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Mitigating Latency in Chord-Based Routing under IPv6

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Abstract

As the transition to IPv6 enables a massive expansion of the peer-to-peer (P2P) network landscape, traditional Chord-based routing protocols face significant performance bottlenecks due to the lack of awareness of the underlying physical network topology. In this paper, we propose eChord, a topology-aware routing system designed to mitigate latency in large-scale IPv6 environments by exploiting network locality. The key of eChord is a bifurcated routing architecture that maintains dual routing states: a *localFinger* table for intra-domain routing within autonomous systems (AS) and a *globalFinger* table for inter-domain connectivity. By optimizing the identifier space and introducing a locality factor ρ to prioritize local lookups, eChord can effectively reduce the reliance on high-latency backbone links. We then perform a multi-dimensional efficiency analysis of the eChord system, in terms of expected hop number, end-to-end latency, and state maintenance overhead. Numerical simulations are finally provided to demonstrate that the proposed eChord system can significantly outperform standard Chord in various network scales. In particular, in a network of 10^6 nodes distributed across 500 ASs with a locality factor of $\rho = 0.8$, the proposed eChord system reduces the average routing latency by approximately 75% compared to the traditional, locality-agnostic Chord protocol.

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1. Introduction

IPv6 has been extensively studied as the fundamental solution to IPv4 address exhaustion, with a focus on architectural evolution and transition mechanisms [1–3]. To enable the coexistence of both protocols, three primary transition strategies have been proposed: dual-stack, tunneling, and translation [4, 5]. It is generally accepted that dual-stack architectures offer the most reliable native connectivity, whereas tunneling mechanisms, such as 6to4 and ISATAP, are utilized to encapsulate IPv6 packets over existing IPv4 infrastructure. The architectural design of the IPv6 protocol itself was optimized by simplifying the header structure to a fixed 40 bytes and eliminating the header checksum. This design decision was intended to reduce processing overhead at intermediate routers, thereby shifting fragmentation responsibilities to the source node and streamlining the packet forwarding process within the network core [6–8].

The performance analysis and the comparisons between IPv4 and IPv6 have been conducted across various operating systems and network topologies to evaluate throughput, latency, and jitter [9–11]. It has been observed in empirical studies that native IPv6 networks often exhibit performance parity with IPv4, benefiting from the streamlined header processing despite the larger address size [12–14]. However, distinct performance degradation is frequently recorded when transition tunneling techniques are employed, as the encapsulation and decapsulation processes are found to introduce additional CPU overhead and increased round-trip time (RTT). Furthermore, maximum transmission unit (MTU) issues have been identified as a critical factor in performance bottlenecks, where the additional header overhead in tunneling scenarios often leads to packet fragmentation and reduced effective throughput [15–17].

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In further, the system optimization on IPv6 networks has been performed as a critical area of research to address the requirements of modern mobility and quality of service (QoS) [18–20]. Standard mobile IPv6 (MIPv6) was initially found to suffer from high handover latency. Consequently, optimization protocols such as hierarchical mobile IPv6 (HMIPv6) and fast handovers (FMIPv6) were developed to localize signaling and minimize packet loss during network switching [21, 22]. Security optimization is also integrated into the system design through the mandatory support for IPsec, allowing authentication headers (AH) and encapsulating security payloads (ESP) to be processed end-to-end [23–25]. Additionally, network traffic optimization is facilitated by the flow label field in the IPv6 header, which is utilized to identify packet sequences requiring special handling, thereby ensuring that QoS parameters for real-time applications, such as VoIP and streaming media, are strictly maintained [26, 27].

This paper introduces **eChord**, a topology-aware routing system designed to minimize the end-to-end latency in large-scale IPv6 environments by leveraging network locality. The core of eChord is a bifurcated routing architecture that decouples routing states into two distinct structures: a *localFinger* table for intra-domain routing within autonomous systems (AS) and a *globalFinger* table for inter-domain connectivity. By refining the identifier space and introducing a locality factor ρ to prioritize local lookups, eChord significantly reduces dependence on high-latency backbone links. We then conduct a comprehensive efficiency analysis on the eChord system, evaluating key metrics including expected hop number, end-to-end latency, and state maintenance overhead. Numerical simulations are finally provided to demonstrate that eChord consistently outperforms the standard Chord protocol across diverse network scales. Specifically, in a network of 10^6 nodes distributed across 500 ASs with a locality factor of $\rho = 0.8$, the proposed system reduces average routing latency by approximately 75% compared to the traditional, locality-agnostic Chord protocol.

