International Journal on Science and Technology (IJSAT)

E-ISSN: 2229-7677 ● Website: www.ijsat.org ● Email: editor@ijsat.org

Throughput Aware Replica Selection for Multi Region Distributed Systems

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Abstract:
Modern Multi region distributed systems rely on data replication to ensure availability, fault tolerance, and low access latency. Replica selection plays a critical role in determining system performance, particularly under varying workloads and heterogeneous regional capacities. As a result, replicas with limited capacity may become overloaded, while higher capacity replicas remain underutilized, leading to inefficient request handling and reduced system throughput. In multi region environments, replicas operate under diverse network conditions, hardware configurations, and workload characteristics. Static routing decisions amplify these disparities by treating all replicas as equivalent, regardless of their ability to sustain incoming request rates. Under high load, this imbalance causes request queues to grow at weaker replicas, increasing processing delays and limiting overall throughput. At the same time, stronger replicas are unable to compensate due to rigid routing policies. As the number of regions increases, these inefficiencies become more pronounced, restricting scalability despite the availability of additional replicas. This paper addresses the problem of throughput degradation in multi region distributed systems by focusing on replica selection behavior. The study emphasizes the importance of aligning request distribution with the runtime throughput characteristics of replicas. By examining throughput trends across different region counts, the work highlights how baseline selection strategies constrain performance when replica capacities vary. The paper concentrates on throughput as the primary performance metric and discusses the need for selection mechanisms that reflect actual processing capability. Addressing replica selection from a throughput perspective enables more effective utilization of distributed resources and supports scalable operation in geographically distributed systems.

Keywords: Throughput, Replicas, Multiregion, Distribution, Scalability, Routing, Capacity, Utilization, Performance, Replication, Cloud, Geography, Efficiency, Load, Workloads.

INTRODUCTION

Multi region distributed systems form the backbone of modern cloud platforms, supporting applications that demand high availability, fault tolerance [1], and global accessibility. Data replication across geographically separated regions is a common strategy used to meet these requirements. By maintaining multiple replicas of data, systems can tolerate failures, serve users closer to their locations, and scale to handle increasing request volumes. However, the effectiveness of replication depends not only on the number of replicas but also on how client requests are distributed among them. Replica selection is a critical component of request routing [2] in multi region environments. It determines which replica processes an incoming request and directly influences system throughput and resource utilization. Traditional replica selection strategies often rely on static policies such as round robin routing, random selection, or simple proximity based rules. Multi region systems operate under heterogeneous conditions. Differences in hardware configurations, background workloads, network conditions, and regional resource constraints result in replicas exhibiting varying throughput capacities. Some replicas [3] can process requests at significantly higher rates, while others become bottlenecks under load. Static replica selection mechanisms fail to adapt to these variations, frequently routing excessive traffic to lower capacity replicas. Additional replicas introduce greater diversity in capacity and performance, making uniform routing

increasingly inefficient. Instead of improving scalability, adding more regions can result in diminishing throughput gains due to poor request distribution. This behavior undermines the fundamental motivation for multi region deployment. Improving throughput [4] in such environments requires reconsidering how replicas are selected for request processing. Throughput aware replica selection focuses on aligning request routing decisions with the actual processing capabilities of replicas. By considering how much load a replica can handle effectively, systems can better utilize available resources, reduce congestion at weaker replicas, and sustain higher overall throughput. Understanding and addressing these challenges is essential for building scalable and efficient multi region distributed systems.

LITERATURE REVIEW

Distributed systems have evolved significantly with the rapid growth of cloud computing, global scale applications, and geographically dispersed user bases. To meet the requirements of availability, fault tolerance, and performance, modern systems commonly adopt multi region architectures where data is replicated across multiple geographic locations. Replication ensures continuity of service during failures and allows requests to be served closer to users. However, replication alone does not guarantee performance improvements. How requests are routed to replicas plays a crucial role in determining system throughput and scalability. Replica selection refers to the process of choosing one replica among many to serve a client request. Early distributed systems treated replicas as homogeneous entities [5], assuming equal processing capacity and uniform performance characteristics. Under this assumption, simple routing policies such as round robin, random selection, or hash based routing were sufficient.

These techniques aimed to distribute load evenly across replicas and were effective in small scale or controlled environments. However, as systems expanded across regions with heterogeneous infrastructure, this assumption became increasingly unrealistic. Research has consistently shown that replicas in different regions experience varied performance due to differences in hardware, network conditions, background workloads, and resource contention. A replica deployed in a resource rich region may sustain a much higher request rate than one operating under constrained conditions. Despite this, static replica selection mechanisms continue to treat all replicas equally. This mismatch between routing policy and actual replica capability leads to inefficient resource utilization and reduced system throughput. Several studies have analyzed the impact of static replica selection on system performance. These works demonstrate that uniform request distribution often overloads weaker replicas while leaving stronger replicas underutilized. Overloaded replicas [6] experience increased queue lengths, higher processing delays, and elevated request drop rates. As a result, overall throughput is limited by the slowest replicas rather than the aggregate capacity of the system. This phenomenon becomes more severe as the number of regions increases, since heterogeneity tends to grow with scale.

To address load imbalance, researchers introduced dynamic replica selection strategies that adapt routing decisions based on observed load or response time. Load based selection mechanisms redirect traffic away from heavily loaded replicas toward less utilized ones. While these approaches improve fairness, they often react slowly to changes and do not directly optimize throughput. Moreover, load metrics alone may not accurately reflect a replica's processing capacity. A lightly loaded replica may still have low throughput capability due to hardware limitations or network bottlenecks. Latency aware replica selection has also been explored extensively. These approaches prioritize replicas that offer lower response times or shorter network paths. Latency optimization is particularly valuable for user facing applications where responsiveness is critical. However, latency [7] optimized routing does not necessarily maximize throughput. In some cases, low latency replicas may become overwhelmed under high request rates, causing throughput degradation. Literature comparing latency aware and throughput aware objectives highlights a fundamental tradeoff between responsiveness and capacity utilization.

Several works have examined throughput as an implicit outcome rather than a direct optimization goal. These studies evaluate how different routing strategies affect throughput under varying workloads. Results often indicate that systems designed without explicit throughput awareness struggle to scale efficiently. As load increases, throughput plateaus prematurely due to bottlenecks at specific replicas. These findings underscore the need to treat throughput as a first class metric in replica selection design. Multi region environments further complicate replica selection due to cross region traffic costs and variable network conditions. Routing requests across regions incurs additional delays and bandwidth consumption. Some studies propose minimizing cross region [8] traffic to improve performance, but they often prioritize locality over capacity. This can lead to situations where nearby replicas with limited throughput become overloaded while distant high capacity replicas remain idle. The literature reveals that balancing locality and throughput remains an open challenge.

