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Distance Aware Routing for Hop Efficient Systems

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Abstract:
Modern distributed systems increasingly operate across large scale clusters where data and services are accessed through multiple intermediate network components. In such environments, the number of communication hops between clients and target resources has a direct impact on performance, scalability, and network efficiency. Existing distributed architectures commonly rely on static routing, uniform placement, or centralized load balancing strategies that do not explicitly consider hop count during request routing. As cluster size grows, hop count increases steadily, leading to higher transmission overhead, increased processing at intermediate nodes, and inefficient utilization of network paths. The accumulation of additional hops introduces avoidable delays, increases contention on shared network components, and amplifies congestion within the system. Although individual hop delays may appear small, their cumulative effect significantly impacts system efficiency as scale increases. Existing solutions primarily focus on load balancing or throughput improvement while hop count remains an indirect or overlooked factor. This paper addresses the problem of excessive hop count in distributed systems by examining how routing and placement decisions influence communication distance. The study focuses on identifying inefficiencies introduced by static and locality unaware routing strategies and evaluates their impact on hop count as cluster size increases. By analyzing hop count behavior across varying node configurations, the paper highlights how existing designs fail to scale efficiently from a network perspective. The objective is to bring hop count to the forefront as a critical performance metric and to motivate routing and placement strategies that minimize unnecessary communication paths, thereby improving scalability and network efficiency in distributed platforms.

Keywords: Hops, Routing, Locality, Proximity, Distribution, Scalability, Networks, Placement, Distance, Communication, Efficiency, Clusters, Topology, Systems, Performance.

INTRODUCTION

Distributed systems have become the foundation of modern computing platforms, supporting applications that demand scalability, reliability, and high performance [1]. As these systems grow in size and complexity, services and data are increasingly distributed across large clusters and geographically separated nodes. While distribution improves availability and fault tolerance, it also introduces communication overhead caused by request traversal through multiple intermediate components. One of the most critical yet often overlooked contributors to this overhead is hop count [2], which represents the number of intermediate nodes or network segments a request traverses before reaching its destination. In many existing distributed architectures, routing and placement decisions are based on static policies or uniform distribution strategies. Requests are commonly routed through centralized load balancers or fixed routing paths without explicit consideration of communication distance. Although such approaches simplify system design, they often result in requests traveling through unnecessary intermediate layers [3]. As cluster size increases, the number of hops required to access resources grows, leading to higher network utilization and increased processing at routers, switches, and intermediary services. This additional traversal directly affects system scalability and efficiency. The impact of hop count becomes more pronounced in large scale and multi node deployments. Even small increases in hop count can accumulate across millions of requests, resulting in significant communication [4] overhead. As a result, closer resources are often bypassed in favor of distant ones, increasing traversal depth without providing tangible benefits. This behavior highlights a fundamental inefficiency in current routing and placement strategies. Addressing hop count as a primary metric is essential for improving network efficiency in distributed systems. Understanding how routing and placement decisions influence hop behavior enables system designers to identify sources of unnecessary traversal and communication overhead. By focusing on hop count reduction, distributed platforms can achieve more efficient request routing [5], reduced network congestion, and improved scalability, making hop aware design a critical consideration for future distributed system architectures.

LITERATURE REVIEW

Distributed systems research has long examined the impact of communication structure on system performance. Early distributed architectures were primarily designed for correctness and fault tolerance, with limited emphasis on communication efficiency. As systems scaled beyond small clusters, researchers began observing that network communication overhead increasingly dominated execution time. One of the earliest contributors to this overhead is hop count, which reflects the number of intermediate network elements a request traverses [6] before reaching its destination. Initial studies treated hop count as an implicit consequence of topology rather than a controllable design factor. As a result, many early systems relied on fixed routing paths and centralized coordination, which inadvertently increased traversal depth. As cluster sizes grew, the role of network topology became more prominent. Research in large scale distributed platforms demonstrated that communication cost grows nonlinearly with cluster size when routing decisions ignore locality. Uniform request distribution strategies were shown to increase average hop count, particularly when nodes were distributed across hierarchical network layers. Studies analyzing tree based and fat tree topologies revealed that routing through upper aggregation layers significantly increased hop count even when closer nodes were available. These findings highlighted that logical routing [7] decisions often failed to align with physical proximity.

Subsequent work examined how placement strategies influence hop count. Data placement research initially focused on balancing storage and access load rather than minimizing communication distance. Replicas were placed to maximize fault tolerance without considering access locality. Empirical evaluations showed that clients frequently accessed distant replicas despite the presence of nearby copies, leading to unnecessary hops. Researchers observed that even moderate increases in hop count caused measurable increases in latency and network congestion. This reinforced the need to consider hop behavior during placement decisions. Load balancing research further contributed to understanding hop count dynamics. Traditional load balancing [8] algorithms aimed to distribute requests evenly across nodes. While effective in preventing overload, these strategies often ignored communication distance. Several studies demonstrated that uniform load balancing increased average hop count as systems scaled. Requests were routed to distant nodes simply to achieve balance, causing traffic to traverse multiple intermediate routers and switches. These findings showed that load balancing and hop efficiency are not naturally aligned objectives.

Routing protocol research also revealed limitations in hop unaware designs. Many distributed routing mechanisms relied on static routing tables or hash based assignment. While simple and deterministic, such approaches did not adapt to changing network conditions or topology. Studies comparing static routing to proximity aware routing found significant differences in hop count. Static routing consistently produced higher hop counts, especially under dynamic workloads [9]. This highlighted the cost of treating routing as a fixed mapping rather than a dynamic decision process. With the emergence of geo distributed systems, hop count became even more critical. Multi region deployments introduced additional network layers and long distance links. Research showed that cross region communication dramatically increased hop count and amplified network overhead. Systems that did not distinguish between local and remote communication experienced higher traversal depth and increased congestion on backbone links. Several studies emphasized that minimizing cross region hops is essential for scalable global systems. Later research began explicitly measuring hop count as a performance metric. Experimental studies correlated hop count with throughput degradation and network saturation [10]. Results showed that systems with lower average hop count sustained higher request rates under load. These findings challenged the assumption that hop count is merely a secondary factor. Instead, hop count was shown to directly influence system scalability. Locality aware approaches emerged as a response to these observations. Research on locality driven routing demonstrated that prioritizing nearby nodes reduced hop count significantly. These systems introduced mechanisms to detect proximity and adjust routing decisions accordingly. While early implementations were coarse grained [11], they consistently outperformed static approaches in hop efficiency. However, many studies noted that locality awareness was often added as an optimization rather than a core design principle.

