Analysis of SRv6 Deterministic Network Scenarios

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Abstract: Conceptualization of Deterministic Networking (DN), has developed as the central paradigm of the contemporary architecture of the network, which proposes precise Quality of Service (QoS) that adheres to the requirements of high precision applications, which include not only telemedicine surgeries and autonomous driving but also industrial automation. In this context, SRv6 Deterministic Networking arises as a transformational technology essentially using Segment Routing over IPv6 (SRv6) in computation of end-to-end paths custom-built for specific service requirements hence ensuring strictest Service Level Agreement (SLA) compliance. This paper proposes a hierarchical-based end-to-end deterministic networking scheme to heterogeneous scenarios using SRv6 technology. Each of the heterogeneous network domains is abstracted as separate objects, through utilization of that novel scheme, and at the same time, makes it associated with a parent controller to carry out intra-domain management. Emerging controllers collect information in details about different topologies and also SLA metrics present inside the network thus helping to make a decision during path computation and allocation of resources. The scheme is then tested for its efficacy on the CENI test network in a laboratory setting. Testing generates strong statistics, which reveal that the performance of the network latency addition is below 100 milliseconds, network reliability is at 99.999%, and the capacity to support a network bandwidth of more than 100 gigabits per second. Specifically, the scheme achieves remarkable performance from the Yangtze River Delta region to the Beijing-Tianjin-Hebei regional network, with latency within 100 milliseconds and jitter under 10 milliseconds, effectively meeting the stringent real-time demands of diverse applications. This paper proposes an alternative to bridge the heterogeneous networks with SRv6 Deterministic Networking that allow provision of source-to-destination and destination-to-source paths in a reliable way so as to strictly guarantee SLAs. The proposed scheme made possible through laboratory testing would not only advance the state-of-the-art in DN but also stands a promising approach to addressing the evolving needs of the modern network infrastructures.

Keywords: Deterministic Networking; SRv6; Heterogeneous Networks; End-to-End Paths; Service Level Agreement (SLA)

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1 Introduction

Deterministic Networking (DN) is a network count that provides deterministic quality of service to provide more accurate and better quality network transmission services to high precision users (e.g., telemedicine surgeries, remote combat, autonomous driving, etc.).

SRv6 Deterministic Networking is a network where the control plane uses SRv6 technology to calculate the paths according to the service requirements and ultimately provide a network that meets the end-to-end SLA requirements of the service [1]. Currently, the main focus is on the development and practice of this technology, including field-level scenarios, cross-domain scenarios, and

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heterogeneous network scenarios. The critical technology for the on-site scenario is "industrial protocol + TSN," the key technology for the cross-domain scenario is "DetNet + path planning," and [2] the key technology for the heterogeneous network scenario is "time slot mapping + resource planning." The key technology for heterogeneous network scenarios is "time slot mapping + resource planning." The applications are mainly aimed at realizing large bandwidth and high reliability in heterogeneous big data transmission scenarios, such as urban arithmetic networks, large-scale cross-broad area arithmetic network convergence, etcetera.

At present, the main research directions of deterministic network are as follows four directions:

Flexible Ethernet (FlexE): The basic idea is to decouple the MAC layer and PHY layer by increasing the time division multiplexing Shim layer to get a more flexible physical channel rate to realize three application modes, namely, link bundling, sub-rate, and channelization, and to carry all kinds of rate-demanding services [3].

Time-Sensitive Networking (TSN): dominated by IEEE organization, used to solve the problem of deterministic guarantee of Layer 2 network, currently mainly used in the automotive control field, factory intranet, smart grid, 5G, and other scenarios. TSN achieves zero congestion packet-loss transmission through a series of protocol standards to provide low latency and jitter with an upper-bound guarantee, providing time-sensitive traffic with a deterministic guarantee [4]. Provides deterministic transmission guarantees for delay-sensitive traffic. It mainly includes a precise network time synchronization mechanism, traffic shaping mechanism for scheduling different priority traffic, resource reservation mechanism, and time-sensitive traffic configuration mechanism.

Deterministic Networking (DetNet): led by the IETF organization, it defines a typical L2/L3 network architecture, i.e., DetNet, which aims to realize forwarding along multi-hop paths with deterministic latency, controllable low packet loss, and high reliability, focusing on IP layer scheduling guarantees, to expand deterministic networks through IP/MPLS and other technologies [5]. The goal is to extend the deterministic network to the WAN through IP/MPLS, etc. DetNet technologies mainly include resource reservation, release/reuse of idle network resources, centralized control, explicit routing, jitter mitigation, congestion protection, multipath routing, etc.