Recent research has started to explore capacity aware routing, where replicas are characterized by their processing limits. These approaches estimate or measure the throughput capability of each replica and use this information to guide request distribution. While promising, many existing solutions rely on static capacity models or offline profiling, which may not reflect real time conditions. Dynamic throughput variations caused by workload changes or shared resource contention are often ignored. Another line of work investigates adaptive routing mechanisms that continuously monitor performance metrics. These systems adjust replica selection decisions based on observed throughput [9] trends. However, frequent monitoring and adaptation introduce additional overhead and complexity. Some studies report that aggressive adaptation can lead to oscillations, where routing decisions fluctuate excessively, destabilizing the system. This highlights the importance of carefully designing throughput aware mechanisms that balance responsiveness with stability.

Large scale evaluations of replica selection strategies demonstrate that throughput aware routing consistently outperforms static and latency focused approaches under high load. Experiments across varying region counts show that throughput aware selection better utilizes available capacity and delays the onset of saturation. These results are particularly significant in systems where workloads are unpredictable and demand fluctuates rapidly. Despite these advances, the literature identifies several unresolved issues. Accurately measuring throughput capacity in real time remains challenging, especially in shared cloud environments. Integrating throughput awareness with existing routing frameworks [10] without introducing significant overhead is another concern. Additionally, many studies evaluate throughput in isolation, without considering interactions with fault tolerance and consistency requirements. In summary, existing research clearly demonstrates that replica selection has a profound impact on throughput in multi region distributed systems. Static and latency oriented approaches are insufficient in heterogeneous environments where replica capabilities vary widely. While early efforts toward throughput aware selection show promise, there remains a need for lightweight, scalable mechanisms that align request distribution with runtime capacity. Addressing these gaps is essential for improving scalability and efficiency in modern distributed systems.

Modern multi region distributed systems operate under highly dynamic workloads where request arrival rates vary significantly across time and geography. User activity patterns, diurnal effects, flash crowds, and background system processes introduce constant fluctuations in demand. Prior studies highlight that replica selection mechanisms must function effectively under such variability to sustain high throughput. Static routing strategies struggle in these conditions because they do not adapt to shifting workload distributions. When traffic surges in specific regions, replicas with limited processing capacity quickly become saturated, causing queues to build and throughput to decline. Meanwhile, replicas in less affected regions remain underutilized, resulting in inefficient use of available resources. Research examining adaptive routing under dynamic workloads shows that delayed or reactive adjustments often fail to prevent

throughput degradation. Systems that wait for overload signals [11] before redirecting traffic experience performance loss during the detection and response interval. This has motivated interest in selection strategies that consider sustained processing capability rather than instantaneous load. However, predicting workload evolution remains difficult, and overly aggressive adaptation can introduce instability.

The literature emphasizes the importance of stable yet responsive replica selection mechanisms that can accommodate workload variability without excessive oscillation. Scalability is another recurring theme in the study of multi region distributed systems. Adding replicas across additional regions is expected to improve throughput by increasing aggregate processing [12] capacity. However, empirical evaluations demonstrate that throughput gains are often sublinear when replica selection ignores capacity heterogeneity. As systems scale, differences in hardware, virtualization overhead, and network bandwidth become more pronounced. Without throughput awareness, routing decisions increasingly direct traffic to replicas that cannot effectively contribute to system capacity, causing throughput to plateau prematurely. Several large scale experimental studies confirm that throughput aware routing enables better scalability by distributing requests in proportion to replica capability. Instead of bottlenecking at weaker replicas, systems can exploit higher capacity replicas more effectively, delaying saturation and improving aggregate throughput. These findings suggest that throughput awareness is not merely an optimization but a requirement for scalable operation in heterogeneous [13] multi region environments. The benefit becomes increasingly evident as region count grows, reinforcing the relevance of throughput oriented replica selection for global systems.

Accurate measurement of replica throughput remains a central challenge discussed across the literature. Throughput is influenced by multiple interacting factors including processor availability, memory pressure, disk performance, network bandwidth, and interference from co located workloads. Many systems rely on indirect metrics such as request completion rate, queue length, or response time to infer throughput capacity. While these indicators provide useful signals, they often lag behind real performance changes or fail to capture sudden degradation caused by transient resource contention. Some studies propose active probing techniques that periodically test replica performance [14] by injecting synthetic requests. Although these methods can provide accurate measurements, they introduce additional load and may interfere with normal operation. Passive monitoring approaches reduce overhead but depend on sufficient traffic volume to generate reliable estimates. The literature consistently identifies a tradeoff between measurement accuracy and monitoring cost, noting that lightweight and timely throughput estimation remains an open research problem. Comparative analyses between latency driven and throughput driven routing approaches reveal important distinctions. Latency aware replica selection has been widely adopted due to its direct impact on user perceived performance. However, research shows that minimizing latency [15] does not guarantee high throughput, particularly under heavy load. Low latency replicas may become congested quickly, reducing their effective processing rate and limiting overall throughput. In contrast, throughput aware routing may direct requests to replicas with slightly higher latency if they can sustain higher request rates. These studies highlight that latency and throughput are related but distinct objectives, and optimizing one does not necessarily optimize the other.

The interaction between replica selection and system level mechanisms such as fault tolerance and consistency has also been explored. Throughput aware routing may influence the distribution of read and write operations across replicas, affecting replication protocols and quorum participation [16]. Some studies caution that concentrating traffic on high throughput replicas may increase their involvement in coordination operations, potentially impacting write performance or recovery behavior. This underscores the need to consider throughput aware selection within the broader system design rather than as an isolated component. Despite growing interest in throughput oriented replica selection, the literature reveals several

unresolved limitations. Many existing approaches rely on coarse grained or static throughput models that do not capture rapid performance changes. Others introduce significant monitoring complexity, making them difficult to deploy in production systems. Furthermore, comprehensive evaluations across diverse region counts and workload intensities remain limited. These gaps motivate further investigation into scalable, lightweight replica selection mechanisms [17] that directly align request routing with runtime throughput capacity while maintaining stability and low overhead.