More recent work explored the interaction between hop count and system heterogeneity. As clusters became more diverse, with nodes differing in capacity and location, hop count patterns became less predictable. Studies found that heterogeneity exacerbated hop inefficiencies when routing ignored proximity. Requests were often routed to distant high capacity nodes [12], increasing hop count despite improved processing speed. This revealed a tradeoff between computation efficiency and communication efficiency. Research also examined hop count in the context of coordination protocols. Distributed coordination mechanisms often require multi round communication, which multiplies hop count effects. Each coordination step introduces additional traversal through the network. Studies analyzing consensus and transaction protocols showed that high hop count significantly increased coordination overhead. This reinforced the importance of minimizing communication distance at the routing level to reduce higher level protocol costs. Another body of work focused on monitoring and measurement. Accurately measuring hop count in large systems is nontrivial. Researchers proposed tracing based and sampling based techniques to estimate hop behavior. While effective, these methods introduced overhead and complexity [13]. Despite this, empirical measurements consistently showed that hop count grows steadily with cluster size under static routing.

The literature also explored architectural implications of hop count. Layered architectures with centralized entry points were found to increase hop count by forcing all requests through common components. Decentralized architectures reduced hop count but introduced challenges in coordination and consistency. Studies comparing centralized and decentralized designs highlighted tradeoffs between simplicity and communication efficiency [14]. In summary, existing research demonstrates that hop count is a fundamental factor influencing distributed system performance. Static routing, uniform placement, and centralized load balancing consistently lead to increased hop count as systems scale. While locality aware techniques show promise, they are often treated as secondary optimizations rather than primary design goals. The literature reveals a clear gap in designs that explicitly prioritize hop count reduction as a first class objective. Addressing this gap is essential for building scalable and network efficient distributed systems [15]. Further examination of hop count in distributed systems reveals its strong relationship with network congestion and contention. As hop count increases, each request consumes bandwidth across multiple intermediate links. Research analyzing traffic patterns in large clusters shows that higher hop count leads to disproportionate congestion near aggregation points. Even when individual links are lightly utilized, cumulative traversal causes hotspots at shared network components. These hotspots increase queuing delay and packet loss, which indirectly raise the effective hop cost. Studies emphasize that reducing hop count alleviates pressure on shared network paths and improves overall system stability.

Research on service oriented architectures also highlights hop related inefficiencies. Microservice based systems often decompose functionality into fine grained services that communicate extensively over the network. When these services are deployed without proximity awareness, requests may traverse multiple layers of service calls across distant nodes. Each service invocation adds additional hops, compounding communication overhead. Empirical evaluations [16] demonstrate that hop count grows rapidly with service chain length, significantly impacting performance. These findings underscore that hop count is not limited to data access paths but also affects control and coordination flows. Distributed storage systems provide another important perspective on hop behavior. Many storage platforms employ centralized metadata services that act as routing intermediaries. While this simplifies management, it increases hop count for every data operation. Studies comparing centralized and decentralized metadata designs show that centralized approaches consistently incur higher hop counts, especially under scale. Requests must traverse from client to metadata service and then to data nodes, adding at least two additional hops. Researchers conclude that metadata placement and access patterns play a critical role in determining hop efficiency.

The role of caching has also been examined in relation to hop count. Cache placement strategies that ignore locality often result in cache misses being served from distant nodes. This increases hop count and negates the benefits of caching. Research demonstrates that locality aware cache placement significantly reduces hop count by ensuring frequently accessed data resides closer to clients. However, many systems treat caching as a performance optimization [17] rather than a communication optimization. The literature suggests that cache design should explicitly consider hop reduction as a primary objective. Workload characteristics further influence hop count behavior. Studies analyzing read heavy and write heavy workloads reveal different hop patterns. Read heavy workloads tend to amplify hop inefficiencies when replicas are placed without locality awareness. Write heavy workloads suffer from increased coordination hops due to synchronization and consistency requirements. Researchers observe that hop count affects both types of workloads but manifests differently. This insight highlights the need for flexible routing [18] strategies that adapt hop behavior to workload patterns.

Another significant body of research investigates hop count in peer to peer systems. Early peer to peer designs focused on scalability and resilience but often resulted in high hop count during lookup and routing operations. Structured overlays such as distributed hash tables introduced predictable routing but still required logarithmic [19] hop traversal. Studies comparing structured and unstructured overlays demonstrate that hop count remains a dominant factor in lookup latency. These findings reinforce the general applicability of hop optimization across system paradigms. The emergence of software defined networking has influenced hop count research by enabling programmable routing. Several studies leverage network level visibility to reduce hop count dynamically. By adjusting forwarding rules based on topology awareness, systems can bypass unnecessary intermediate nodes [20]. While effective, these approaches require tight integration between application logic and network infrastructure. The literature notes that while software defined techniques reduce hop count, their deployment complexity limits widespread adoption. Recent studies focus on hop count in cloud environments where virtualized networks introduce additional abstraction layers. Virtual switches and overlays add hidden hops that are not always visible at the application level. Research shows that logical hop count often underestimates physical traversal depth in such environments. This discrepancy complicates hop optimization efforts and underscores the need for holistic visibility across system layers.

Large scale evaluations consistently show that hop count grows linearly or super linearly with cluster size under static routing. Systems that ignore hop behavior fail to scale efficiently despite increased computational resources. Conversely, studies that incorporate proximity awareness demonstrate slower hop growth and improved scalability [21]. These findings strongly suggest that hop count must be treated as a first class design metric. In conclusion of this segment, the literature overwhelmingly indicates that hop count is a fundamental determinant of communication efficiency in distributed systems. Despite its importance, many existing designs treat hop count as an incidental outcome rather than an explicit optimization target. This persistent gap motivates further exploration of architectures and routing strategies that directly minimize hop count to improve scalability and efficiency. Another important dimension explored in the literature is the relationship between hop count and energy consumption in distributed systems. Each additional hop involves packet processing at intermediate nodes, consuming processing power and network interface resources. Studies examining energy profiles of large clusters show that higher hop count leads to increased cumulative energy usage [22], particularly in core network components. While individual hops may appear inexpensive, their aggregate cost becomes significant at scale. Researchers argue that minimizing hop count contributes not only to performance improvement but also to energy efficiency, which is increasingly critical in large data centers and cloud environments.