2. Proposed eChord System

In this section, we describe the architecture of the proposed eChord system, a hierarchical peer-to-peer routing framework optimized for the IPv6 address structure. Unlike the uniform identifier space of the standard Chord protocol, the proposed eChord system exploits network topology locality by bifurcating the logical ring into intra-domain and inter-domain layers.

2.1. Formalization of the Identifier Space

Let $\mathcal{A}$ be the set of all valid 128-bit IPv6 addresses. We define a mapping function $\mathcal{F} : \mathcal{A} \to \mathcal{I}$, where $\mathcal{I} = \{0, 1, \dots, 2^m - 1\}$ is the circular identifier space ($m = 128$). For any node N_i with address $A_i \in \mathcal{A}$, the address is partitioned into a network prefix P_i of length L and an interface identifier H_i such that $A_i = P_i \parallel H_i$. The node identifier $v_i \in \mathcal{I}$ is generated via a concatenated cryptographic hash:

$$v_i = \text{Hash}(P_i \parallel H_i) \pmod{2^m}. \tag{1}$$

This mapping ensures that nodes belonging to the same autonomous system, defined by the set $\mathcal{C}_k = \{N_i \mid P_i = P_k\}$, are logically grouped. We define the logical distance between two nodes v_i and v_j as:

$$d(v_i, v_j) = (v_j - v_i) \pmod{2^m}. \tag{2}$$

2.2. Dual-Tier Routing State Constraints

To optimize routing locality, each node v_i maintains a bifurcated routing state $\mathcal{R}_i = \{LF_i, GF_i\}$. The local table facilitates $O(\log |\mathcal{C}_i|)$ routing within the same AS. The j-th entry of LF_i is defined as the first node that succeeds v_i by at least 2^{j-1} within the local cluster $\mathcal{C}_i$:

$$LF_i[j] = \text{successor}(v_i + 2^{j-1}) \cap \mathcal{C}_i, \quad j \in \{1, \dots, m\}. \tag{3}$$

The global table maintains inter-AS connectivity. To minimize state redundancy, an identifier v_k is eligible for GF_i only if it resides in the "global gap" not covered by the local successor:

$$v_k \in GF_i \implies v_k \in \mathcal{I} \setminus [v_i, \text{Succ}(v_i)_{LF}]. \tag{4}$$

This constraint ensures that the global table only bridges long-range logical jumps that transcend the local administrative boundary.

2.3. Node Integration and SPNIS Logic

When a new node N_A joins the system, it should first resolve its Same Prefix Node Information Set (SPNIS). We define the SPNIS as the subset of active nodes sharing the longest common prefix match:

$$\text{SPNIS}(N_A) = \{N_i \in \text{System} \mid \text{PrefixMatch}(A_A, A_i) \geq L\}. \tag{5}$$

If SPNIS $\neq \emptyset$, N_A selects a bootstrap node N_B by solving the following proximity optimization problem in the identifier space:

$$N_B = \arg \min_{N_i \in \text{SPNIS}} d(v_A, v_i). \tag{6}$$

By joining through N_B, the node N_A inherits a routing state that is already localized to its physical network segment, accelerating the convergence of LF_A.

2.4. Global Consistency and State Update

To maintain the global reachability of N_A, the system employs a delegated registration mechanism. Let $\mathcal{H}_P = \text{Hash}(P_A)$ be the hash of the network prefix. The system identifies a supervisor node N_S such that:

$$v_S = \text{successor}(\mathcal{H}_P). \tag{7}$$

N_A performs an atomic registration U to update the prefix directory at N_S:

$$U : \mathcal{M}_S \leftarrow \mathcal{M}_S \cup \{(v_A, \text{IP}_A)\}, \tag{8}$$

where $\mathcal{M}_S$ is the metadata cache at node N_S. This formalizes the transition of N_A from an isolated node to a globally routable entity within the eChord hierarchy. Through this multi-tier registration, eChord maintains a global lookup complexity of $O(\log N)$ while reducing the expected physical latency $E[L]$ by a factor proportional to the local density $|\mathcal{C}_i|/N$.

3. Efficiency Analysis

In this section, we provide a rigorous theoretical analysis of the eChord system performance. We utilize a analytical model based on Chord's asymptotic properties, extending it to the hierarchical topology of eChord. We focus on three key metrics: routing path length (hops), end-to-end latency considering locality, and the storage overhead of routing tables.