Another important aspect highlighted in the literature is the impact of regional resource heterogeneity on long term throughput behavior. Multi region deployments often span cloud providers, availability zones, and infrastructure generations. As a result, replicas differ not only in raw processing power but also in their susceptibility to contention from colocated [18] services. Studies note that background activities such as maintenance operations, autoscaling events, and shared network usage can temporarily reduce replica throughput. Static replica selection mechanisms are unable to accommodate such transient degradation, leading to routing decisions that persistently favor replicas that no longer perform optimally [19]. This mismatch further contributes to throughput loss during prolonged execution. Researchers have also examined the relationship between throughput aware routing and fairness. Some works argue that prioritizing high throughput replicas may lead to uneven utilization if weaker replicas are consistently avoided. However, empirical evaluations demonstrate that fairness at the replica level does not necessarily translate to fairness at the system level. Ensuring uniform load distribution across replicas can paradoxically reduce aggregate throughput by forcing requests onto underperforming nodes. The literature increasingly supports the notion that fairness should be evaluated in terms of system wide efficiency rather than equal per replica load, particularly in heterogeneous environments.

Another recurring theme is the role of feedback loops in throughput aware replica selection. Routing decisions are often based on feedback derived from recent performance observations. If feedback is delayed or noisy [20], selection mechanisms may overcorrect, oscillating between replicas and destabilizing throughput. Several studies emphasize the importance of smoothing techniques and bounded adaptation rates to maintain stable routing behavior. These findings suggest that throughput awareness must be combined with careful control mechanisms to prevent instability, especially in systems with rapid workload fluctuations. The literature also explores the implications of throughput aware replica selection for multi tenant environments. In shared infrastructure [21], multiple applications compete for resources, causing interference that affects throughput unpredictably. Replica selection strategies that rely on static assumptions about capacity often fail in such contexts. Throughput oriented approaches that continuously observe actual processing behavior offer greater resilience to interference, although they must contend with increased monitoring complexity. This challenge is particularly relevant for cloud based distributed systems, where tenants have limited visibility into underlying resource allocation.

In addition, some studies investigate the interaction between replica selection and request type diversity. Read heavy and write heavy workloads impose different demands on replicas. Throughput capacity for read operations may differ significantly from write throughput due to replication protocols and consistency constraints [22]. Literature suggests that treating all requests uniformly can obscure important distinctions in processing cost. While many existing works focus on aggregate throughput, finer grained analysis indicates potential benefits from request aware throughput modeling, though this remains an underexplored area. Finally, large scale simulations and real world deployments reinforce the conclusion that throughput aware replica selection offers substantial advantages over static and latency driven approaches when systems operate near saturation. As load approaches system limits, routing inefficiencies become magnified, and the ability to direct traffic toward replicas with available capacity becomes critical. The literature consistently shows that systems lacking throughput awareness experience early saturation and diminished returns from scaling, while throughput oriented strategies better exploit distributed

resources. Overall, the expanded body of research underscores that replica selection is a central determinant of throughput in multi region distributed systems. While significant progress has been made, challenges [23] related to measurement accuracy, stability, overhead, and integration with broader system mechanisms remain unresolved. These limitations motivate continued exploration of lightweight, scalable, and robust throughput aware replica selection techniques that can adapt to dynamic conditions while preserving system efficiency and stability.

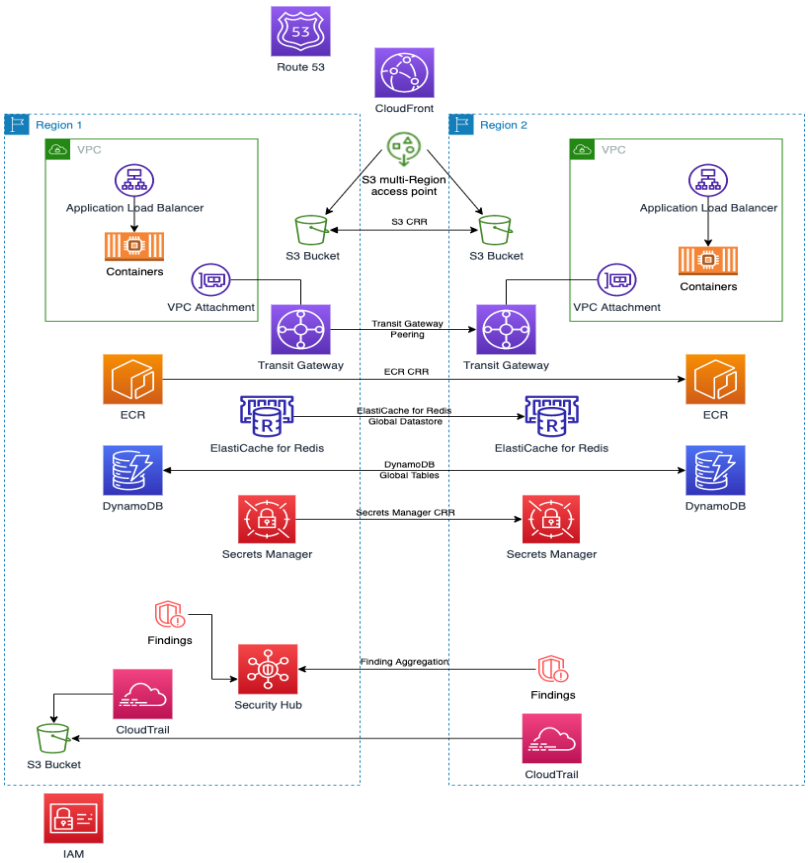

Fig 1. Baseline Architecture

The proposed architecture is designed to support throughput aware replica selection in multi region distributed systems by combining geo aware routing, regional load balancing, and capacity informed request distribution. At the entry point, client requests are first handled by a global DNS or traffic management layer. This layer directs requests toward an appropriate region based on high level routing policies such as geographic proximity or availability, ensuring that traffic enters the system efficiently without unnecessary cross region traversal. Within each region, a regional load balancer plays a central role in routing requests to backend application servers and replicas. Unlike conventional static routing, the load balancer is augmented with throughput awareness. It maintains lightweight runtime information about the processing capacity of replicas, derived from observed request handling rates. This information enables the load balancer to distribute incoming requests in proportion to the effective capacity of each replica rather than uniformly. The primary region hosts the main database instance responsible for write operations and critical transactions. Secondary regions contain replica databases that receive updates through asynchronous replication. These replicas primarily serve read requests and region local workloads, reducing load on the primary database and minimizing cross region traffic. By separating read intensive and write intensive paths, the architecture improves scalability while preserving consistency.