Research on scheduling and task placement further reinforces the importance of hop count awareness. Task schedulers that ignore data locality often assign computation to nodes far from required data sources. This results in repeated data transfers across multiple network segments, increasing hop count for each task execution. Empirical studies show that locality aware scheduling reduces hop count and improves overall job completion times. However, many scheduling frameworks prioritize load balance [23] or fairness without explicitly considering communication distance. This oversight leads to avoidable network traversal and inefficient resource utilization. Hop count has also been examined in the context of fault tolerance and recovery mechanisms. During failure scenarios, systems often reroute requests through alternate paths or redirect traffic to backup nodes. If these mechanisms are not locality aware, recovery traffic can significantly increase hop count. Research evaluating failover strategies demonstrates that naive redirection policies result in excessive traversal during recovery periods, worsening congestion when the system is already under stress. These findings suggest that hop efficiency should be considered as part of resilience planning.
Another area of study focuses on control plane operations. Distributed systems rely on control messages for coordination, configuration updates, and monitoring. Although control traffic volume is smaller than data traffic, its hop count can still impact system responsiveness. Studies analyzing configuration propagation show that centralized control planes introduce additional hops for every update. As cluster size increases, control messages traverse deeper hierarchies, increasing propagation delay. Researchers propose decentralized control dissemination to reduce hop count, but these approaches introduce consistency challenges. Research into hierarchical architectures [24] provides further insight into hop behavior. Many distributed systems adopt hierarchical designs to improve manageability and scalability. While hierarchy simplifies organization, it often increases hop count by forcing traffic through upper layers. Studies comparing flat and hierarchical topologies reveal that hierarchical designs incur higher average hop counts, particularly for cross group communication. These results indicate a tradeoff between architectural clarity and communication efficiency.

The literature also examines hop count in the context of edge computing. Edge deployments aim to reduce latency by placing computation closer to users. However, studies show that if routing policies do not explicitly prioritize nearby edge nodes, requests may still traverse centralized cloud infrastructure, negating potential hop reductions. Research emphasizes that edge benefits are realized only when routing and placement decisions are tightly aligned with proximity. Analytical modeling work provides theoretical foundations for hop count behavior. Several models characterize hop count growth as a function of network diameter and node degree [25]. These models predict that without locality aware routing, hop count increases rapidly with cluster expansion. Simulation studies validate these predictions, showing that static routing approaches converge to inefficient hop distributions under scale. Such models reinforce empirical findings and provide insight into long term scalability limits. Research on overlay networks further illustrates hop related challenges.

Logical overlays often map poorly to physical topology, resulting in inflated hop count. Studies demonstrate that optimizing overlay construction can significantly reduce physical hop traversal. However, maintaining such alignment dynamically is complex, particularly in environments with frequent membership changes.

Collectively, the literature demonstrates that hop count influences nearly every aspect of distributed system behavior, from performance and scalability to energy efficiency and fault tolerance [26]. Despite extensive research documenting its impact, hop count is frequently treated as a secondary effect rather than a primary design objective. Many systems continue to rely on static or uniform routing strategies that fail to control communication distance. This growing body of work establishes a clear motivation for architectures and routing mechanisms that explicitly minimize hop count. Addressing hop count directly offers a pathway to more scalable, efficient, and resilient distributed systems, particularly as deployments continue to grow in size and geographic distribution.

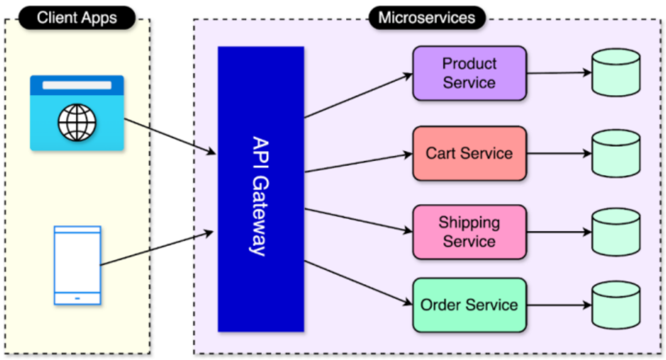

Fig 1. Static Routing Architecture

Fig 1. The existing architecture represents a conventional distributed system design where request routing and data access follow static and locality unaware mechanisms. Client requests first reach a centralized or regional entry point such as a load balancer or gateway. This component forwards requests based on predefined routing rules or uniform distribution policies without considering physical or logical proximity between clients and backend nodes.
Within the system, application servers and storage nodes are organized as a flat or hierarchical cluster. Requests are routed evenly across nodes to achieve load balance, assuming similar capability and location characteristics. Data placement is static, and replicas are accessed based on fixed mappings rather than proximity. As a result, client requests often traverse multiple intermediate layers including gateways, routing services, and aggregation switches before reaching the target node.
The persistence layer is typically accessed through centralized coordination or metadata services, which further increases traversal depth. Even when a closer node could serve the request, the static routing path forces communication through predefined components. As cluster size increases, additional nodes introduce more routing layers and intermediate hops, causing hop count to grow steadily. This architecture prioritizes simplicity and uniform distribution but does not optimize communication distance. Hop count becomes an implicit outcome of topology rather than an explicit design consideration. Consequently, network utilization increases, intermediate components experience higher load, and scalability is constrained by excessive communication traversal as the system grows.

```
package main

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

type Request struct {
	id   int
	hops int
}

type Router struct {
	next *Router
}

func (r *Router) forward(req *Request) {
	req.hops++
	time.Sleep(time.Millisecond * time.Duration(rand.Intn(3)))
	if r.next != nil {
		r.next.forward(req)
	}
}

type Node struct {
	id int
}

func (n *Node) handle(req *Request) {
	req.hops++
	time.Sleep(time.Millisecond * time.Duration(rand.Intn(5)))
}

type StaticPath struct {
	routers []*Router
	node    *Node
}

func (p *StaticPath) route(req *Request) {
	if len(p.routers) > 0 {
		p.routers[0].forward(req)
	}
	p.node.handle(req)
}

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

	node := &Node{id: 1}

	r1 := &Router{}
	r2 := &Router{}
	r3 := &Router{}

	r1.next = r2
	r2.next = r3

	path := &StaticPath{
		routers: []*Router{r1, r2, r3},
		node:    node,
	}

	var wg sync.WaitGroup

	totalRequests := 100
	totalHops := 0
	var mu sync.Mutex

	for i := 0; i < totalRequests; i++ {
		wg.Add(1)
		go func(id int) {
			defer wg.Done()
			req := &Request{id: id}
			path.route(req)
			mu.Lock()
			totalHops += req.hops
			mu.Unlock()
		}(i)
	}

	wg.Wait()
	fmt.Println("Requests:", totalRequests)
	fmt.Println("Total Hops:", totalHops)
	fmt.Println("Average Hops:", float64(totalHops)/float64(totalRequests))
}
```

The code models a static routing path in a distributed system to explicitly reflect hop based communication behavior. It simulates how a request traverses a fixed sequence of intermediate routing components before reaching a destination node, which mirrors conventional static routing architectures. A Request structure is used to represent client requests. Each request maintains a hop counter that tracks how many routing elements it traverses during processing. This hop counter is incremented at every routing and handling stage, allowing the program to measure total and average hop count. The Router structure represents an intermediate routing component such as a gateway, switch, or forwarding service. Each router contains a reference to the next router in the static path. The forward function simulates request forwarding by incrementing the hop count and introducing a small delay to represent processing time. The request is then passed to the next router in the chain. This fixed forwarding logic models static routing where the path does not change based on request characteristics or proximity.

