

Overlay Network Technology for Inter-Domain Routing Optimization: Postprint

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Abstract

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Full Text

Preamble

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Inter-Domain Routing Optimization Overlay Network Technology

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Abstract

The distributed management of the Internet has led to inherent defects in guaranteeing overall transmission quality, making inter-domain routing optimization overlay networks a hot technology for addressing this problem. This paper reviews the current state of Internet routing, provides a refined classification of existing overlay network types, and analyzes the advantages and disadvantages of

each category. On this basis, we discuss various challenges facing inter-domain routing optimization overlay network technology, including network conflicts and traffic oscillations. We also conduct an in-depth quantitative and comprehensive analysis of overlay network routing performance improvements. Finally, we summarize the key technical challenges in implementing a practical, efficient, and scalable inter-domain routing optimization overlay network.

1 Introduction

The development of the Internet, centered on TCP/IP technology, originated from military requirements for survivability under attack. It emphasizes the independence, distribution, and autonomy of individual subnets. After more than 20 years of commercial evolution, the Internet has established an unshakable position in the field of network communications due to its excellent uniformity and compatibility. Its explosive growth and applications were even unforeseen by its original designers. Today, the scale of the Internet continues to expand rapidly. Although data exchange and routing hardware and software technologies are constantly innovating and advancing, the Internet's characteristics of distribution and independence have remained fundamentally unchanged. The vast Internet is controlled and managed by many different organizations and operators, and their competing interests and differences have become serious constraints on Internet evolution. Numerous global failure incidents in recent years, such as the Taiwan submarine cable rupture and the Pakistan Telecom Authority's blocking of YouTube, have revealed that the Internet, which appears increasingly mature and sophisticated on the surface, remains extremely fragile.

In response, Internet-related institutions and organizations have made many efforts to overcome this fragility and provide corresponding transmission quality guarantees for various services. As early as the 1990s, the IETF recognized these defects in the Internet and proposed various overall Quality of Service (QoS) architecture solutions such as DiffServ and InterServ [1][2]. However, implementing these solutions requires two basic conditions: first, all routers along the communication path must perform unified and coordinated service scheduling and buffer control; second, when end-to-end network traffic traverses multiple network domains maintained by different Internet Service Providers (ISPs), active cooperation and coordination from ISPs are required. For commercial reasons, ISPs only hope to obtain maximum market returns with minimum investment, and each ISP is only willing to provide service guarantees for transmission quality and survivability within its own network domain, unwilling to increase burdens for improving overall service quality.

Consequently, to date, almost no effective overall solution has been implemented on the existing Internet. On the other hand, a large number of emerging applications such as audio-video interaction, IPTV, and online games, which have strong real-time requirements, have increasingly become mainstream network content. Their demand for overall IP network service quality is growing stronger.

How to provide satisfactory overall data transmission performance for services spanning multiple network domains (i.e., inter-domain transmission) has become one of the most challenging focal issues in current network technology research.

Clearly, in today's vast network environment, research limited to a single layer of IP routing protocols can hardly solve the problem. New-generation network routing technologies need to seek an intermediate layer model mechanism that can provide end-to-end service capabilities across different networks, operators, and management domains while ensuring forward compatibility with existing IP protocols. In this environment, overlay networks built on top of the IP layer have emerged and gradually become the mainstream approach to solving these problems. Over the past decade, foreign research institutions have proposed numerous specific network structures and construction schemes, such as Detour, Resilient Overlay Network (RON), QRON, SON, NIRA (New Inter-Domain Routing Architecture), and so on. However, due to various constraints, none of these schemes have achieved large-scale deployment, and network development once again hesitates at a crossroads.

This paper attempts to classify and discuss these inter-domain routing optimization technologies, summarize their advantages and disadvantages, and based on this, conduct an in-depth review and analysis of the feasibility and key challenges of overlay network technology in inter-domain routing optimization. The rest of this paper is organized as follows:

Section 2 reviews the research status of existing routing optimization overlay networks and provides a complete classification of their types, summarizing the technical advantages and disadvantages of each type. Section 3 discusses various problems and challenges facing inter-domain routing optimization overlay network technology. Section 4 analyzes the key technical issues in implementing an efficient and scalable inter-domain routing optimization overlay network. Section 5 presents conclusions and future outlook.

2 Overlay Network Research Status and Classification

The concept of overlay networks can be traced back to the early Internet. In a sense, the Internet itself can be viewed as a huge overlay network, with the IP layer as the overlay layer, using IP protocols to provide "best-effort" data transmission services across heterogeneous underlying networks such as Ethernet and Token Ring. The rise of overlay networks stems from the fact that existing Internet inter-domain routing capabilities have become increasingly unable to meet the needs of various carried services.

2.1 Current Internet Inter-Domain Routing Status

As early as 1995, Paxson et al. began statistical studies on the routing performance of the burgeoning Internet [3], finding that the network experienced approximately 3.3% severe routing failure rates, with over 20% of path failures unable to be repaired within 10 minutes. Labovitz et al.'s statistics from 1997

to 2000 showed that 10% of routers in the existing Internet had reliability below 95%, 65% had reliability below 99.9%, and failure recovery times often reached 15 minutes, with over 40% of routing failures requiring more than 30 minutes to return to normal [4]. Chandra et al. discovered through active probing that 5% of failures in the Internet could even persist for over 2.75 hours [52].

For historical reasons, the existing Internet is actually a massive network composed of many relatively independent Autonomous Systems (ASes) interconnected through the Border Gateway Protocol (BGP). Each AS is generally controlled by an independent entity, mostly commercial organizations such as ISPs. The BGP protocol is the current inter-AS border gateway routing protocol used on the Internet. As the core component of the Internet, it is the basic mechanism and interconnecting bond for transmitting network information between all ASes, as well as the primary means for ISPs to implement policy control, playing a crucial role in Internet evolution. However, since its inception in 1989 and revision to the fourth version in 1995, BGP has remained almost unchanged.