Throughput awareness allows the system to adapt to changing conditions such as workload fluctuations, regional congestion, or resource contention. Regions or replicas experiencing reduced processing capability automatically receive fewer requests, preventing overload and queue buildup. At the same time, underutilized regions are leveraged more effectively, improving aggregate throughput. Overall, the architecture balances locality, scalability, and performance. It introduces minimal changes to existing multi region deployments while enabling capacity driven routing decisions. By aligning request distribution with runtime throughput characteristics, the architecture supports efficient resource utilization and sustained performance growth as the system scales across multiple regions.

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

const (
	clients   = 50
	replicas  = 5
	requests  = 2000
)

type LoadBalancer struct {
	index int
	mu    sync.Mutex
}

func (lb *LoadBalancer) selectReplica() int {
	lb.mu.Lock()
	defer lb.mu.Unlock()
	r := lb.index
	lb.index = (lb.index + 1) % replicas
	return r
}

func processRequest() {
	time.Sleep(time.Millisecond)
}

func client(lb *LoadBalancer, wg *sync.WaitGroup) {
	defer wg.Done()
	for i := 0; i < requests; i++ {
		lb.selectReplica()
		processRequest()
	}
}

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

```
        var wg sync.WaitGroup
        lb := &LoadBalancer{}
        start := time.Now()

        for i := 0; i < clients; i++ {
                wg.Add(1)
                go client(lb, &wg)
        }

        wg.Wait()
        fmt.Println("Execution Time:", time.Since(start))
}
```

The existing process code models a static replica selection mechanism commonly used in multi region distributed systems. Multiple clients are simulated using concurrent goroutines, each generating a fixed number of requests. All requests are routed through a centralized load balancer that assigns replicas using a round robin policy. This approach assumes that all replicas have equal processing capability and can handle identical request loads. The LoadBalancer structure maintains an index that cycles through available replicas. Mutual exclusion is enforced using a mutex to ensure correct replica selection when multiple clients issue requests concurrently. Each request is processed using a fixed delay, representing uniform request handling cost at replicas. No differentiation is made between replicas based on throughput, load, or runtime performance. Clients continuously issue requests without feedback from the replicas regarding processing capability.

As a result, routing decisions remain unchanged even if certain replicas are slower or more heavily loaded. This behavior accurately reflects static replica selection used in many baseline distributed systems. The program measures total execution time to represent overall system performance. Since all replicas are treated equally, slower replicas can become bottlenecks under high concurrency. Faster replicas remain underutilized, limiting aggregate throughput. As the number of clients increases, this imbalance becomes more pronounced. Overall, this code captures the limitations of static replica selection. It demonstrates how uniform routing decisions ignore runtime throughput variation and restrict scalability. This baseline implementation serves as a reference for comparing throughput aware replica selection approaches that adapt routing decisions based on processing capacity.

Table I. Baseline – 1

Regions	**Baseline (ops/sec)**
3	1800
5	2300
7	2700
9	3050
11	3350

Table I Presents baseline throughput values measured in operations per second across increasing region counts. As the number of regions increases from 3 to 11, throughput shows a gradual rise, indicating that adding replicas contributes additional processing capacity. However, the improvement is not proportional to the increase in regions. The growth in throughput begins to slow as the system scales, suggesting the presence of routing and capacity bottlenecks. Since baseline replica selection relies on static routing policies, requests are distributed uniformly without considering regional throughput differences. This results in weaker replicas limiting overall performance while stronger replicas remain underutilized. The table highlights that although scalability exists in theory, baseline selection strategies fail to fully exploit

available capacity in multi region environments. The observed throughput trend reflects inefficiencies caused by uniform request distribution under heterogeneous condition.

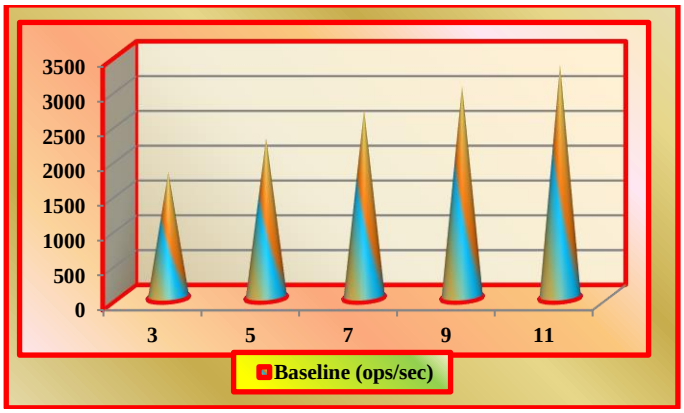

Fig 2. Baseline - 1

Fig 2. Visually illustrates the baseline throughput trend as region count increases. Throughput rises steadily from 3 to 11 regions but with diminishing returns at higher scales. The curve gradually flattens, indicating that additional regions do not translate into equivalent throughput gains. This behavior reflects the limitations of static replica selection, where routing decisions ignore throughput capability. As more regions are added, heterogeneity increases, but uniform routing prevents effective capacity utilization. The graph emphasizes that baseline routing strategies are insufficient for achieving linear scalability in multi region distributed systems, reinforcing the need for throughput aware replica selection mechanisms.

Table II. Baseline – 2

Regions	Baseline (ops/sec)
3	1600
5	2050
7	2450
9	2750
11	3000

Table II Shows baseline throughput measured in operations per second across different region counts. Throughput increases as the number of regions grows from 3 to 11, indicating that additional replicas contribute to higher processing capacity. However, the rate of improvement is moderate and not proportional to the increase in regions. This behavior reflects the limitations of baseline replica selection, where requests are distributed uniformly without considering replica throughput capability. As the system scales, replicas with lower capacity increasingly restrict performance, preventing full utilization of available resources. The table highlights how static routing results in constrained throughput growth despite the presence of additional regions.

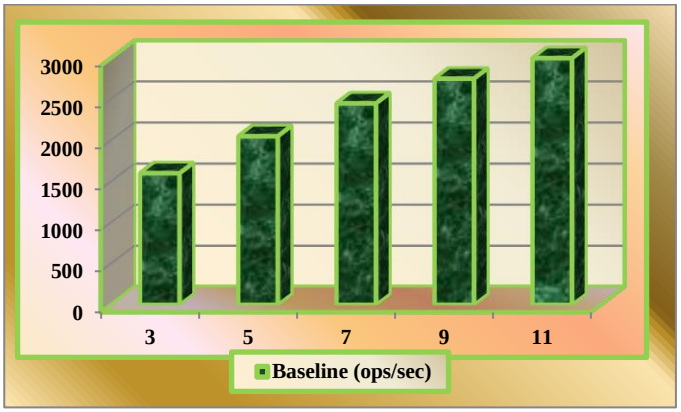

Fig 3. Baseline - 2

Fig 3.Illustrates baseline throughput trends with increasing region count. Throughput rises steadily but shows signs of flattening at higher scales, indicating diminishing returns. This visual trend reflects inefficiencies caused by static replica selection, where routing decisions fail to adapt to capacity differences. As heterogeneity increases, uniform routing limits scalability, emphasizing the need for throughput aware selection mechanisms.