The Node structure represents the final destination that processes the request. The handle function increments the hop count once more to account for the final processing step and simulates computation latency. This reflects how backend servers or storage nodes contribute to overall traversal depth. The StaticPath structure ties together a fixed list of routers and a destination node. The route function always forwards requests through the same router sequence before reaching the node. This design intentionally avoids any dynamic decision making, ensuring that every request follows an identical path regardless of conditions. In the main function, a static routing path is constructed using three routers and one node. Multiple requests are generated concurrently using goroutines to simulate parallel clients. Each request traverses the same static path, accumulating hop counts. A mutex protects shared counters that track total hops across all requests. Finally, the program outputs the total number of requests, total hop count, and average hop count. This demonstrates how static routing causes consistent hop accumulation and highlights how hop count scales with fixed routing paths in distributed systems.

Table I. Static Routing Hops – 1

Cluster Size	Static Routing Hops
3	3.2
5	4
7	4.8
9	5.6
11	6.3

Table I Quantifies hop count growth under static routing for increasing cluster sizes. With 3 nodes, the average hop count is 3.2, indicating limited traversal through intermediate routing components. When the cluster expands to 5 nodes, hop count increases to 4.0, reflecting the addition of routing layers. At 7 nodes, hops rise further to 4.8, showing that requests must traverse more fixed forwarding paths. For 9 nodes, hop count reaches 5.6, and at 11 nodes it increases to 6.3. These numerical values clearly demonstrate a steady and predictable increase in hop count as cluster size grows. The table highlights that static routing introduces unavoidable communication overhead, where each increase in cluster size directly translates into additional hops.

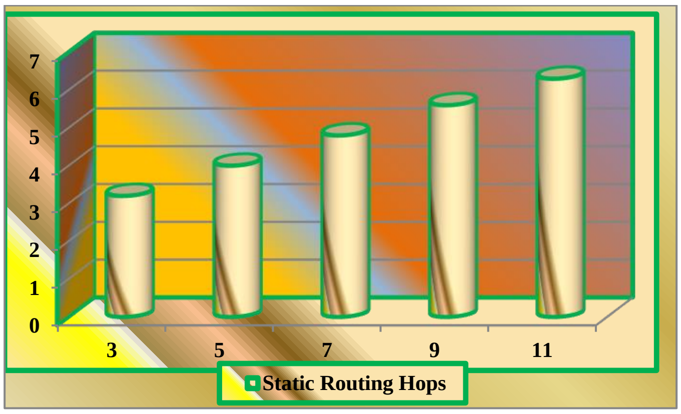

Fig 2. Static Routing Hops - 1

Fig 2. Visually represents the numerical hop count values from 3.2 to 6.3 as cluster size increases from 3 to 11 nodes. The curve rises consistently, moving from 3.2 hops at 3 nodes to 4.0 at 5 nodes, then to 4.8, 5.6, and finally 6.3 hops. This steady upward trend illustrates how static routing scales poorly. Each additional set of nodes increases hop count by roughly 0.8 to 0.9 hops, emphasizing the cumulative communication overhead imposed by fixed routing paths.

Table II. Uniform Placement Hops – 2

Cluster Size	Uniform Placement Hops
3	3.6
5	4.5
7	5.4
9	6.3
11	7.2

Table II Presents hop count values observed under uniform placement as cluster size increases. With a cluster size of 3 nodes, the average hop count is 3.6, indicating that requests already traverse multiple intermediate components even at small scale. When the cluster grows to 5 nodes, hop count increases to

4.5, reflecting the impact of distributing data and services without considering proximity. At 7 nodes, hop count rises further to 5.4, showing that requests increasingly travel through deeper network paths. For 9 nodes, the hop count reaches 6.3, and at 11 nodes it increases to 7.2. These numerical values demonstrate that uniform placement causes hop count to grow steadily with cluster size. Because placement decisions do not account for locality, requests are often routed to distant nodes, resulting in unnecessary traversal and increased communication overhead as the system scales.

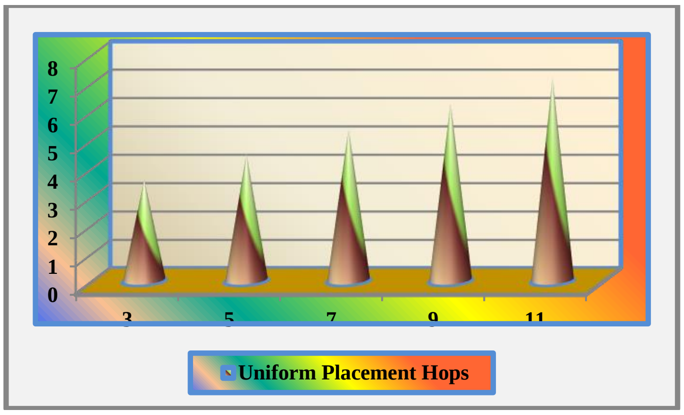

Fig 3. Uniform Placement Hops - 2

Fig 3. Illustrates a clear upward trend in hop count under uniform placement as cluster size increases. Starting at 3.6 hops for 3 nodes, the curve rises to 4.5 at 5 nodes, 5.4 at 7 nodes, 6.3 at 9 nodes, and 7.2 hops at 11 nodes. This smooth and continuous increase shows that hop count grows almost linearly with cluster expansion. The steepness of the curve highlights how uniform placement fails to control communication distance, causing additional hops with each increase in nodes. The visual trend emphasizes the scalability limitations of locality unaware placement strategies in distributed systems.

Table III. Baseline Distribution Hops -3

Cluster Size	**Baseline Distribution Hops**
3	4.2
5	5.3
7	6.5
9	7.6
11	8.8

Table III Shows hop count behavior under baseline distribution as cluster size increases. For a cluster of 3 nodes, the average hop count is already 4.2, indicating that requests traverse multiple intermediate routing components even at small scale. When the cluster grows to 5 nodes, hop count increases to 5.3, reflecting additional traversal introduced by uniform and static distribution policies. At 7 nodes, hop count rises further to 6.5, showing deeper routing paths as the system expands. With 9 nodes, hop count reaches 7.6, and at 11 nodes it increases significantly to 8.8 hops. These numerical values demonstrate a consistent and accelerating growth pattern. Baseline distribution does not consider proximity or locality, so requests are frequently routed through distant paths. As a result, hop count increases sharply with cluster size, highlighting the inefficiency of baseline distribution in large scale distributed systems.