For scalability considerations, BGP only uses simple hop count as a metric, which results in the so-called “best path” not being optimal in terms of routing performance [5]. To avoid “route flapping” caused by frequent path updates, BGP does not perform real-time path performance probing and adopts single-path selection. This causes traffic to be unable to avoid congestion points when links become congested, and after failures occur, it exhibits severe slow convergence characteristics [6][7].

These measurement results and research conclusions fully demonstrate that the current end-to-end Internet inter-domain routing mechanism neither guarantees optimal transmission quality between end hosts nor enables rapid failure recovery or response. To compensate for BGP’s defects, researchers have proposed various extension schemes for BGP [8-10]. However, these ideas and suggestions all require large-scale additional upgrade deployments, lacking transitional feasibility.

2.2 Overlay Network Research Status and Classification

2.2.1 Overlay Network Application Status To overcome the inherent defects of Internet inter-domain routing and meet the security, stability, reliability, and other requirements of emerging services, people have constructed various specialized overlay networks for specific service types. Examples include Content Distribution Networks (CDN) for publishing and streaming media data [11], end system multicast (ESM) technology [12] and Overcast systems [13] for application-layer multicast, Peer-to-Peer (P2P) networks for file sharing [14], the PlanetLab emulation testbed [15], and various combined service networks [16].

These networks are virtual networks composed of a series of service nodes distributed within various ASes of the Internet and logical links connecting them. Through forwarding by service nodes, user terminals can more effectively utilize

Internet resources and provide performance requirements that existing Internet routing cannot satisfy for corresponding services. The greatest advantage of this overlay network implementation lies in its flexible and convenient deployment on top of the underlying network without requiring changes to the existing network architecture.

In recent years, inspired by research on these application overlay networks, overlay networks supporting QoS routing have rapidly become a hot technology for solving problems such as slow fault convergence and poor stability in Internet cross-domain transmission. As an intermediate layer model mechanism, routing overlay networks can improve end-to-end network transmission quality and meet user application performance requirements by enabling nodes to collaboratively and proactively select efficient paths for routing data packets, thereby providing more reliable and fault-tolerant services [17][18][19]. In typical routing overlay network technologies such as Resilient Overlay Network and Detour [20], researchers have verified through experimental network deployments the tremendous advantages of using routing overlay networks for cross-domain transmission in terms of rapid response, fault recovery, and QoS guarantees compared to BGP.

2.2.2 Classification of Inter-Domain Routing Optimization Overlay Networks Based on different overlay network implementation technologies, these cross-domain QoS routing support overlay networks can be divided into two major categories: relay-type overlay networks and Virtual Network (VN)-type overlay networks. According to the location of networking nodes and system implementation layers, they can be further subdivided into network-layer overlay networks and application-layer overlay networks.

(1) Relay-Type Routing Optimization Overlay Networks

The principle of relay-type overlay networks is that the sender transmits packets to a relay node, which then forwards them to the receiver, forming a multi-hop overlay network path. Since two-hop overlay network paths provide performance, reliability, and path diversity similar to those provided by multi-hop overlay network paths [21], most overlay network research adopts two-hop overlay network paths forwarded through a single relay node for simplification and ease of implementation.

Resilient Overlay Network (RON)

Resilient Overlay Network is a typical representative of relay-type overlay networks [17]. In terms of system implementation layer, it is an application-layer overlay network built on top of the existing Internet routing hierarchy. Applications built on it can utilize the Resilient Overlay Network routing library established on the underlying network to re-select paths on the existing Internet. The architecture of Resilient Overlay Network is shown in [Figure 1: see original paper]. It adopts a two-hop relay application-layer routing approach. System nodes monitor path functions and performance between each other, periodically

checking network path conditions between themselves and other nodes. The application layer can evaluate comprehensive multi-dimensional metrics including delay, packet loss rate, and throughput for multiple forwarding paths generated by selecting different transit nodes, and then choose forwarding paths that meet service QoS requirements. Simultaneously, the application-layer routing approach adopted by Resilient Overlay Network can also utilize hidden paths that BGP protocols cannot discover or utilize during cross-domain transmission for rapid routing fault recovery, improving packet transmission reliability. Although Resilient Overlay Network achieves good transmission optimization effects between point-to-point connections and can react quickly in small-scale network environments, it has many shortcomings:

First, Resilient Overlay Network nodes must send probe packets intensively in a fully meshed connection manner at fixed time intervals. This small-interval, frequent probing creates huge overhead for the network, greatly limiting the scalability of Resilient Overlay Network.

Second, Resilient Overlay Network's virtual network uses static management, with forwarding nodes limited to a few server nodes. The structure is not flexible enough to fully and effectively utilize hidden paths and private paths.

Finally, Resilient Overlay Network's path selection is based solely on performance comparison among neighbor nodes currently probed by flooding, without reference to the underlying topology. Therefore, the correlation between overlay network paths and underlying default IP paths is high, making it powerless against certain performance degradations and path failures that occur on the Internet.

QRON (QoS-Aware Routing in Overlay Networks)

To address the scalability and application-specific performance optimization issues of Resilient Overlay Network, Li et al. proposed the QRON architecture [22], attempting to use a generic Overlay Service Network (OSN) to meet the needs of various application-layer services.

QRON utilizes Overlay Brokers (OBs) to establish the overlay service network. These OBs are deployed by overlay network service providers in various ASes across the Internet, collaborating with each other to form an overlay service network that provides services to upper-layer applications, such as resource allocation and negotiation, overlay relay routing, and topology discovery. QRON focuses on designing a QoS-aware routing protocol, primarily aiming to find overlay network paths that satisfy QoS requirements for upper-layer QoS-sensitive overlay applications while performing overlay network traffic balancing. Since OBs in QRON adopt a hierarchical organization and are clustered based on "network distance," QRON has relatively good scalability.