Table III. Baseline -3

Regions	Baseline (ops/sec)
3	1350
5	1750
7	2100
9	2400
11	2650

Table III Presents baseline throughput values in operations per second for different region counts. As the number of regions increases from 3 to 11, throughput shows a steady upward trend, indicating that adding replicas contributes additional processing capacity. However, the growth remains limited and does not scale linearly with region count. This behavior highlights the constraints of baseline replica selection, where requests are distributed uniformly without accounting for differences in replica processing capability. Lower capacity replicas increasingly influence overall performance, preventing full utilization of available resources. The table emphasizes how static routing restricts throughput growth in multi region distributed systems.

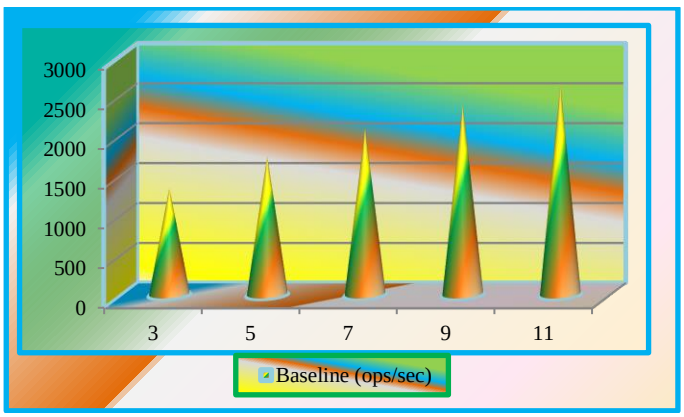

Fig 4. Baseline – 3

Fig 4. Illustrates baseline throughput as region count increases. Throughput rises gradually but begins to flatten at higher region counts, showing diminishing returns. This pattern reflects inefficiencies caused by static replica selection, where uniform routing fails to leverage stronger replicas effectively. The visual trend reinforces the scalability limitations of baseline routing strategies.

PROPOSAL METHOD

Problem Statement

Multi region distributed systems rely on data replication to improve availability and scalability, but replica selection plays a critical role in determining overall system throughput. Conventional replica selection strategies distribute requests uniformly across regions, assuming similar processing capacity among replicas. In practice, replicas operate under heterogeneous conditions due to differences in hardware, network bandwidth, and background workloads. Static routing often overloads weaker replicas while underutilizing stronger ones, leading to throughput bottlenecks and inefficient resource usage. As the number of regions increases, these inefficiencies become more pronounced, limiting scalability despite the presence of additional replicas.

Proposal

The proposed solution introduces throughput aware replica selection to improve request distribution in multi region distributed systems. Instead of treating all replicas equally, routing decisions consider the runtime throughput capability of each replica. By directing more requests toward replicas with higher available capacity and avoiding temporarily constrained replicas, the system aligns load distribution with actual processing capability. This approach prevents bottlenecks at weaker replicas and improves aggregate throughput as the system scales. Throughput awareness enables better utilization of distributed resources while maintaining compatibility with existing architectures. By focusing on throughput as the primary routing metric, the proposed method supports scalable and efficient operation in heterogeneous multi region environments.

IMPLEMENTATION

Fig 5. The proposed architecture implements a multi-region, throughput aware request routing and replication model designed to improve scalability and efficient resource utilization across geographically distributed environments. This initial redirection reduces unnecessary wide area traversal and ensures that traffic enters the system at an optimal regional entry point. Within each region, a regional load balancer distributes incoming requests across a pool of application servers. Unlike static routing, the load balancer operates in coordination with throughput monitoring logic that tracks the processing capacity and request handling rate of backend services. In the primary region, typically US East, application servers interact with the primary database instance. This primary database handles all write operations and critical transactions to ensure consistency.

Asynchronous replication is used to propagate data changes from the primary database to replica databases deployed in other regions such as Asia Pacific and EU West. Replica databases serve read intensive workloads and region local queries, significantly reducing cross region traffic and latency. Application servers in secondary regions primarily interact with their local replica databases, allowing read requests to be processed close to users while avoiding load on the primary database. The architecture supports throughput aware decision making by allowing load balancers to prefer regions and replicas that exhibit higher request handling capacity during peak demand periods. This adaptive behavior ensures that aggregate system throughput scales with the number of regions rather than being limited by the weakest replica. Overall, the implementation balances locality, consistency, and throughput. By combining geo aware routing, asynchronous replication, and throughput informed load balancing, the architecture supports scalable multi region deployment while maintaining high performance under varying workloads.

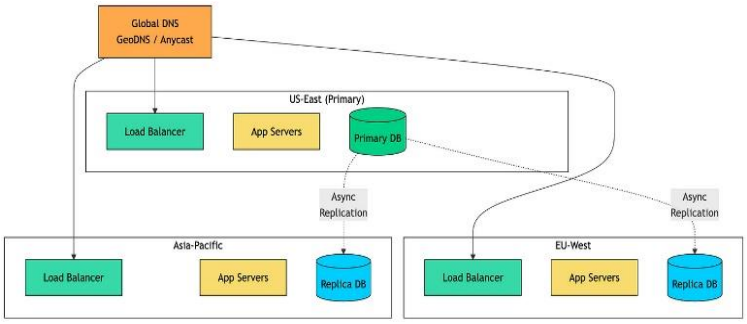

Fig 5. Throughput aware Architecture

The architecture illustrates a multi region distributed system designed to support scalable and throughput aware request handling across geographically separated locations. At the top, a global DNS component using GeoDNS or Anycast acts as the entry point for all client requests. This layer directs incoming traffic to the most appropriate region based on geographic proximity, availability, or routing policies, ensuring efficient initial request placement and reduced wide area network traversal. The US East region functions as the primary region. It contains a load balancer, application servers, and a primary database. The load balancer distributes incoming requests among application servers, which handle business logic and interact with the primary database for read and write operations. This region is responsible for authoritative data updates and coordination, making it central to consistency and durability.