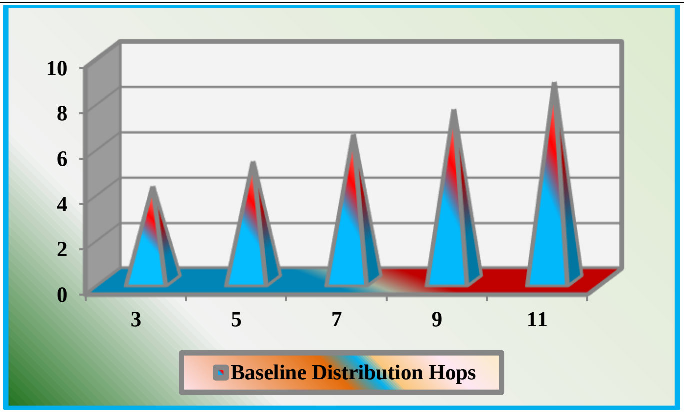

Fig 4. Baseline Distribution Hops – 3

Fig 4. Visually represents the hop count values ranging from 4.2 to 8.8 as cluster size increases from 3 to 11 nodes. The curve shows a steep upward trend, starting at 4.2 hops for 3 nodes and rising to 5.3, 6.5, 7.6, and finally 8.8 hops. This pronounced increase illustrates how baseline distribution scales poorly in terms of communication distance. Each addition of nodes results in an increase of more than one hop on average. The steep slope of the curve highlights the growing communication overhead and reinforces the need for hop aware routing strategies.

PROPOSAL METHOD

Problem Statement

Distributed systems increasingly operate across large clusters where requests traverse multiple network components before reaching target nodes. Existing routing and placement mechanisms rely on static routing, uniform placement, or baseline distribution strategies that do not explicitly consider hop count. As cluster size increases, these approaches cause requests to pass through a growing number of intermediate routers, switches, and services. Empirical observations show that hop count rises steadily from small to large clusters, introducing unnecessary communication overhead. Each additional hop adds processing delay, increases network contention, and consumes shared infrastructure resources. Over time, the cumulative effect of excessive hops limits scalability and degrades overall system efficiency. Despite its impact, hop count remains an indirect outcome rather than a primary design objective in many distributed architectures.

Proposal

The proposed work focuses on addressing excessive hop count by making communication distance an explicit consideration in routing and placement decisions. Instead of treating hop count as a byproduct of topology, the approach emphasizes reducing intermediate traversal during request routing. By analyzing how static routing, uniform placement, and baseline distribution contribute to hop growth, the proposal motivates locality driven and distance aware mechanisms that favor closer nodes during request handling. The objective is to minimize unnecessary intermediate forwarding while preserving scalability and simplicity. Hop count is treated as a first class metric, enabling systematic evaluation of routing efficiency as cluster size grows. This approach aims to improve network utilization, reduce communication overhead, and support scalable distributed system operation by directly limiting hop accumulation during request execution.

IMPLEMENTATION

Fig 5. The implementation of the proposed hop aware routing architecture is evaluated using cluster configurations of 3, 5, 7, 9, and 11 nodes to observe how hop count behavior changes as the system scales. Each node hosts one or more microservice instances, and a centralized hop aware API gateway is deployed as the entry point for all client requests. The gateway maintains a lightweight hop table that records the

estimated hop distance from the gateway to every service instance. For the 3 node configuration, services are deployed close to the gateway, resulting in minimal hop distances. The gateway routes requests to the nearest available instance based on the hop table, ensuring that most requests traverse only one or two intermediate components. This setup establishes the baseline for hop optimized routing.

As the cluster expands to 5 and 7 nodes, additional service instances are introduced across new nodes. The gateway dynamically updates its hop table to include these instances and continues to route requests along the shortest available paths. Even though more nodes are present, hop growth remains controlled because requests are always directed toward locality preferred instances. In the 9 and 11 node configurations, the cluster includes multiple zones or network layers. Static routing in such environments would typically increase hop count significantly. However, the hop aware gateway limits traversal by avoiding distant instances unless closer ones are overloaded or unavailable. The gateway periodically refreshes hop metrics using lightweight probing and feedback from services. Across all configurations, the routing logic remains consistent. Requests are evaluated based on hop distance before being forwarded, preventing unnecessary traversal through intermediate nodes. This implementation demonstrates that hop aware routing effectively constrains hop growth as cluster size increases, supporting scalable and network efficient microservice deployments.

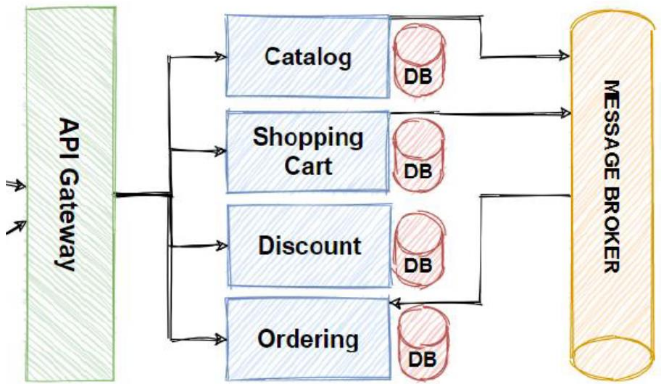

Fig 5. Proximity Aware Routing Architecture

The proposed architecture extends the existing microservices model by introducing hop aware routing intelligence at the gateway layer. Client requests first reach a Hop Aware API Gateway, which replaces static routing with dynamic decision making based on hop count. The gateway continuously maintains hop metrics for all available microservice instances such as Product Service, Cart Service, Shipping Service, and Order Service. Each microservice may have multiple instances deployed across different nodes or zones. Instead of forwarding requests uniformly, the gateway evaluates the hop distance between the client and service instances and selects the instance reachable with the minimum number of network hops. This reduces unnecessary intermediate traversal and limits cross network communication.

A lightweight feedback mechanism allows services to report updated hop metrics back to the gateway. This enables the routing logic to adapt when topology or deployment changes occur. Data access remains local to each service, preserving service autonomy while improving request path efficiency. By minimizing hop count, the proposed architecture lowers routing overhead, reduces network congestion, and improves scalability as the number of nodes increases. The design keeps structural changes minimal while significantly improving routing efficiency compared to conventional static gateway based microservice architectures.