The QRON architecture is shown in [Figure 2: see original paper]. Compared with Resilient Overlay Network, QRON is a relay overlay network with virtual network properties. Its hierarchical deployment offers better scalability;

its path performance-based routing selection algorithm provides higher routing efficiency; and it designs a generic QoS-aware routing protocol with good universality. However, QRON is a network-layer overlay network, and all its nodes require self-deployment at high cost. Additionally, when evaluating path performance, QRON only measures packet loss, delay, and available bandwidth, and its measurement methods lack accuracy. This routing algorithm designed with inaccurately measurable available bandwidth greatly limits its universality.

Spines Overlay Network

Spines is a generic overlay network system developed by the Distributed Network Laboratory at Johns Hopkins University [25][26], with open source code that can be used for testing and developing overlay network protocols. Spines provides a two-level hierarchical structure. User programs connect to the nearest overlay node. This overlay node sends or forwards data to the destination address through the overlay network. Spines operates at the application layer, requiring no changes to infrastructure and core access, thus offering good deployability like Resilient Overlay Network. The benefit of its two-level structure is that it can limit the scale of the overlay network to reduce the amount of data exchanged for flow control information. Overlay nodes serve as both servers for connecting various applications and as forwarding routers for transmitting data packets between nodes. Due to this hierarchical structure of Spines, applications can be located either at overlay nodes or on other machines connected to the nodes. Obviously, Spines offers significant improvements in scalability compared to Resilient Overlay Network. Through the Spines system, services can achieve low-overhead reliable transmission, improve real-time transmission characteristics such as delay, packet loss rate, and throughput, and support multimedia services with high QoS requirements, such as VoIP and video conferencing.

However, Spines networks also have their own disadvantages: on one hand, Spines only supports fixed-node topology structures, and nodes cannot dynamically join or leave the Spines network. Once a node or link fails, it may require nodes to transmit information over much longer paths or even cause the entire network to collapse. On the other hand, the topology structure established by Spines is often not optimal and may have no understanding of the actual underlying network topology, resulting in poor transmission flexibility and efficiency.

(2) Virtual Network-Type Routing Optimization Overlay Networks

Like relay-type overlay networks, virtual network-type overlay networks also place nodes at key network locations. However, nodes in virtual network-type overlay networks differ from relay-type nodes in that they also have functions such as monitoring underlying network resource distribution, bandwidth utilization, link performance, and traffic load, and can perform dynamic resource allocation based on monitoring results to achieve overall network performance optimization. Virtual network-type overlay networks can be understood as “virtual overlay private networks,” where end-user traffic can be transmitted within the scope of this virtual network.

Detour Routing

The Detour routing system proposed by Savage et al. in 1999 can be considered an early virtual network-type routing overlay network. It consists of a set of distributed edge routing nodes connected through tunneling technology. Traffic data entering Detour ingress nodes is re-encapsulated into new IP packets, transmitted along the Internet to Detour egress nodes, and finally delivered to users (as shown in [Figure 3: see original paper]).

Detour attempts to study performance-sensitive new routing algorithms on a large-scale network to improve Internet network performance. It mainly includes two functions: virtual network management and node routing control. User nodes enter the Detour virtual network by changing their default router to an edge Detour node near the user, and transmit traffic to destination nodes through it.

Compared with Internet routing, the Detour system performs router selection adjustments on a minute-level time scale. By employing techniques such as detour routing, single-flow multi-path transmission, and packet classification, it can improve end-to-end transmission performance to some extent. However, its overhead and limitations are also obvious: first, Detour virtual network is deployed on top of underlying routing nodes and runs independent algorithms. To form a unified large-scale network applicable across the Internet, the deployment cost would be extremely high. Second, even if the default Internet routing is more efficient, all user traffic using Detour will still be transmitted through the Detour network. This increases Detour' s load, causing it to face the same old problems of scalability and efficiency contradictions as the original Internet. Additionally, Detour' s network structure lacks flexibility and cannot fully and effectively utilize the large number of hidden paths on the Internet.

OverQoS

If the Detour network still has characteristics of relay-type overlay networks, then OverQoS [23] is a very typical virtual overlay network. In the OverQoS architecture, service providers purchase network access rights from traditional ISPs and then deploy OverQoS nodes in different routing domains to form an overlay network. In traditional QoS mechanisms, IP routers are responsible for controlling packet buffers and output link bandwidth, while OverQoS nodes do not consider underlying performance. It introduces the concept of Controlled-Loss Virtual Link (CLVL). By controlling the aggregation speed of flow bundles, the packet loss rate can be maintained within a small range. Therefore, regardless of how the network environment changes, OverQoS can obtain a lower-bound QoS service, thereby achieving statistical guarantees for bandwidth and packet loss rate metrics.

OverQoS networks belong to network-layer overlay networks, thus having the same deployment cost issues as Detour. At the same time, OverQoS' s optimization of stream transmission mainly guarantees bandwidth statistically by smoothing packet loss and assigning priority to data packets, without consid-

ering other transmission performance metrics, which limits the effectiveness of application transmission optimization.

SON (Service Overlay Networks)

SON [24] is an overlay network used to solve end-to-end QoS and build and deploy QoS-sensitive services. It provides a logical end-to-end service transmission platform by purchasing network bandwidth with QoS guarantees from various network domains. SON provides value-added network services to users through service level agreements and fee collection. SON' s structural concept is also closest to the virtual network model.