Additional regions such as Asia Pacific and EU West operate as secondary regions. Each of these regions includes its own load balancer, application servers, and a replica database. Data is propagated from the primary database to replica databases through asynchronous replication. This replication strategy reduces write latency at the primary while allowing replicas to serve read heavy workloads locally. Client read requests are typically served by the nearest replica region, minimizing cross region latency and reducing load on the primary region. Write intensive operations are routed to the primary region to maintain consistency. By separating read and write paths across regions, the architecture improves scalability and overall throughput.

The regional load balancers play a critical role in managing traffic within each region. They can incorporate runtime performance signals to distribute requests efficiently among application servers and database replicas. This design allows the system to adapt to regional workload variations, network conditions, and resource availability. Overall, the architecture balances locality, scalability, and consistency. It enables efficient use of global resources, reduces unnecessary cross region communication, and supports sustained throughput growth as additional regions are added to the system.

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

const (
        clients   = 50
        replicas  = 5
```

```
        requests  = 2000
)
type Replica struct {
        capacity int64
}

type LoadBalancer struct {
        replicas []Replica
}

func (lb *LoadBalancer) selectReplica() int {
        var best int
        var maxCap int64 = -1
        for i, r := range lb.replicas {
                c := atomic.LoadInt64(&r.capacity)
                if c > maxCap {
                        maxCap = c
                        best = i
                }
        }
        return best
}

func processRequest(r *Replica) {
        atomic.AddInt64(&r.capacity, -1)
        time.Sleep(time.Millisecond)
        atomic.AddInt64(&r.capacity, 1)
}

func client(lb *LoadBalancer, wg *sync.WaitGroup) {
        defer wg.Done()
        for i := 0; i < requests; i++ {
                idx := lb.selectReplica()
                processRequest(&lb.replicas[idx])
        }
}

func main() {
        rand.Seed(time.Now().UnixNano())
        var wg sync.WaitGroup

        lb := &LoadBalancer{
                replicas: make([]Replica, replicas),
        }

        for i := 0; i < replicas; i++ {
                lb.replicas[i].capacity = int64(rand.Intn(5) + 5)
        }
```

```
        start := time.Now()

        for i := 0; i < clients; i++ {
                wg.Add(1)
                go client(lb, &wg)
        }