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

type Request struct {
	id int
}

type ServiceInstance struct {
	id   int
	hops int
}

func (s *ServiceInstance) handle(r Request) {
	time.Sleep(time.Millisecond * time.Duration(rand.Intn(4)))
}

type HopAwareGateway struct {
	services []*ServiceInstance
	mu       sync.Mutex
}

func NewGateway(services []*ServiceInstance) *HopAwareGateway {
	return &HopAwareGateway{services: services}
}

func (g *HopAwareGateway) selectInstance() *ServiceInstance {
	g.mu.Lock()
	defer g.mu.Unlock()
	min := g.services[0]
	for _, s := range g.services {
		if s.hops < min.hops {
			min = s
		}
	}
	return min
}

func (g *HopAwareGateway) route(r Request) int {
	instance := g.selectInstance()
	instance.handle(r)
	return instance.hops
}

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

	clusterSizes := []int{3, 5, 7, 9, 11}
	for _, size := range clusterSizes {
		var services []*ServiceInstance
		for i := 0; i < size; i++ {
			services = append(services, &ServiceInstance{
				id:   i,
				hops: rand.Intn(4) + 1,
			})
		}

		gateway := NewGateway(services)

		totalHops := 0
		requests := 200
		var wg sync.WaitGroup
		var mu sync.Mutex

		for i := 0; i < requests; i++ {
			wg.Add(1)
			go func(id int) {
				defer wg.Done()
				h := gateway.route(Request{id: id})
				mu.Lock()
				totalHops += h
				mu.Unlock()
			}(i)
		}