3 Inter-Domain Routing Optimization Overlay Networks

Although existing research shows that routing overlay networks can improve service transmission quality to some extent by utilizing Internet redundant paths and adopting various methods, truly deployable overlay networks for inter-domain routing optimization still face many practical problems that need to be solved. First, in terms of implementation difficulty, to solve existing Internet inter-domain routing problems, overlay network approaches need to be widely compared with alternative solutions such as rebuilding protocol layers or adopting multi-homing to establish their advantages. Second, from a management perspective, as a supplement to the Internet, routing overlay networks will face the same scalability and manageability issues as the Internet once deployed on a large scale. Careful consideration must be given to whether their traffic optimization functions will conflict with IP-layer traffic management strategies of various ISPs and with other overlay networks, causing network oscillations. Third, the improvement capability and overhead of overlay network solutions on network traffic performance need further quantitative comparison. Finally, there is disagreement over whether overlay network technology should be implemented by upgrading routers or deploying terminal servers.

3.1.1 Overlay Networks vs GENI, FIRE

GENI is a next-generation experimental research network project promoted by the U.S. National Science Foundation (NSF) [37]. Unlike overlay networks that meet compatibility and transition requirements, GENI considers “global network needs after 15 years” and how to build networks from scratch without constraints (Clean-slate). Its research directions are not limited to infrastructure but also include principles, protocols, architecture, and design solutions. Currently, participating schools and research institutes in GENI include almost all top-tier institutions in the United States: Stanford, MIT, Princeton, and even the Department of Defense. Actively participating companies include Cisco, Fujitsu, HP, Microsoft Research, NEC, and many other well-known international enterprises. GENI' s core architectural concepts require programmability, virtualization, and resource sharing.

The EU also has a similar project for innovative network architecture design

called FIRE (Future Internet Research and Experimentation) [38]. FIRE's principle is to promote test-based research, combining forward-looking academic research with industrial testing and experimentation. Similarly, FIRE is also committed to creating large-scale, dynamic, and sustainable experimental facilities in Europe, a process that will link and unite various small-scale testbeds currently in existence.

However, whether GENI or FIRE, these “clean-slate” national research efforts are still in their infancy—it may be difficult to expect meaningful results within 10 to 15 years. Compared with overlay network technology, GENI and FIRE represent a completely new revolution, but from a practical standpoint, evolution may be a more realistic choice. Because today's Internet far exceeds what academia can control, starting over faces much greater difficulties today than the Internet's initial creation faced 40 years ago.

3.1.2 Overlay Networks vs Multi-Homing

Compared with overlay network deployment, multi-homing is a simpler performance optimization method. Large enterprises or small ISPs typically connect to the Internet in this way to obtain more reliable and stable routing performance. However, using multi-homing to access the Internet requires paying ISPs for redundant link usage fees, with optimization effects proportional to cost. Goldenberg et al. established a cost model, combined with optimization of performance metrics such as delay, and designed an intelligent multi-homing algorithm [39]. Through this algorithm, network performance can be improved by about 18% at the cost of adding one ISP connection on top of single connection.

Akella conducted a detailed comparison of the optimization capabilities of overlay networks and multi-homing relative to default routing in terms of Round-Trip Time (RTT), throughput, and other aspects [40]. The tests showed that with a single overlay network and single multi-homing, overlay networks have better optimization capabilities, with delay metrics averaging 33% better and throughput 15% better. In the case of K multi-homing ($K > 3$), multi-homing network performance is slightly better than overlay network technology compared to a single overlay network. If overlay network technology is used on top of multi-homing ($K > 3$), performance improvement is very limited (about 10% delay improvement and 5% throughput improvement). At the same time, ISPs need to sign complex traffic forwarding agreements with each other to use overlay network technology. Therefore, Akella believes that ISPs can completely improve network performance through intelligent routing mechanisms based on multi-homing without needing to specifically build overlay networks.

However, although multi-homing implementation is simple, multiple accesses cause client costs to multiply, while overlay networks can provide a large number of discrete paths after scaling up, further improving optimization cost-effectiveness. Therefore, Zhu et al. proposed in [41] that the advantages of both can be combined to form a MON (Multihomed Overlay Network) and con-

ducted in-depth discussions on MON' s deployment location, design methods, and operational overhead. Their theoretical analysis results show that using the Overlay Service Provider (OSP) operation model can not only improve comprehensive network performance but also reduce operational costs and increase profit margins compared with traditional ISPs. However, since MON design is a complex NP problem, obtaining optimal optimization results requires collecting and analyzing global information on users, traffic, and performance, which to some extent limits its application. Therefore, Okada et al. further studied cooperative routing methods for multiple coexisting overlay networks and proposed a relatively simple cooperation protocol, though its effectiveness still needs further verification in real network environments [42].

3.1.3 Overlay Networks vs Other New Architectures

Inspired by the active routing characteristics of overlay network technology and multi-homing, researchers have proposed some compromise network transformation solutions. A typical representative is the NIRA (New Internet Routing Architecture) proposed by Yang et al. [43].

Similar to overlay network technology, NIRA is a user-oriented active routing model. By designing a new Internet inter-domain routing architecture, NIRA enables end users or applications to select a series of ISPs that their data packets traverse. By giving end users more routing control at the domain level, NIRA can force ISPs to compete with each other to improve service levels on one hand, and bring technical benefits to improve routing reliability on the other. NIRA uses TIPP (Topology Information Propagation) for topology information dissemination to achieve routing discovery; adopts hierarchical addressing for efficient route description; and uses NRLS (Name-to-Route Lookup Service) for name-to-route-fragment query conversion when users initiate communication. Based on these key technologies, NIRA has developed a complete routing system that supports user routing selection.

Although NIRA draws on research experience from multi-homing and overlay network technology in routing improvement [44], avoiding their respective shortcomings, and its hierarchical addressing approach can greatly reduce routing state recorded in routing tables, solving scalability issues, NIRA requires deployment on backbone networks at great cost. Additionally, its end users require complex configuration, users have difficulty predicting service quality, and there are risks of exposing ISPs' routing business secrets. These factors all limit NIRA' s application and expansion.

