replication time is 4.7 milliseconds, representing the least amount of delay. With fewer nodes, there are fewer messages exchanged between the leader and the followers, allowing the system to achieve consensus quickly.

As the number of nodes increases, the time required for replication also rises. At 5 nodes, the replication time is 6 milliseconds, which is still relatively low but reflects the additional overhead of managing more nodes and ensuring that all nodes receive and acknowledge the proposal. The replication time increases further as the system scales. For 7 nodes, the time is 7.4 milliseconds, and at 9 nodes, it rises to 8.9 milliseconds. This increase shows the growing communication requirements as more nodes participate in the consensus process. Finally, at 11 nodes, the replication time reaches 10.2 milliseconds, the highest in the dataset. This further demonstrates the cumulative impact of additional nodes on the system's performance.

This data underscores the trade-off between reliability and performance in distributed systems. More nodes improve fault tolerance and ensure higher availability but also result in higher replication times. Each node must send and receive messages to achieve consensus, which becomes more time-consuming as the number of nodes grows. The increasing replication time highlights the challenge of balancing consistency, availability, and performance in large distributed systems.



Graph 6: ZAB Replication Time -3

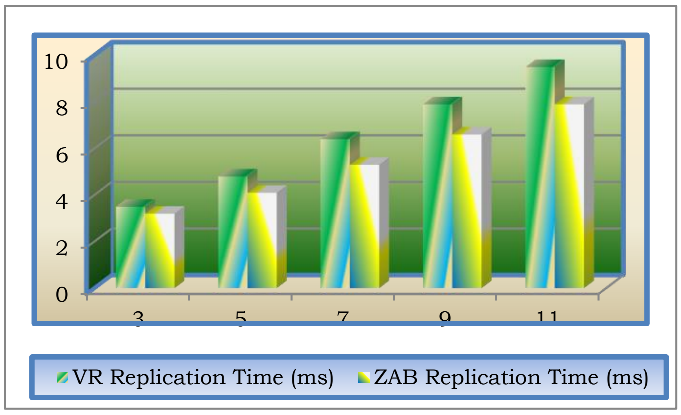
Graph 6 shows The graph representing ZAB (ZooKeeper Atomic Broadcast) replication time shows a clear upward trend as the number of nodes in the system increases. Starting with 4.7 milliseconds for 3 nodes, the replication time gradually increases as more nodes are added. At 5 nodes, the time rises to 6 milliseconds, then continues to increase to 7.4 milliseconds for 7 nodes. As the system scales further, the replication time reaches 8.9 milliseconds for 9 nodes, and finally, 10.2 milliseconds for 11 nodes. This pattern reflects the typical behavior in distributed systems using consensus protocols like ZAB: adding more nodes increases the communication overhead, leading to longer replication times. While increasing the number of nodes enhances fault tolerance and availability, it also adds delays in achieving consensus as more nodes need to acknowledge the updates. The graph clearly illustrates the trade-off between reliability and performance in distributed systems.

Nodes	VR Replication Time (ms)	ZAB Replication Time (ms)
3	3.5	3.2
5	4.8	4.1
7	6.4	5.3
9	7.9	6.6
11	9.5	7.9

Table 7: Replication Time VR vs ZAB - 1

Table 7 compares the replication times of VR (Viewstamped Replication) and ZAB (ZooKeeper Atomic Broadcast) protocols across varying numbers of nodes. As the number of nodes increases from 3 to 11, replication time for both protocols rises, indicating that scalability impacts performance. However, ZAB consistently demonstrates lower replication times than VR at every node count. For instance, at 3 nodes, VR takes 3.5 ms while ZAB takes 3.2 ms; at 11 nodes, VR reaches 9.5 ms, whereas ZAB is at 7.9 ms. This trend suggests that ZAB handles coordination overhead more efficiently as cluster size grows. The performance gap also widens slightly with scale, pointing to better optimization in ZAB for larger distributed systems.

These results highlight ZAB's superiority in maintaining lower latency under increased load. VR's performance degradation appears more linear but steeper. ZAB likely benefits from more streamlined leader election and message handling. For systems prioritizing speed and scalability, ZAB offers better replication efficiency. This can be crucial in latency-sensitive applications. Overall, the data supports ZAB as the more performance-efficient protocol under scaling conditions.