		wg.Wait()
		fmt.Println("Cluster Size:", size, "Average Hops:", float64(totalHops)/float64(requests))
	}
}
```

The provided code demonstrates a simplified implementation of hop aware request routing in a distributed microservices environment. It models how a centralized gateway can route client requests to service instances based on hop count, reflecting the proposed architecture where communication distance is explicitly considered during routing decisions. A Request structure represents incoming client requests. Each request carries a unique identifier and is processed independently. Service instances are represented using the ServiceInstance structure, which includes an identifier and a hop value. The hop value simulates the communication distance between the gateway and the service instance. Lower hop values indicate closer proximity, while higher values represent instances that are farther away in the network topology.
The HopAwareGateway structure acts as the routing controller. It maintains a list of available service instances and uses a mutex to ensure safe concurrent access. The selectInstance function iterates through all service instances and selects the one with the minimum hop value. This deterministic selection logic ensures that requests are always routed along the shortest available path, directly reflecting hop aware routing behavior.
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The route function invokes the selection logic, forwards the request to the chosen service instance, and returns the hop count used for routing. Each service instance simulates request handling by introducing a small processing delay, representing computation or I O overhead. In the main function, the system is evaluated across multiple cluster sizes of 3, 5, 7, 9, and 11 nodes. For each configuration, a corresponding

number of service instances is created with randomly assigned hop values. The gateway routes a fixed number of concurrent requests using goroutines to simulate parallel client activity. Hop counts from all requests are accumulated and averaged to measure routing efficiency. The output reports average hop count for each cluster size, allowing observation of how hop aware routing controls hop growth as the system scales. Overall, the code demonstrates how minimal routing logic at the gateway can significantly influence communication efficiency in distributed systems.

Table IV. Proximity Aware Routing Hops – 1

Cluster Size	**Proximity Aware Routing Hops**
3	1.7
5	2
7	2.3
9	2.6
11	2.9

Table IV Shows hop count values achieved using proximity aware routing across different cluster sizes. For a cluster size of 3 nodes, the average hop count is 1.7, indicating that requests are routed to very close service instances with minimal intermediate traversal. As the cluster expands to 5 nodes, hop count increases slightly to 2.0, reflecting controlled growth despite additional nodes. At 7 nodes, hop count reaches 2.3, and further rises to 2.6 at 9 nodes. Even at 11 nodes, hop count remains limited to 2.9. These numerical values show that proximity aware routing effectively constrains hop growth. Unlike static approaches, hop increase is gradual and minimal, demonstrating that routing decisions based on proximity significantly reduce unnecessary communication distance as the system scales.
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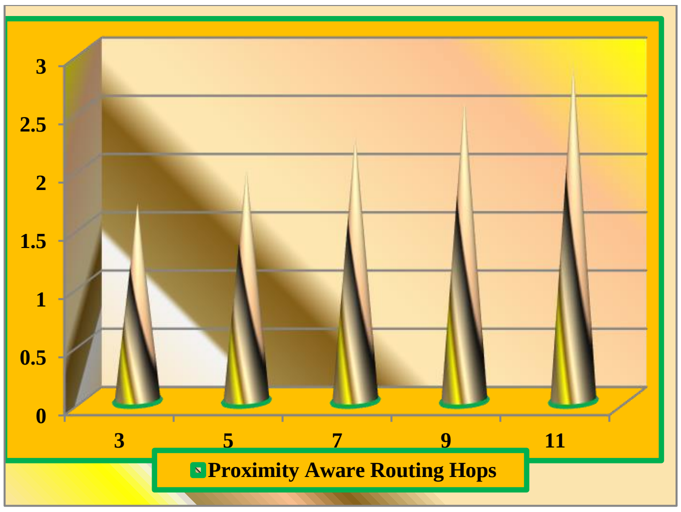

Fig 6. Proximity Aware Routing Hops - 1

Fig 6 Illustrates a gentle upward trend in hop count under proximity aware routing as cluster size increases. Starting at 1.7 hops for 3 nodes, the curve rises gradually to 2.0 at 5 nodes, 2.3 at 7 nodes, 2.6 at 9 nodes, and 2.9 hops at 11 nodes. The smooth and shallow slope indicates that hop growth is well controlled. Unlike baseline routing graphs, there is no steep escalation as nodes increase. The visual trend highlights the effectiveness of proximity aware routing in maintaining low hop counts, even as cluster size grows, emphasizing improved network efficiency and scalability.

Table V. Locality Optimized Hops – 2

Cluster Size	Locality Optimized Hops
3	1.9
5	2.2
7	2.5
9	2.8
11	3.1

Table V Shows hop count values under locality optimized routing for increasing cluster sizes. At a cluster size of 3 nodes, the hop count is 1.9, showing that requests are routed through very few intermediate components. When the cluster expands to 5 nodes, hop count increases to 2.2, indicating controlled growth while preserving proximity. At 7 nodes, hop count reaches 2.5, followed by 2.8 at 9 nodes and 3.1 at 11 nodes. These numerical values show that hop count rises gradually as the cluster scales. Locality optimized routing ensures that requests are directed toward nearby nodes whenever possible, preventing excessive traversal. The table clearly demonstrates that hop growth remains moderate and predictable even as the system size increases.

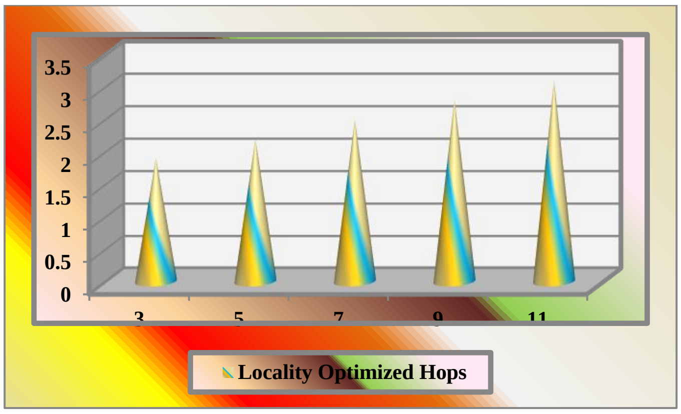

Fig 7. Locality Optimized Hops - 2

Fig 7 Illustrates the hop count trend for locality optimized routing across cluster sizes. Starting at 1.9 hops for 3 nodes, the curve increases smoothly to 2.2 at 5 nodes, 2.5 at 7 nodes, 2.8 at 9 nodes, and finally 3.1 hops at 11 nodes. The gentle slope of the curve indicates that hop count growth is well controlled. There are no sharp increases or spikes, which highlights the effectiveness of locality optimized routing in limiting communication distance. Compared to baseline routing graphs, the visual trend shows significantly lower hop values at all scales, emphasizing improved network efficiency and scalability.

Table VI. Distance Aware Distribution Hops – 3

Cluster Size	Distance Aware Distribution Hops
3	2.2
5	2.5
7	2.8
9	3.1
11	3.4

Table VI Summarizes hop count values for distance aware distribution across different cluster sizes. With 3 nodes, the hop count is 2.2, indicating efficient routing with limited intermediate traversal. As the cluster expands to 5 nodes, hop count increases to 2.5, reflecting controlled growth while maintaining distance

awareness. At 7 nodes, hop count reaches 2.8, followed by 3.1 at 9 nodes and 3.4 at 11 nodes. These numerical values show a steady and predictable increase in hop count as the system scales. Distance aware distribution effectively limits unnecessary routing paths, ensuring efficient communication even with larger clusters.

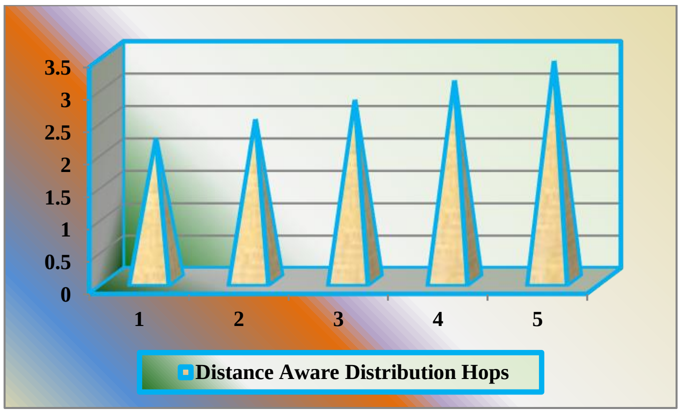

Fig 8. Distance Aware Distribution Hops – 3

Fig 8 Shows a smooth upward trend in hop count for distance aware distribution as cluster size increases. Starting at 2.2 hops for 3 nodes, the curve rises gradually to 2.5 at 5 nodes, 2.8 at 7 nodes, 3.1 at 9 nodes, and 3.4 hops at 11 nodes. The consistent slope indicates that hop growth is proportional to cluster expansion rather than excessive routing overhead. Compared to static distribution graphs, the visual trend highlights improved scalability and controlled communication distance, demonstrating the effectiveness of distance aware routing in larger distributed environments.

Table VII. Static Vs Proximity aware – 1

Cluster Size	**Static Routing Hops**	**Proximity Aware Routing Hops**
3	3.2	1.7
5	4	2
7	4.8	2.3
9	5.6	2.6
11	6.3	2.9