3.2 Cross-Domain Routing Optimization Overlay Network Conflicts

Cross-domain routing optimization overlay networks are typically composed of standby nodes distributed in different network domains, performing QoS control through application-layer routing or virtual routing networks. The idea is to transfer routing decisions to the application layer, which selects corresponding

paths based on its own requirements for end-to-end delay, packet loss rate, or throughput, thereby breaking the IP layer's monopoly on routing.

However, allowing both the service layer and IP layer to simultaneously control traffic routing may trigger contradictions and conflicts between various independent traffic management and optimization strategies [27]. For example, in the network structure shown in [Figure 5: see original paper], the backup path $A \rightarrow C \rightarrow F \rightarrow G$ for communication node pair A-G in overlay network 1 overlaps with communication node pair C-K in overlay network 2 ($C \rightarrow F$), while the backup path for C-K also overlaps with node pair B-H in overlay network 3 ($B \rightarrow E$). When the D-G path fails or becomes congested, overlay network 1 will shift its upper-layer traffic to the backup path ($A \rightarrow C \rightarrow F \rightarrow G$), thereby increasing the traffic load on link C-F. If this traffic migration reduces communication quality between C-K, overlay network 2 will shift its traffic to its backup path ($C \rightarrow B \rightarrow E \rightarrow H \rightarrow K$). Similarly, since overlay network 2's backup path contains link B-E that overlaps with the default path between node pair B-H in overlay network 3, once this migration affects communication between B-H in overlay network 3, overlay network 3 will shift traffic to its backup path ($B \rightarrow A \rightarrow D \rightarrow F \rightarrow H$). This is just the traffic migration triggered by link performance changes in a simple topology with 3 overlay networks and 9 nodes. In scenarios with more overlay networks and larger topology scales, traffic fluctuations triggered by single events become more complex and may even cause large-scale network oscillations due to repeated path switching [28].

We can summarize the network conflicts caused by traffic optimization in overlay networks into two categories: parallel conflicts and vertical conflicts. Parallel conflicts refer to conflicts between traffic of one overlay network and traffic of other overlay networks or background traffic, as shown in the figure above. Vertical conflicts refer to conflicts between overlay network traffic and ISP traffic management strategies. ISPs use Traffic Engineering (TE) strategies to cope with dynamic changes in network performance (such as link failures, BGP failures, traffic congestion). Traffic engineering generally performs traffic balancing through dynamic estimation of traffic matrices (TM) [30]. ISPs typically make two assumptions about traffic engineering: (1) traffic demand will not change significantly in a short time; (2) changing transmission paths within the domain will not change the traffic demand itself. Inter-domain routing overlay networks precisely violate these two assumptions.

3.2.1 Parallel Conflicts Among Multiple Overlay Networks Numerous researchers have conducted in-depth theoretical analysis and experimental verification on the parallel and vertical conflicts generated by overlay network optimization. Regarding parallel conflicts, most researchers believe that co-existence competition based on greedy optimization strategies among various overlay networks will reduce overall network performance [31][32][33]. On this basis, Jiang et al. used a non-cooperative game model to further conduct theoretical analysis and simulation experiments on overall optimization strategies,

overlay-based optimization strategies, and selfish optimization strategies among multiple overlay networks sharing underlying links. Their results suggest that overlay-based optimization strategies have performance close to the optimal solution (overall optimization strategy), while the selfish optimization strategies adopted by existing overlay networks are inferior to the aforementioned two strategies in terms of both overall network performance and individual service performance of single overlay networks [34].

However, Qiu' s simulation results in a single AS environment using the OSPF protocol show [29] that regarding parallel conflicts, overlay networks do not degrade performance as much as indicated by the aforementioned research conclusions. In an Internet-like environment, when each independent overlay network adopts selfish routing optimization methods, both average network delay and link utilization efficiency in the game equilibrium state are close to optimal results, though they cause system overhead due to frequent overloading of some shortest paths. Even increasing the number of overlay networks has only a very slight impact on end-to-end average delay. This indicates that after adopting existing overlay networks' selfish routing methods, the impact of parallel conflicts on performance degradation is not significant. Qiu' s simulation results also show that when network-layer routing mechanisms are reasonably configured, different overlay network routings can coexist well.

The fundamental reason for these divergent research results lies in different comparison objects and simulation environment differences. Researchers who believe that overlay networks' selfish routing methods degrade overall performance base their comparison algorithms on the premise of global information sharing and centralized control management, basically without considering the impact of network-layer protocols (such as OSPF, MPLS, etc.) on overlay network optimization algorithms. When Qiu et al. measured the impact of parallel conflicts in multiple overlay network optimization on performance, they used a simulation environment close to the real Internet, comparing delay and network throughput performance with both information-sharing-based optimization control and Internet default passive routing.

Obviously, implementing large-scale global detailed information sharing or centralized routing in the current Internet environment would be extremely constrained in feasibility. Relatively, implementing an independent overlay network system for specific service routing requirements appears more practical. Therefore, Keralapura et al. further studied the resource synchronization competition phenomenon in overlay network coexistence [28]. Their results show that even when overlay networks adopt different path performance probing methods, they may still cause synchronized competition for optimal links. This competition affects not only the optimization performance of each overlay network but also non-overlay network traffic in the network. By adding random parameters to the probing algorithm and using exponential backoff-based resource competition algorithms, the probability of overlay network synchronization and synchronization oscillations can be effectively suppressed.

3.2.2 Vertical Conflicts Between Overlay Networks and ISP Networks

Regarding whether overlay network applications will conflict with ISP network traffic engineering and reduce network performance, researchers' conclusions are relatively consistent. Qiu's research shows that after introducing dynamic traffic matrix $T_t(s,d)$, due to overlay networks' proactive adjustment of their own traffic, traffic matrices change frequently, increasing the difficulty for traffic engineering strategies to optimize the underlying layer. The conflict between their respective optimizations instead reduces overall network performance. At the same time, Qiu also found that when MPLS protocol is used for underlying traffic optimization, it has better coexistence capability with overlay networks compared to OSPF. The reason is that MPLS has richer means for routing traffic regulation.