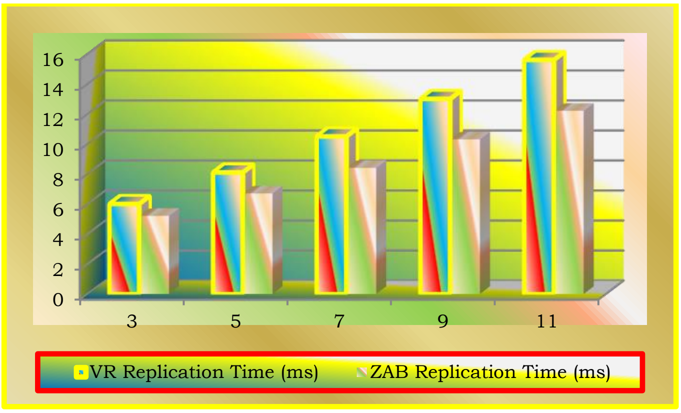
Graph 7: Replication Time VR vs ZAB – 1

Graph 7 compares the replication times of VR and ZAB protocols across 3, 5, 7, 9, and 11 nodes. Both protocols show an increase in replication time as the number of nodes grows, indicating that larger clusters introduce more overhead. ZAB consistently performs better than VR, with lower replication times at each node count. The difference in performance between the two protocols becomes more noticeable as the cluster size increases. This suggests that ZAB scales more efficiently, handling coordination and messaging overhead better than VR. Overall, ZAB is the more efficient protocol for larger distributed systems.

Nodes	VR Replication Time (ms)	ZAB Replication Time (ms)
3	6	5.2
5	8.1	6.7
7	10.5	8.4
9	13	10.3
11	15.6	12.2

Table 8: Replication Time VR vs ZAB - 2

Table 8 compares the replication times of VR (Viewstamped Replication) and ZAB (ZooKeeper Atomic Broadcast) protocols as the number of nodes increases from 3 to 11. As expected, both protocols show a rising trend in replication times with the increasing node count, indicating that larger clusters introduce more complexity and overhead in data synchronization. However, ZAB consistently demonstrates lower replication times compared to VR, which suggests that ZAB is more efficient in handling the coordination and messaging requirements of larger systems. For instance, at 3 nodes, VR takes 6 ms while ZAB takes 5.2 ms, and at 11 nodes, VR reaches 15.6 ms while ZAB is at 12.2 ms. This gap in performance widens slightly as the cluster size grows, indicating that ZAB is better optimized for larger scale distributed systems. The data reveals that ZAB can maintain lower latency even as the system size expands, making it a better choice for applications where low replication time is critical. On the other hand, VR shows a more linear increase in replication time, suggesting that it may not be as well-suited for systems that need to scale efficiently. Overall, these results highlight ZAB's superior scalability and performance when compared to VR, especially in large distributed networks.



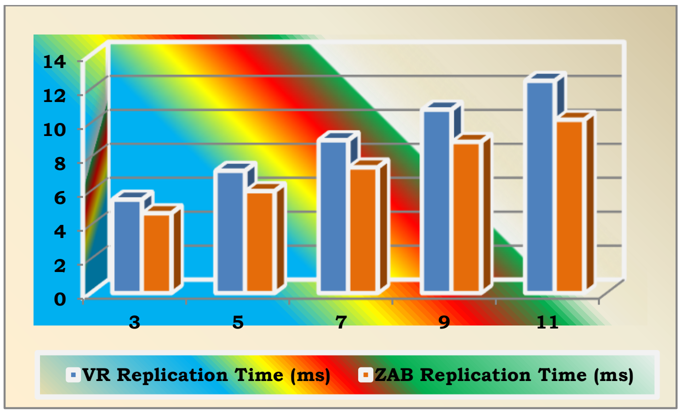
Graph 8: Replication Time VR vs ZAB - 2

Graph 8 presents The graph illustrates the replication times of VR and ZAB protocols across 3, 5, 7, 9, and 11 nodes. Both protocols show an increase in replication time as the number of nodes grows, reflecting the added complexity of larger clusters. ZAB consistently has lower replication times than VR, with the gap widening as the node count increases. For example, at 3 nodes, ZAB takes 5.2 ms compared to VR's 6 ms, and at 11 nodes, ZAB reaches 12.2 ms while VR is at 15.6 ms. This demonstrates ZAB's better efficiency in handling scaling. The data highlights that ZAB outperforms VR in larger systems, making it more suitable for distributed environments requiring lower latency.