Let N denote the total number of nodes in the network, and M denote the number of AS. We assume the nodes are uniformly distributed across domains, such that the average number of nodes per AS is $N_{AS} = N/M$.

3.1. Asymptotic Routing Complexity

In the standard Chord protocol, the routing process resolves a query in $O(\log N)$ hops with high probability. eChord modifies this by splitting the routing state into local and global scopes. For a query where the target key resides within the same AS as the source node, eChord utilizes the *localFinger* table. Since the local network forms a Chord ring of size N_{AS}, the expected number of hops $E[H_{local}]$ is governed by the logarithmic properties of the local ring:

$$E[H_{local}] = \frac{1}{2}\log_2(N_{AS}) = \frac{1}{2}\log_2\left(\frac{N}{M}\right). \tag{9}$$

This demonstrates that for localized traffic, eChord reduces the lookup complexity from $O(\log N)$ to $O(\log(N/M))$, providing significant optimization when M is large.

For inter-domain queries, the node should route to the boundary of the local scope or utilize the *globalFinger* table. The global table effectively overlays a coarser Chord ring over the entire identifier space. The expected number of hops for a global query, H_{global}, approximates the standard Chord behavior but is influenced by the density of the global fingers:

$$E[H_{global}] \approx O(\log N). \tag{10}$$

Although the hop numbers are asymptotically similar to standard Chord, the hierarchical lookup effectively decomposes the search space. The total path length H_{total} can be bounded by:

$$H_{total} \le O(\log N_{AS}) + O(\log M). \tag{11}$$

This summation confirms that eChord maintains the scalability of the original protocol while favoring local segments.

3.2. Latency Analysis with Locality Awareness

Latency is the critical metric where eChord aims to differentiate itself. Unlike previous simplistic models, we introduce a locality factor ρ $(0 \le \rho \le 1)$, representing the probability that a query targets a node within the same AS. Let δ_{intra} be the average transmission delay for an intra-domain hop, and δ_{inter} be the delay for an inter-domain hop. Typically, $\delta_{inter} \gg \delta_{intra}$ (e.g., 100ms vs 10ms). The expected end-to-end latency $E[L]$ for eChord is calculated as the weighted sum of local and global query latencies:

$$\begin{aligned} E[L_{eChord}] = \rho \cdot (E[H_{local}] \cdot \delta_{intra}) \\ + (1-\rho) \cdot (E[H_{global\_path}] \cdot \bar{\delta}), \end{aligned} \tag{12}$$

where $\bar{\delta}$ represents the average link latency in a mixed path. Specifically, a global path consists of both internal forwarding and cross-domain jumps. We can approximate the global path latency as:

$$L_{global} \approx \alpha \cdot \delta_{intra} + \beta \cdot \delta_{inter}, \tag{13}$$

where $\alpha + \beta = E[H_{global}]$. Comparing this to the standard Chord, which is agnostic to locality:

$$\begin{aligned} E[L_{Chord}] = E[H_{Chord}] \cdot ((1 - P_{local\_link})\delta_{inter} \\ + P_{local\_link}\delta_{intra}). \end{aligned} \tag{14}$$

In standard Chord, the probability of a link being local (P_{local_link}) is roughly $1/M$, which is very small. Thus, standard Chord latency is dominated by δ_{inter}.

Overall, the proposed eChord system minimizes the latency effectively when $\rho \to 1$ (high data locality). However, if $\rho \to 0$ and the network size N scales up, the overhead of maintaining the hierarchical structure may cause $E[L_{eChord}]$ to exceed $E[L_{Chord}]$. Specifically, the potential path stretch caused by routing through specific gateways or sparse global fingers.

3.3. Storage and Maintenance Overhead

The efficiency of P2P systems is also defined by the state maintenance cost. While the standard Chord protocol requires a single finger table with a complexity of $O(\log N)$, eChord maintains two distinct tables to support its hierarchical topology: a *localFinger* table of size $O(\log(N/M))$ and a *globalFinger* table of size $O(\log N)$. The total state size for eChord is:

$$S_{eChord} = O(\log \frac{N}{M}) + O(\log N) \approx O(\log N). \quad (15)$$

While the asymptotic storage complexity remains logarithmic, the constant factor is higher for eChord. This is because that as the network grows, the maintenance traffic for the dual-table structure consumes more bandwidth, potentially impacting the effective latency under high load conditions.