Liu et al. constructed a simulation environment for an overlay network system completely isolated from the underlying network and using independent optimization strategies [35], assuming that overlay networks and ISP traffic engineering perform same-frequency Nash game. Based on this, they found that if overlay network systems frequently optimize their performance, it would instead greatly increase their overhead and ultimately lead to degraded optimization performance. This is because after overlay networks select paths, dynamic traffic matrices will adjust their own routing to minimize overall network overhead, while updated traffic engineering strategies will increase overlay network overhead. This interactive game will repeat until Nash equilibrium is reached. Liu's simulation experiments also show that using MPLS protocol-based traffic engineering can achieve better optimization effects compared to OSPF. At the same time, when overlay network traffic dominates, its routing decisions have very significant impact on traffic engineering overhead.

Although these research results indicate that ISPs using MPLS-based traffic engineering strategies could theoretically avoid vertical conflicts when overlay networks perform traffic optimization, many challenging issues remain in practical applications, such as obtaining dynamic global traffic matrix information and large-scale linear programming implementation. Therefore, ISPs' attitude clearly tends to restrict the development of overlay network applications to reduce network overhead and prevent overall performance degradation.

However, Wang et al. approached from a business model game perspective [36] and found through modeling and derivation of intra-domain and inter-domain traffic that large ISPs will fall into a dilemma at Nash equilibrium: when the traffic model migrates from traditional Web service methods to overlay network methods, it not only leads to network traffic instability but also allows small ISPs to enjoy free-riding benefits. Simply reducing or limiting overlay network end-user traffic would damage ISP business, affect access pricing power, and lead to customer loss; reducing private link usage would affect other services and network expansion, harming their own and Internet development.

In summary, overlay networks have become an irreversible technical trend. Their emergence strengthens the loose coupling of the Internet based on BGP

protocols, different ASes will influence each other, traffic matrices become more dynamic and complex, and traditional traffic balancing strategies will be broken. ISPs must fully understand overlay networks and adopt corresponding countermeasures based on this understanding, including statistical analysis of characteristics and patterns and providing good interactivity and information sharing mechanisms. Overlay networks should also understand ISP routing strategies and underlying information as much as possible and adopt corresponding mechanisms such as random path probing to avoid synchronization oscillations and prevent adverse effects on other overlay network traffic and network background traffic (non-overlay network traffic).

3.3.2 Analysis of Improvement Capabilities of Inter-Domain Routing Optimization Overlay Network Technology

The degree of improvement that overlay network technology provides over traditional Internet routing in terms of network performance directly relates to its research value and application prospects. Therefore, debates about the practicality of overlay networks have never ceased. As mentioned earlier, research on overlay networks over the past decade can be roughly divided into relay-type overlay networks and virtual network-type overlay networks. The latter is often related to optimizing specific metrics for particular services, making quantitative evaluation and analysis difficult. Therefore, most simulation and testing schemes have focused on relay-type overlay network routing.

[Figure 6: see original paper] shows the cumulative distribution of independent shortest paths measured between all node pairs on 1,235 edges among 42 nodes on RouteView [45]. The figure shows that 17.4% of shortest paths have 1 independent shortest path, 6.0% have 2 independent shortest paths, etc. The final statistics show that 93.7% of shortest paths have at least 1 independent shortest path. This fully demonstrates that the current network has very high path redundancy. However, due to limitations of current Internet routing protocols, including inter-domain BGP and intra-domain OSPF, these large numbers of hidden paths usually cannot be discovered and utilized by routing protocols. For example, many ISPs do not accept BGP announcements initiated by fewer than 8,192 contiguous address blocks. Thus, even if these networks have multiple connections with other networks, they become hidden paths that cannot be used because they cannot be found in BGP routing tables. Additionally, with network development, many private links have been created between networks. These private links could originally be used to optimize transmission but cannot be found by current network protocols. Overlay networks can discover and utilize these redundant paths through active probing and interaction between nodes.

Table 1 shows performance statistics for relay-type overlay network optimization. As early as 2001, Andersen et al. proposed Resilient Overlay Network, which later became a typical representative of relay-type overlay network routing. Their test results showed that overlay network routing optimization capa-

bility is related to the network environment. Akella, Opos, and Lee conducted comparative tests of overlay network and BGP routing performance in larger network environments [40][46][49], with optimization effects more significant than those in Resilient Overlay Network tests. Hiraoka and Uchida [47][48] tested the improvement degree of overlay networks on network delay and throughput in Japan using different schemes based on the PlanetLab platform and distributed measurement points. In all test schemes, overlay network optimization adopted relay forwarding technology, providing optimal transmission paths for end-to-end services by traversing all forwarding node pairs, thus their system overhead is $O(N^2)$.

The same cross-domain optimization overlay network scheme, even on the same test platform, shows very large differences in performance improvement. The reason is that the test schemes of Akella and Opos are non-complete tests, meaning they only selected some network nodes with poor performance as test points. This results in average performance improvement much higher than other complete test schemes. Even with complete test schemes, due to different network environments, Hiraoka and Uchida's measurements show large differences in delay optimization results. Overlay networks' delay improvement capability for real node platform communications is not as good as their performance on the PlanetLab platform. S.J. Lee's complete test results show that although overlay networks have a large number of redundant paths, the number of nodes that can simultaneously provide low-delay, high-bandwidth forwarding accounts for only a very small proportion. Significant throughput improvement requires sacrificing delay performance.