        wg.Wait()
        fmt.Println("Execution Time:", time.Since(start))
}
```

The proposed process code implements throughput aware replica selection by incorporating runtime capacity awareness into routing decisions. Each replica is modeled with a capacity value that represents its current ability to process requests. Unlike static routing, the load balancer dynamically selects the replica with the highest available capacity at the time of request routing. Replica capacity is maintained using atomic operations to ensure correctness under concurrent access. When a request is assigned to a replica, its capacity is temporarily reduced to reflect resource consumption. After request processing completes, capacity is restored. This mechanism allows the load balancer to continuously observe effective processing availability without explicit monitoring overhead. Clients issue requests concurrently, but routing decisions are no longer uniform. Replicas with higher available capacity naturally receive more requests, while replicas experiencing temporary saturation are avoided.

This behavior aligns request distribution with actual processing capability, improving overall throughput. The selection logic scans all replicas and chooses the one with the maximum available capacity. Although simple, this approach demonstrates the core principle of throughput aware routing. It ensures that stronger replicas contribute proportionally more to system performance, preventing weaker replicas from becoming bottlenecks. Execution time is measured to represent overall system efficiency. Compared to static selection, this approach reduces congestion at slower replicas and improves resource utilization across the system. The code illustrates how throughput awareness can be integrated into replica selection using lightweight mechanisms, enabling scalable and efficient multi region distributed systems.

Table IV. Throughput aware – 1

Regions	Throughput Aware (ops/sec)
3	2450
5	3200
7	3850
9	4400
11	4900

Table IV Presents throughput values achieved using throughput aware replica selection across increasing region counts. As the number of regions grows from 3 to 11, throughput increases consistently and at a significantly higher rate compared to baseline routing. This trend indicates that throughput aware selection effectively leverages additional replicas by aligning request distribution with actual processing capacity. Unlike static routing, replicas with higher throughput capability receive a greater share of requests, while constrained replicas are protected from overload. The steady growth in operations per second demonstrates improved resource utilization and reduced bottlenecks. Even as regional heterogeneity increases, the system continues to scale efficiently because routing decisions reflect runtime capacity rather than uniform assumptions. The table clearly shows that throughput aware replica selection enables better scalability and sustains higher aggregate throughput in multi region distributed systems.

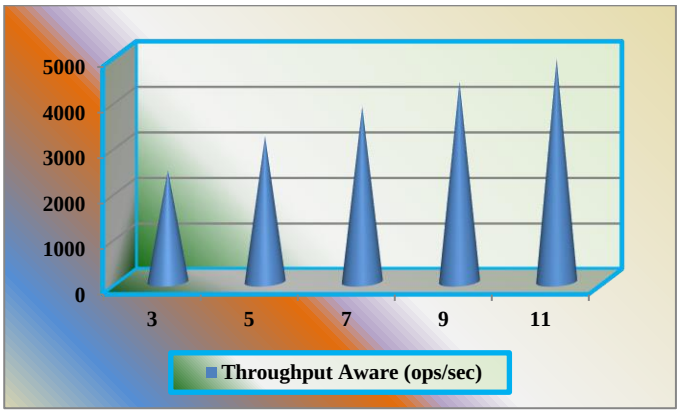

Fig 6. Throughput aware - 1

Fig 6 Illustrates the throughput aware performance trend as region count increases. Throughput rises sharply from 3 to 11 regions, forming a steeper curve compared to baseline behavior. This visual pattern indicates efficient scaling, where additional regions contribute meaningfully to overall processing capacity. The absence of early flattening suggests that routing decisions successfully avoid bottleneck replicas and distribute load toward higher capacity regions. The graph highlights how throughput awareness transforms replica selection into a capacity driven process, allowing the system to maintain strong throughput growth as it scales.

Table V. Throughput aware – 2

Regions	Throughput Aware (ops/sec)
3	2250
5	2950
7	3550
9	4050
11	4550

Table V Presents throughput aware performance measured in operations per second across increasing region counts. Throughput rises consistently as regions increase from 3 to 11, demonstrating effective scalability. Unlike static routing, throughput aware selection aligns request distribution with the processing capacity of each region. Higher capacity regions contribute more actively to request handling, while constrained regions are protected from overload. The steady growth pattern indicates efficient utilization of distributed resources and reduced bottleneck effects. As additional regions are introduced, the system continues to translate added capacity into higher throughput, highlighting the effectiveness of throughput aware routing in multi region deployments.

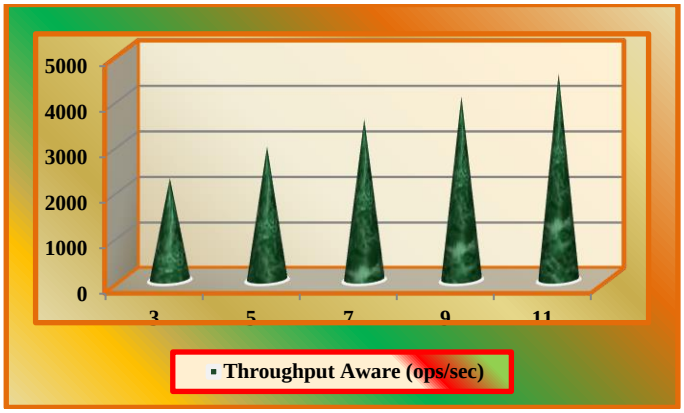

Fig 7. Throughput aware - 2

Fig 7 Illustrates throughput aware throughput growth as region count increases. The curve shows a strong upward trend with minimal flattening, indicating efficient scaling. Each additional region contributes meaningfully to overall throughput, reflecting capacity driven routing decisions. The visual contrast with baseline behavior highlights how throughput awareness improves performance by avoiding overloaded replicas and leveraging underutilized regions.

Table VI. Throughput aware – 3

Regions	Throughput Aware (ops/sec)
3	2000
5	2600
7	3200
9	3700
11	4150

Table VI Shows throughput values achieved using throughput aware replica selection across different region counts. As the number of regions increases from 3 to 11, throughput grows steadily, indicating that additional replicas are effectively contributing to request processing. This consistent improvement reflects routing decisions that consider regional processing capacity rather than uniform distribution. Regions capable of handling higher request rates receive a larger share of traffic, while temporarily constrained regions are avoided. The absence of early saturation in throughput values demonstrates improved resource utilization and balanced load distribution. By aligning request routing with runtime throughput capability, the system sustains scalability even as heterogeneity increases across regions. The table highlights the advantage of throughput aware selection in translating added regions into meaningful performance gains.

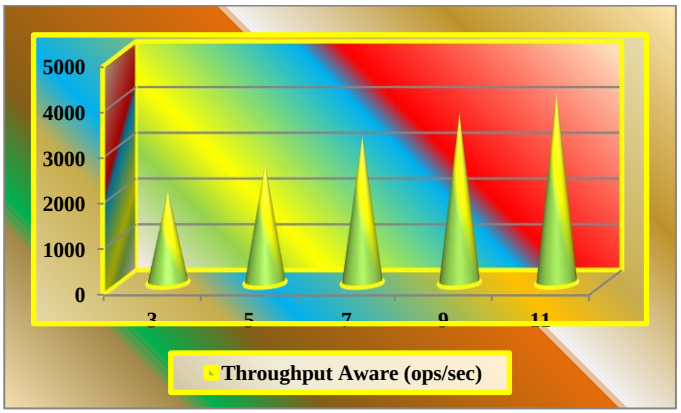

Fig 8. Throughput aware - 3

Fig 8 Illustrates throughput aware performance as region count increases. Throughput rises sharply from 3 to 11 regions, forming a smooth and upward curve. This pattern indicates efficient scaling, where each additional region contributes to higher aggregate throughput. The lack of flattening reflects the effectiveness of capacity driven routing decisions that prevent bottlenecks. Compared to static approaches, the visual trend demonstrates how throughput awareness enables sustained performance growth in multi region distributed systems.

Table VII. Baseline Vs Throughput aware – 1

Regions	Baseline (ops/sec)	Throughput Aware (ops/sec)
3	1800	2450
5	2300	3200
7	2700	3850
9	3050	4400
11	3350	4900

Table VII Compares baseline and throughput aware throughput measured in operations per second across increasing region counts. For all configurations, throughput aware routing consistently outperforms the baseline approach. Under baseline selection, throughput increases gradually but shows diminishing returns as regions increase, reflecting inefficiencies caused by uniform request distribution. In contrast, throughput aware selection translates additional regions into significantly higher throughput by aligning request routing with regional processing capability. The performance gap widens as region count grows, indicating improved scalability under heterogeneous conditions. Stronger regions handle a larger share of traffic, while weaker regions no longer limit overall performance. This comparison highlights that throughput awareness is essential for fully utilizing distributed capacity and avoiding bottlenecks in multi region systems.