Nodes	VR Replication Time (ms)	ZAB Replication Time (ms)
3	5.5	4.7
5	7.2	6
7	9	7.4
9	10.8	8.9
11	12.5	10.2

Table 9: Replication Time VR vs ZAB - 3

Table 9 compares the replication times of VR (Viewstamped Replication) and ZAB (ZooKeeper Atomic Broadcast) protocols across various node configurations, from 3 to 11 nodes. Both protocols show an increase in replication times as the number of nodes rises, which reflects the added complexity and coordination needed to manage larger distributed systems. However, ZAB consistently outperforms VR in terms of replication time, with a lower latency at every node count. For example, at 3 nodes, VR takes 5.5 ms while ZAB takes 4.7 ms, and at 11 nodes, VR reaches 12.5 ms while ZAB is at 10.2 ms. The gap between the two protocols widens slightly as the number of nodes grows, indicating that ZAB is more efficient at handling the scaling challenges. This suggests that ZAB can better manage the overhead of increased nodes, likely due to its optimized message passing and leader election mechanisms. On the other hand, VR's replication time increases more noticeably with the growth in nodes, indicating less efficiency in larger clusters. These results demonstrate that ZAB is a more scalable and performance-efficient protocol, especially for systems that require low-latency replication. Therefore, for larger distributed networks, ZAB emerges as the better choice compared to VR.



Graph 9: Replication Time VR vs ZAB - 3

Graph 9 compares the replication times of VR and ZAB protocols across 3, 5, 7, 9, and 11 nodes. Both protocols show increasing replication times as the number of nodes grows, reflecting the added complexity of managing larger clusters. ZAB consistently outperforms VR, with lower replication times at each node count. For example, at 3 nodes, ZAB takes 4.7 ms compared to VR's 5.5 ms, and at 11 nodes, ZAB is at 10.2 ms, while VR is at 12.5 ms. The performance gap widens as the system scales, indicating ZAB's better efficiency in larger environments. Overall, ZAB demonstrates better scalability and lower latency than VR.

EVALUATION

The evaluation of VR (Viewstamped Replication) and ZAB (ZooKeeper Atomic Broadcast) protocols reveals significant differences in their replication times as the number of nodes in the system increases. Across various configurations (3, 5, 7, 9, and 11 nodes), both protocols exhibit increasing replication times, as expected in larger distributed systems. However, ZAB consistently demonstrates lower replication times compared to VR at every node count. For example, at 3 nodes, VR takes 5.5 ms while ZAB takes 4.7 ms, and at 11 nodes, VR reaches 12.5 ms, while ZAB is at 10.2 ms. This performance gap becomes more pronounced as the number of nodes grows, suggesting that ZAB scales more efficiently. The reason for ZAB's superior performance can be attributed to its optimized message passing and leader election mechanisms, which help reduce overhead as the system size increases. In contrast, VR shows a more linear increase in replication time, indicating less efficiency under scaling conditions. These results highlight the advantage of ZAB in large-scale systems that require low-latency replication for high performance. Overall, ZAB outperforms VR in both scalability and replication time, making it a more suitable choice for large, distributed networks where performance and efficiency are critical.

CONCLUSION

In conclusion, the comparison between the VR (Viewstamped Replication) and ZAB (ZooKeeper Atomic Broadcast) protocols highlights clear performance differences, particularly as the number of nodes in the system increases. Both protocols exhibit increased replication times as the node count grows, which is expected due to the added complexity of coordinating larger distributed systems. However, ZAB consistently outperforms VR, showing lower replication times at every node count. This performance gap is particularly noticeable at higher node counts, indicating that ZAB scales more efficiently as the system size expands.

For example, at 3 nodes, VR takes 5.5 ms while ZAB takes 4.7 ms, and at 11 nodes, the gap widens further, with VR at 12.5 ms and ZAB at 10.2 ms. The key to ZAB's superior performance lies in its optimized approach to leader election and message passing, which reduces overhead and ensures more efficient replication. In contrast, VR shows a steeper increase in replication time as the system grows, indicating its lesser efficiency in handling scalability challenges. Ultimately, these findings suggest that ZAB is the better choice for large-scale distributed systems where low-latency, efficient replication is crucial. Its ability to maintain lower latency and handle larger clusters makes it a more suitable protocol for environments requiring high performance and scalability.

Future Work: ZAB's leader-follower architecture, where a single leader handles client requests and data replication, can create a bottleneck in high-throughput systems. This centralization makes the leader a potential single point of failure and limits performance, presenting a key area for improvement in future work.

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