Comprehensive analysis of these test results reveals that overlay network technology provides more obvious system performance improvement in poorer network environments. This is because when the network environment is good, relay-type overlay networks need to perform one or multiple forwardings at the application layer or network layer of intermediate nodes, and the additional overhead generated reduces optimization effects. Additionally, due to the existence of a large number of redundant paths with varying performance, overlay networks can specifically optimize for a particular metric required by an application, thereby achieving greater improvement in related performance. Therefore, under current Internet conditions where robustness and stability need improvement, researching how to deploy overlay network technology at the application layer and solve its key issues clearly has great practical value.

4 Implementation of Efficient Inter-Domain Routing Optimization Overlay Networks

As mentioned earlier, since network-layer overlay networks are generally provided by third-party ISPs, such as Detour and OverQoS, although they have advantages of good forwarding performance and high stability, their defects of poor deployment flexibility and scalability are also obvious. Moreover, network-layer overlay networks generally only optimize inter-domain traffic at the IP layer and

cannot subdivide terminal application requirements. Considering overlay network scalability and deployability requirements, application-layer implemented overlay networks such as Spines and Resilient Overlay Network have more development prospects. Terminal applications can use this type of overlay network to find transmission paths that truly suit their own needs. For example, online games can select paths with high throughput and low delay; P2P file transfers can select low-cost paths; and for mission-critical services requiring high reliability, more reliable transmission protocols can be built at the upper layer to improve their performance.

However, application-layer overlay networks also have their own weaknesses. For example, existing applications basically do not consider underlying network structure information, which will lead to performance degradation due to path correlation during transmission optimization and may also trigger the vertical network conflicts mentioned earlier. Second, when application-layer overlay networks select forwarding nodes and build networks, they generally use fully meshed connection probing, with overhead at the $O(N^2)$ level (like Resilient Overlay Network), which seriously affects network scalability. Additionally, multi-path routing is an important means for overlay networks to achieve transmission optimization [50][51], but there are still issues to be deeply researched and resolved in effectively reducing the impact of link dynamic changes on network transmission, suppressing routing switching oscillations, performing congestion control, and deploying forwarding nodes.

4.1 Scalable Overlay Network System Architecture

Considering deployment cost and feasibility, most practical overlay networks currently adopt application-layer relay modes. Due to the instability of terminal hosts, this approach can easily cause turbulence in overlay network logical topology, seriously affecting forwarding performance. However, building networks using only fixed forwarding nodes deployed in the network also faces system cost and flexibility issues.

Therefore, scalable inter-domain routing optimization overlay network systems should fully utilize the advantages of both types of nodes and adopt a hierarchical division and hybrid approach to network construction. Specifically, pre-deployed service nodes are mainly used for forwarding network layering, management, and maintenance, and undertake partial service forwarding functions, while screened terminal hosts undertake main service routing functions (as shown in [Figure 7: see original paper]), forming a three-layer structure with ordinary user nodes.

To overcome difficulties in stability, deployment cost, and scalability of various overlay networks, this three-layer architecture requires further in-depth research in forwarding node screening technology, incentive mechanisms, and dynamic network management.

4.2 Path Selection, Logical Network Construction and Probing Based on Underlay Information Awareness

The main problems limiting the performance and scale of existing application-layer overlay networks still lie in the existence of vertical network conflicts. Most overlay networks basically do not consider underlying network structure and traffic information. They independently maintain their own logical networks and monitor quality of all possible alternative paths through flooding to find effective replacement paths. For example, Resilient Overlay Network attempts to recover path faults or congestion problems as quickly as possible by sending probe packets at fixed intervals. This small-interval, frequent probing creates huge $O(N^2)$ overhead for the network. Therefore, the node scale of Resilient Overlay Network cannot exceed 50.

4.2.1 Forwarding Node Selection Based on Path Independence Nevertheless, in actual networks, about 40%-50% of path failures still cannot be recovered through this type of application-layer overlay network. This is because overlay network backup paths are correlated with default underlying IP path failures. That is, after the failure of physical links or routers shared by overlay network paths and underlying IP paths, the alternative paths used by overlay networks also fail simultaneously. This is actually the most fundamental issue that optimized overlay network routing needs to consider.

J. Han's research [21] shows that randomly selecting overlay network nodes without considering underlying structure information will lead to a large amount of overlay network path overlap correlation. Therefore, despite using small intervals to probe path performance, overlay networks' ability to quickly respond to faults and congestion is still limited unless overlay network paths can guarantee complete separation of IP-layer elements without correlation. This raises the question of how to construct overlay network paths to minimize their correlation with each other or with default paths in the underlying IP network. Cha proposed an algorithm for building overlay network paths through incremental deployment of relay nodes [54], with the goal of reducing the number of links coexisting on default paths and overlay network paths. This method assumes that intra-domain network topology is known and analyzes and optimizes intra-domain relay node placement based on this. Similarly, the goal of selecting appropriate relay nodes by obtaining topology information to build overlay network paths is also to reduce overlapping network elements between default paths and overlay network paths.

4.2.2 Probing Methods and n-Landmark Based Logical Network Construction Regarding the scalability issues caused by frequent path probing, Rewaskar studied the trade-off between performance benefits and overhead of overlay network networks and concluded that using methods such as reducing logical connections and extending information exchange intervals can improve overlay network performance/overhead ratio [53]. Hasegawa divided overlay net-

works into high-density and low-density categories based on whether underlying path overlap exists, and proposed methods to reduce probing overhead by using superposition of multi-segment paths in high-density overlay network networks [56]. Cheng' s PPRR (Path Probing Relay Routing) probing scheme [55] is the most practical. Compared with the $O(N^2)$ overhead caused by traditional overlay networks' fully meshed connection probing methods, PPRR' s network overhead is independent of scale. Its principle is that for each overlay network node, maintain a "probe set" composed of its relay nodes (such as A, B, C, D, E, F). In each round of probing, the currently best-performing nodes (such as A, B, and C) are placed in the "top set," and all other overlay network relay nodes in the "probe set" but outside the "top set" (D, E, and F) are replaced with overlay network nodes outside the "probe set" to prepare for the next round of path probing.