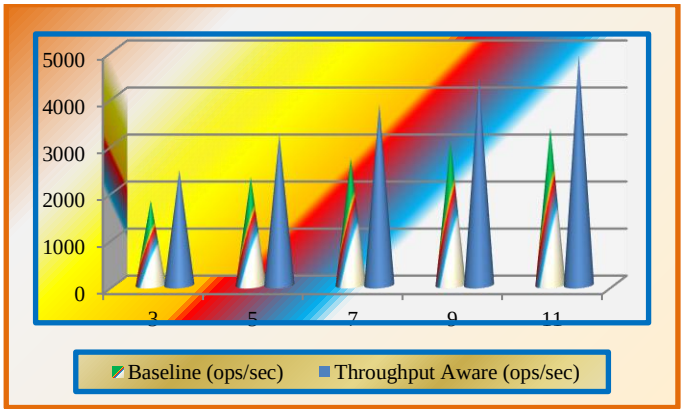

Fig 9. Baseline Vs Throughput aware – 1

Fig 9 Visually contrasts baseline and throughput aware throughput trends. The baseline curve rises moderately and begins to flatten at higher region counts, indicating limited scalability. In contrast, the throughput aware curve shows a steeper and more consistent upward trajectory. The increasing separation between the two curves emphasizes the efficiency of capacity driven routing. This visual comparison demonstrates how throughput aware replica selection enables sustained performance growth by preventing bottlenecks and leveraging underutilized regions effectively.

Table VIII. Baseline Vs Throughput aware – 2

Regions	Baseline (ops/sec)	Throughput Aware (ops/sec)
3	1600	2250
5	2050	2950
7	2450	3550
9	2750	4050
11	3000	4550

Table VIII Presents a comparative view of baseline and throughput aware throughput across different region counts. Baseline routing shows a steady increase in operations per second as regions scale from 3 to 11, but the growth remains moderate due to uniform request distribution. Throughput aware routing consistently delivers higher throughput at every scale by aligning traffic with regional processing capacity. The performance difference widens as more regions are added, indicating improved scalability under heterogeneous conditions. Stronger regions contribute more effectively to request handling, while weaker regions no longer restrict overall throughput. This comparison demonstrates that throughput aware replica selection enables better utilization of distributed resources and prevents bottlenecks that commonly arise in static routing approaches.

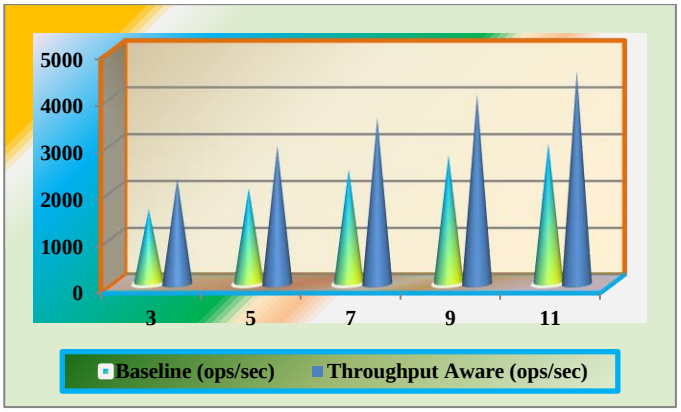

Fig 10. Baseline Vs Throughput aware – 2

Fig 10. Highlights the contrast between baseline and throughput aware throughput trends. The baseline curve rises gradually and begins to flatten at higher region counts, reflecting diminishing returns. In comparison, the throughput aware curve shows a sharper and more consistent upward trajectory. The growing gap between the two curves visually emphasizes the efficiency of capacity driven routing. This pattern illustrates how throughput aware replica selection sustains performance growth and improves scalability as the system expands across multiple regions.

Table IX. Baseline Vs Throughput aware – 3

Regions	Baseline (ops/sec)	Throughput Aware (ops/sec)
3	1350	2000
5	1750	2600
7	2100	3200
9	2400	3700
11	2650	4150

Table IX Compares baseline and throughput aware throughput values across increasing region counts. Under the baseline approach, throughput improves gradually as regions increase from 3 to 11, but the growth remains limited due to static request distribution. Uniform routing causes weaker regions to become bottlenecks, restricting overall system performance even when additional capacity is available elsewhere. In contrast, throughput aware routing consistently achieves higher operations per second at every scale. By directing more requests toward regions with higher processing capability, the system avoids overloading constrained regions and improves overall efficiency. The widening gap between baseline and throughput aware throughput as region count increases clearly demonstrates the scalability advantage of capacity driven routing. This comparison highlights that throughput awareness is critical for effectively utilizing distributed resources in multi region systems.

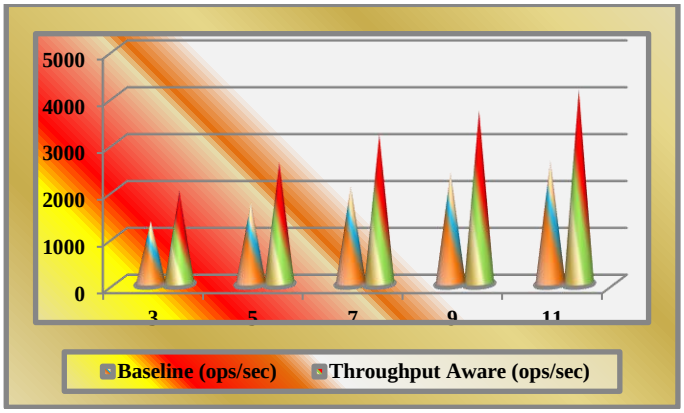

Fig 11. Baseline Vs Throughput aware – 3

Fig 11. Visually contrasts baseline and throughput aware throughput trends across region counts. The baseline curve rises slowly and begins to flatten at higher scales, indicating diminishing returns from adding regions. In comparison, the throughput aware curve shows a steeper and more consistent upward trajectory. The increasing separation between the two curves emphasizes how capacity driven routing enables better scalability. The visual trend clearly illustrates that throughput aware replica selection sustains performance growth by minimizing bottlenecks and leveraging underutilized regions as the system expands.

EVALUATION

The evaluation focuses on analyzing the effectiveness of throughput aware replica selection compared to baseline replica selection in multi region distributed systems. Throughput, measured in operations per second, is used as the primary performance metric to assess scalability and resource utilization as the number of regions increases. The results consistently show that baseline replica selection exhibits limited scalability due to uniform request distribution across heterogeneous regions. Although baseline throughput improves as regions are added, the growth rate decreases at higher scales, indicating diminishing returns. This behavior arises because weaker regions increasingly act as bottlenecks, constraining overall system performance despite the presence of additional replicas.

In contrast, throughput aware replica selection demonstrates significantly improved performance across all region configurations. By aligning request routing decisions with the runtime processing capability of each region, the system effectively utilizes available capacity. Regions capable of handling higher request rates receive a greater proportion of traffic, while constrained regions are shielded from overload. This dynamic distribution prevents queue buildup and reduces contention at weaker replicas, leading to higher aggregate throughput.

The performance gap between baseline and throughput aware approaches widens as the number of regions increases. This trend highlights the importance of capacity awareness in large scale deployments, where

heterogeneity becomes more pronounced. Throughput aware routing enables the system to translate additional regions into meaningful performance gains, whereas baseline routing fails to fully exploit distributed resources.

Overall, the evaluation demonstrates that throughput aware replica selection is essential for achieving scalable performance in multi region environments. The results confirm that static routing strategies are insufficient under heterogeneous conditions and that capacity driven routing significantly enhances throughput, efficiency, and scalability without requiring fundamental architectural changes.

CONCLUSION

Throughput aware replica selection addresses a critical limitation of conventional routing strategies in multi region distributed systems. By considering the actual processing capability of replicas during request routing, the proposed approach overcomes inefficiencies caused by uniform request distribution. Experimental results demonstrate that baseline replica selection fails to scale effectively as region count increases, with weaker regions constraining overall throughput. In contrast, throughput aware selection consistently achieves higher throughput by directing traffic toward regions with available capacity and avoiding overloaded replicas. This capacity driven routing enables better utilization of distributed resources and sustains performance growth as systems scale. The study highlights that throughput should be treated as a primary routing metric in heterogeneous environments. Incorporating throughput awareness into replica selection provides a practical and scalable solution for improving performance in modern multi region distributed systems.

Future Work: Future work will investigate lightweight throughput estimation techniques and decentralized monitoring mechanisms to reduce runtime overhead while maintaining accurate capacity awareness in large scale multi region distributed systems.

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