4. Simulations Results and Discussions

To validate the effectiveness of the proposed eChord protocol, we conduct a series of numerical simulations, focusing on the average routing latency across diverse network configurations. The simulation environment is structured as an IPv6 hierarchy consisting of M autonomous systems, where the total number of nodes N ranges from 10^2 to 10^6 to represent a large-scale peer-to-peer system. The network latencies are categorized into intra-domain delay δ_{intra} and inter-domain delay δ_{inter}, which are set to 10 ms and 100 ms by default, respectively, to simulate the inherent disparity between local and wide-area connections. The performance is assessed across varying degrees of data locality, represented by the factor ρ, which denotes the probability of a lookup target residing within the same AS as the initiator. The main parameters for the simulations in this paper are summarized in Table I.

Fig. 1 illustrates the expected end-to-end latency of the proposed eChord system versus the total network size N, ranging from 10^2 to 10^6 nodes, where there are 50 autonomous systems and the average intra-domain delay δ_{intra} and inter-domain delay δ_{inter} are set to 10 ms and 100 ms, respectively. From this figure, we can find that while the latency increases logarithmically with the total number of nodes N due to the inherent $O(\log N)$ hop complexity of the underlying protocol, the proposed eChord system achieves substantial performance gains as the locality factor ρ increases. This is because of the eChord's bifurcated routing architecture, which maintains a dual routing state to exploit the network topology locality. A higher ρ signifies a larger probability that queries are resolved within the local AS, where the routing process utilizes the *localFinger* table. This localized routing effectively reduces the expected hop number and ensures that the packet transmission is governed by the lower δ_{intra} rather than the significantly higher δ_{inter}, successfully mitigating the high latency typical of standard, locality-agnostic Chord protocols.

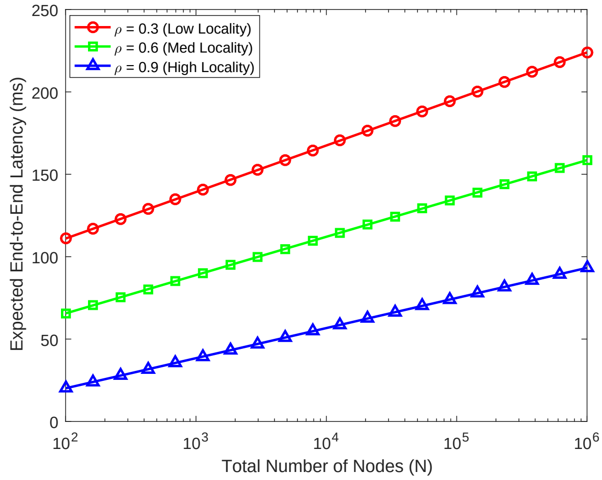

Figure 1. Latency of the proposed eChord system versus the total number of nodes N.

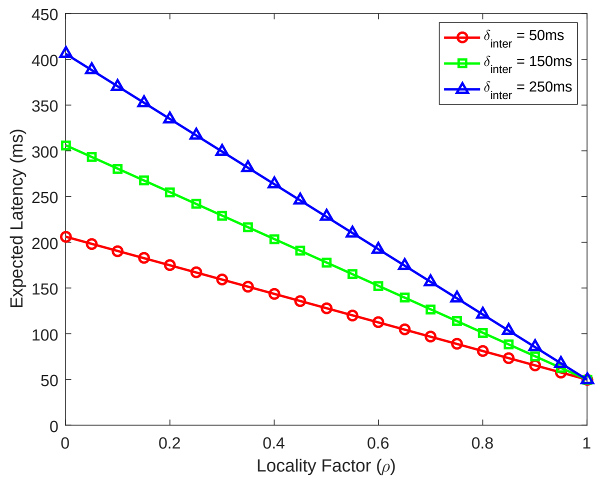

Figure 2. Latency of the proposed eChord system versus the locality factor ρ.