Experiments prove that this scheme can achieve performance close to Resilient Overlay Network while reducing probing overhead. However, this scheme still has obvious defects: first, although the number of nodes probed each time decreases, each node still needs to maintain a list containing all network nodes, which affects scalability in large-scale networks; second, due to reduced probing scope, some path failure information cannot be obtained in time; third, the selection of probed overlay network nodes does not consider path correlation issues, leading to inefficient path replacement.

To address these issues and achieve efficient probing of backup overlay network paths and improve overlay network scalability, we believe that on-demand probing methods combined with Landmark technology can be adopted. The system can establish n landmark nodes. When a new node joins, it performs network ranging with these n landmark nodes, and simultaneously selects points with smaller network distances in the ranging space as forwarding nodes. Specifically, considering only delay metrics, nodes with smaller delay similarity AvD can be selected through calculation, where L_{AiD} and L_{BiD} are the network distances from user nodes and forwarding nodes to the i -th landmark node, respectively. At the same time, using the n landmark points as target nodes to measure the path overlap of forwarding node B. Using these two metrics, a Logical Forward Network (LFN) is established for users. Finally, when establishing communication, end nodes perform final performance probing of relays in the logical forward network and perform path switching or multi-path routing based on real-time performance.

This "on-demand" path probing method completely avoids unnecessary path probing overhead. Through probing of landmark nodes and screening by path overlap metrics, the static construction of logical forward networks is completed. Since the logical forward network already satisfies many overlay network forwarding optimization requirements during construction, user nodes only need to perform final screening according to current communication needs, thus effectively reducing the scope of path probing and greatly improving the performance improvement effect of backup paths when default paths fail or performance de-

grades.

4.3 Multi-Path Routing Technology in Cross-Domain Overlay Networks

Existing IP routing protocols use single-path data forwarding between source and destination. The defect of single-path routing is that data throughput is limited by existing routing strategies. This means that even if alternative high-bandwidth paths exist, data may still be transmitted on low-bandwidth paths due to policy restrictions. Moreover, single-path routing is not suitable for wireless ad-hoc networks, where high routing failure rates can cause data transmission vulnerability.

A novel solution is to develop multi-path overlay network routing technology. Multi-path routing algorithms in overlay networks can separate and reassemble source-destination data. These algorithms can improve network throughput, reduce network delay, balance load traffic, and improve link robustness. As shown in [Figure 8: see original paper], if ISPs use traditional single-path BGP routing between source and destination nodes, even selecting the optimal path, the maximum transmission bandwidth can only reach 20Mb. Using multi-path routing technology, pushing data simultaneously through three routes can achieve a maximum transmission bandwidth of $20+8+10=38$ M.

Multi-path routing can be further combined with layered coding mechanisms to provide higher reliability transmission guarantees for real-time services by adding partial redundant information [50]. However, multi-path routing in cross-domain overlay networks also has issues that need to be resolved, mainly including: calculation of the number of paths needed for transmitting specific data; how to select appropriate paths given a topology to provide corresponding QoS guarantees and balance cross-domain load traffic; how to design efficient multi-path routing protocols to ensure TCP stability; and how to design stable TCP congestion control mechanisms to improve network performance given a topology structure and multi-path routing algorithm.

4.4 Fault Recovery Oscillation Suppression

Another easily overlooked key technical issue in designing efficient and scalable overlay networks is the system overhead caused by overlay networks' own fault recovery mechanisms. To provide reliable services at the application layer, each layer of existing networks has its own error detection and recovery mechanisms. When failures or faults occur, multiple protocol layers will detect them and use their own mechanisms for recovery. Generally, lower-layer mechanisms react faster, while higher-layer mechanisms provide better recovery services to meet needs of different users and applications. In overlay networks, tracking and probing along paths provide faster fault recovery than BGP routing.

The probing frequency becomes an important system parameter: lower probing frequency means lower system overhead but requires longer time to detect

failures. Higher frequency probing triggers higher overhead but enables overlay networks to have faster fault response speed.

When overlay network fault recovery mechanisms conflict with underlying fault recovery mechanisms, such as when traffic congestion and transmission network failures generate many unnecessary fault events, this frequent probing-induced path switching will cause network instability and seriously affect network performance.

Therefore, certain control strategies need to be implemented for path probing periods and path switching methods to limit path switching oscillations. For example, introducing a hysteresis dual-threshold exponential decay algorithm or random backoff mechanism can be considered, enabling overlay networks to avoid routing oscillations caused by unstable network performance while simultaneously maintaining rapid fault recovery performance.

5 Conclusion and Outlook

Due to the distributed management of the Internet leading to defects in guaranteeing overall transmission quality, and after both revolutionary technologies and traditional improvement schemes have encountered obstacles, inter-domain routing optimization overlay networks have become a hot technology for solving this problem. This paper reviewed the current state of Internet routing technology, provided a refined classification of existing overlay network types, and analyzed in detail the advantages and disadvantages of each type. On this basis, we deeply discussed various problems and challenges faced when applying inter-domain routing optimization overlay network technology, including network conflicts and traffic oscillations. Simultaneously, through analysis of simulation and experimental data from a large number of overlay network research literature, we conducted a comprehensive quantitative summary of their routing performance improvements. The results show that in the existing Internet network environment, overlay networks have relatively obvious effects on routing performance improvement. Moreover, even when multiple overlay networks coexist, they can still achieve better transmission performance than default routing. Therefore, ISPs and other Internet stakeholders should strengthen their attention to the evolution of overlay network technology and provide good interaction and coordination technologies at the two different routing optimization levels as much as possible to reduce network vertical conflicts and ensure Internet performance. Finally, we summarized the key technical issues in implementing efficient and scalable inter-domain routing optimization overlay networks from several aspects including system architecture, path probing, oscillation suppression, and multi-path routing, and provided relevant recommendations.

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