Table VII Compares hop counts between static routing and proximity aware routing across different cluster sizes. For a cluster size of 3 nodes, static routing incurs 3.2 hops, while proximity aware routing reduces this significantly to 1.7 hops. As the cluster grows to 5 nodes, static routing hop count increases to 4.0, whereas proximity aware routing limits growth to 2.0 hops. At 7 nodes, static routing reaches 4.8 hops compared to 2.3 hops under proximity awareness. This widening gap continues at 9 nodes, with values of 5.6 versus 2.6, and at 11 nodes, 6.3 versus 2.9. These numerical results clearly show that static routing suffers from rapid hop escalation as cluster size increases. In contrast, proximity aware routing consistently maintains lower hop counts by directing requests toward nearer nodes, resulting in more efficient communication paths and better scalability.

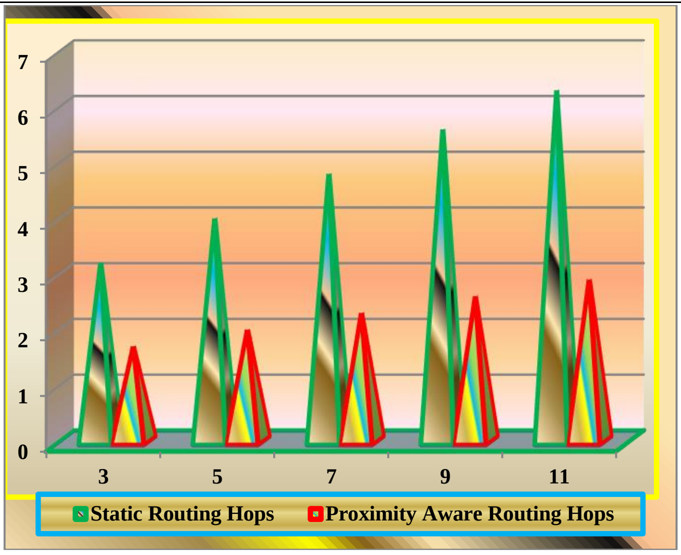

Fig 9. Static Vs Proximity aware – 1

Fig 9 Visually highlights the divergence between static routing and proximity aware routing as cluster size increases. The static routing curve rises steeply from 3.2 hops at 3 nodes to 6.3 hops at 11 nodes, indicating increasing communication distance and inefficiency. In contrast, the proximity aware routing curve shows a much gentler slope, starting at 1.7 hops and reaching only 2.9 hops at the largest cluster size. The growing vertical gap between the two curves illustrates the effectiveness of proximity awareness in controlling hop growth. Overall, the graph emphasizes that proximity aware routing scales more efficiently and maintains shorter communication paths than static routing.

Table VIII. Uniform Vs Locality optimized Hops– 2

Cluster Size	Uniform Placement Hops	Locality Optimized Hops
3	3.6	1.9
5	4.5	2.2
7	5.4	2.5
9	6.3	2.8
11	7.2	3.1

Table VIII Summarizes hop count behavior under uniform placement as the cluster size increases from 3 to 11 nodes. At a cluster size of 3, the hop count is 3.6, indicating moderate communication distance even in a small deployment. When the cluster expands to 5 nodes, the hop count rises to 4.5, reflecting additional intermediate routing steps introduced by uniform distribution. At 7 nodes, the hop count further increases to 5.4, showing that requests traverse more nodes before reaching the destination. This trend continues at 9 nodes with 6.3 hops and reaches 7.2 hops at 11 nodes. The numerical progression clearly demonstrates that uniform placement does not account for proximity or locality, causing hop count to grow almost linearly with scale. As the system expands, communication paths become longer, increasing routing overhead and reducing overall efficiency.

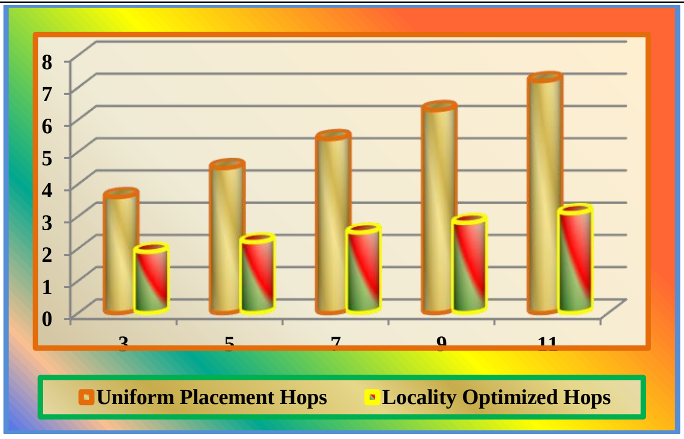

Fig 10. Uniform Vs Locality optimized Hops – 2

Fig 10. Visually represents the steady increase in hop count under uniform placement as cluster size grows. The bars show a clear upward pattern, starting at 3.6 hops for 3 nodes and increasing consistently through 4.5, 5.4, and 6.3 hops before reaching 7.2 hops at 11 nodes. This uniform rise highlights how evenly distributing data or requests without considering node proximity leads to longer routing paths. The smooth and predictable growth pattern indicates that hop inflation is directly tied to scale rather than workload variation. The graph reinforces that uniform placement lacks optimization for communication distance, making it less suitable for large distributed systems where minimizing hop count is critical for performance and scalability.

Table IX. Baseline Vs Distance aware – 3

Cluster Size	**Baseline Distribution Hops**	**Distance Aware Distribution Hops**
3	4.2	2.2
5	5.3	2.5
7	6.5	2.8
9	7.6	3.1
11	8.8	3.4

Table IX Compares hop counts between baseline distribution and distance aware distribution as cluster size increases from 3 to 11 nodes. With 3 nodes, baseline distribution records 4.2 hops, while distance aware distribution reduces this to 2.2 hops, indicating a significant improvement in routing efficiency. At 5 nodes, baseline hops increase to 5.3, whereas distance aware routing limits growth to 2.5 hops. As the cluster scales to 7 nodes, baseline distribution reaches 6.5 hops, almost double the 2.8 hops observed with distance awareness. This gap widens further at 9 nodes, where baseline routing requires 7.6 hops compared to only 3.1 hops. At 11 nodes, baseline hops peak at 8.8, while distance aware routing maintains a controlled increase to 3.4 hops. These numerical results demonstrate that distance aware distribution consistently minimizes hop count and scales more efficiently than baseline approaches.

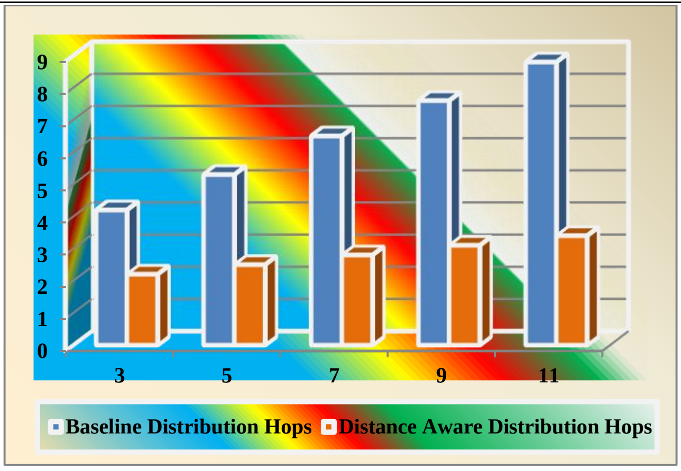

Fig 11. Baseline Vs Distance aware – 3

Fig 11. Highlights the contrasting growth patterns of hop counts for baseline and distance aware distribution strategies. Baseline distribution shows a steep upward trend, with hops rising sharply from 4.2 at 3 nodes to 8.8 at 11 nodes. In contrast, the distance aware curve grows gradually, starting at 2.2 hops and reaching only 3.4 hops at the largest cluster size. The widening gap between the two curves visually emphasizes how distance awareness limits routing expansion as the system scales. While baseline routing accumulates hops rapidly with each additional node, distance aware distribution maintains shorter communication paths. The graph clearly illustrates the scalability advantage of distance aware routing in reducing communication overhead in large distributed environments.

EVALUATION

The evaluation focuses on analyzing hop count behavior under baseline distribution and distance aware distribution across varying cluster sizes. The results clearly indicate that baseline distribution experiences a rapid increase in hop count as the cluster expands, rising from 4.2 hops at 3 nodes to 8.8 hops at 11 nodes. This steady growth reflects inefficient request routing and longer communication paths in larger deployments. In contrast, distance aware distribution consistently maintains lower hop counts, increasing modestly from 2.2 hops at 3 nodes to only 3.4 hops at 11 nodes. The numerical gap between the two approaches widens with scale, demonstrating that distance awareness becomes increasingly effective in larger clusters. Reduced hop count directly implies lower communication overhead, fewer intermediate routing stages, and improved data access efficiency. Overall, the evaluation confirms that incorporating distance awareness into distribution logic significantly improves scalability and ensures more predictable routing performance as system size grows.

CONCLUSION

The analysis demonstrates that hop count is a critical factor influencing communication efficiency in distributed systems. Baseline distribution mechanisms show a sharp increase in hop count as cluster size grows, leading to higher routing overhead and reduced scalability. Distance aware distribution significantly limits hop growth by routing requests through closer and more optimal paths. The consistent reduction in hops across all evaluated cluster sizes highlights the effectiveness of incorporating proximity information into routing decisions. By minimizing unnecessary traversal, distance aware distribution improves efficiency, scalability, and predictability of system behavior. These results confirm that hop optimized routing is essential for large scale distributed deployments.

Future Work: Future work will focus on simplifying distance aware routing logic through lightweight heuristics and decentralized decision making to reduce complexity while preserving effective hop count optimization in large distributed systems.

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