Fig. 2 illustrates the sensitivity of the eChord system's expected latency to the locality factor ρ versus the inter-domain delay, where the inter-domain delays δ_{inter} is set to 50 ms, 150 ms, and 250 ms. Additionally, the number of nodes in the network is set to 10^5 and there are 100 autonomous systems, with the intra-domain delay δ_{intra} set to 10 ms. From Fig. 2, we can see that the latency of the proposed eChord system becomes smaller as the locality factor ρ increases from 0 to 1. Notably, the performance gain is more pronounced in environments with higher δ_{inter}, where the slope of the latency reduction is steeper. This is achieved due to the eChord's topology-aware

Table 1. Simulation Parameter Settings

Parameter (Symbol)	**Value**
Total number of nodes (N)	$10^2 - 10^6$
Number of autonomous systems (M)	$50, 100, 10 \sim 500$
Intra-domain delay (δ_{intra})	10 ms
Inter-domain delay (δ_{inter})	100 ms (or $50 \sim 250$ ms)
Locality factor (ρ)	$0 \sim 1.0$ (e.g., 0.5, 0.8)
Identifier space length (L)	128 bits (IPv6)
Routing state structures ($\mathcal{R}_i$)	$\{LF_i, GF_i\}$

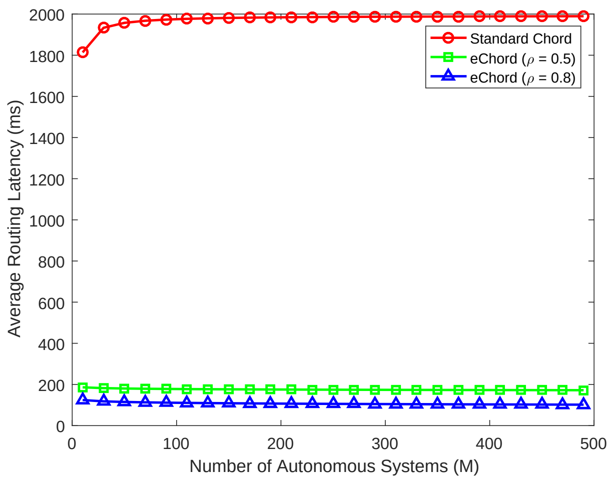

Figure 3. Latency comparison versus the number of autonomous systems M.

routing mechanism. In particular, a higher ρ implies that a larger proportion of lookups can be satisfied within the local AS using the *localFinger* table. This allows the system to "short-circuit" the global routing process, effectively substituting high-latency inter-domain hops with efficient intra-domain transmissions. By minimizing reliance on the δ_{inter} component, the proposed eChord system can effectively mitigate the propagation delays that typically bottleneck the standard Chord performance in wide-area IPv6 networks.

Fig. 3 presents a comparative evaluation of the average routing latency between the standard Chord protocol and the proposed eChord system as the number of autonomous systems M scales from 10 to 500, where there are 10^6 nodes in the network and the intra-domain and inter-domain delays are fixed at 10 ms and 100 ms, respectively. From this figure, we can find a significant and widening performance gap between the two protocols as the network becomes more fragmented with an increasing M. Specifically, the standard Chord's latency remains consistently high due to its locality and agnostic nature, where each routing hop has a high probability $(1 - 1/M)$ of incurring a costly inter-domain delay. In contrast, the proposed eChord system achieves a dramatic reduction in the end-to-end latency, due to the following two reasons. One reason is that as M increases, the number of nodes per AS (N/M) decreases, thereby reducing the expected local hop number $E[H_{local}]$ for eChord. Another reasons is that a higher locality factor ρ (e.g., 0.5 and 0.8) enables the proposed eChord system to resolve a majority of queries within the local domain using the *localFinger* table. By effectively "trapping" the search process within low-latency AS boundaries and bypassing the high-latency backbone links that bottleneck traditional Chord, the proposed eChord system achieves a superior scalability and efficiency in large-scale IPv6 environments.

5. Conclusions

This paper proposed a novel topology-aware routing system to minimize the end-to-end latency in large-scale IPv6 environments through the utilization of network locality. The proposed eChord system employed a bifurcated routing model that decoupled routing states into two separate structures: a localFinger table for intra-domain routing within autonomous systems and a globalFinger table for inter-domain connectivity. By refining the identifier space and incorporating a locality factor ρ to prioritize local lookups, the system substantially decreased reliance on high-latency backbone links. Thorough efficiency analyses were performed to assess key metrics, such as expected hop number, end-to-end latency, and state maintenance overhead. Numerical simulations showed that eChord consistently achieved better performance than the standard Chord protocol. Specifically, in a network of 10^6 nodes distributed across 500 ASs with a locality factor of $\rho = 0.8$, the proposed system reduced average routing latency by approximately 75% relative to the conventional, locality-agnostic Chord protocol.

5.1. acknowledgements

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