Deterministic IP (DIP): led by the CCSA organization, a new three-layer deterministic network technology architecture, which introduces a cyclic scheduling mechanism for forwarding on the data plane and proposes a scheduling-free and efficient path planning and resource allocation algorithm on the control plane, to realize a large-scale scalable end-to-end deterministic and low-latency network system [6]. The main techniques include access control, path planning and resource reservation, path binding, and deterministic cycle forwarding.

Metropolitan Transport Network (MTN): ITU-T organization led to meeting the 5G backhaul and industry private line deterministic bearing needs [7]. MTN (Metropolitan Transport Network) has become a new generation of ITU-T transmission technology standard system. Based on MTN technology, sliced Packet Network (SPN) is a multilayer converged hierarchical switching network technology led by China Mobile. MTN technology can provide SDH-like secure isolation, low latency, and low jitter deterministic capability due to the adoption of the TDM multiplexing and crossover mechanism of the L1 layer of Ethernet, and the services can be multiplexed and forwarded directly according to the TDM time slots of the L1 layer. -T has formed a comprehensive international standard system for transport networks. In addition to synchronization (G.mtn-syn), MTN interface, architecture, protection, equipment, and control standards have been adopted, marking the essential completion of the MTN series of standards.

The research direction of this paper is deterministic IP (DIP), which utilizes SRv6 technology to realize the function of heterogeneous deterministic networks. This paper summarizes and analyzes the established deterministic network schemes and proposes a dedicated technology scheme. Laboratory validation shows that the latency of the network from the Yangtze River Delta region to the Beijing-Tianjin-Hebei region via SRv6 deterministic network is within 100ms, and the jitter is within 10ms, which meets the higher real-time requirements of the application.

2 Existing Technology Solutions

2.1 Heterogeneous Network Solutions

Heterogeneous network scenarios may involve various networks, such as wireless networks, wired networks, wide area networks, local area networks, industrial Ethernet, etc., which often play different roles in different industries and application scenarios and may also span other carriers.

Different connection models exist in multi-domain heterogeneous network environments (tree structure, star topology, mesh layout, etc.) and isolation of various heterogeneous networks in the management domain. Currently, the commonly used solution is to comply with RFC4364's proposed three cross-domain VPN schemes [8]. These three interconnections are broadly representative, covering a wide range of scenarios from loosely to tightly coupled and from segmented to end-to-end, and the specific choice also depends on the differences between the networks and the cost, technology, and so on. Suppose the differences between the networks are significant, and the cost and technical constraints are high. In that case, the back-to-back solution of Option A can be considered to realize cross-domain communication. With the development of technology and product improvement, it can gradually transition to Option B's single-hop cross-domain solution, which recognizes end-to-end collaboration by deploying gateways at the network boundary for conversion and mapping. Suppose there is the ability to achieve integrated management of the entire network to achieve consistency of upper-layer services and consistency of lower-layer forwarding. In that case, you can consider adopting the multi-hop cross-domain scheme of Option C. This can better utilize the end-side equipment to maintain the information on the target side while maintaining the information delivery along the way and reducing the burden on the intermediate equipment.

2.2 Deterministic Routing

The routing of deterministic network cross-domain scenarios requires careful consideration of the routing calculation between different domains and the path selection capability.

The programmable capability of SRv6 is utilized to provide a more powerful Layer 3 network programming space to meet different network path requirements. Combining the label compression of area division and efficient multi-path computation algorithms (e.g., eKSP path computation algorithm, which solves the performance problem of large-scale network path computation and improves the efficiency and accuracy of path computation) reduces the time complexity [9]. It enhances the path compression rate and realizes the path selection more efficiently.

2.3 Multi-constrained Path Intelligent Path Calculation

Through real-time sensing of underlying deterministic resources and network performance data through network posture, it supports intelligent path calculation based on multiple deterministic constraints such as delay, jitter, bandwidth, etc. SRv6's programmability makes it possible to realize multi-deterministic constrained path calculation, and it provides end-to-end deterministic intelligent path selection capability for services [10].

The full-area path computation capability comprehensively considers the network's topological information, resource status, and transmission demand. Path calculation assumes various factors such as bandwidth, delay, bandwidth guarantee, etc., and is flexibly and dynamically adjusted according to the real-time network state.

In heterogeneous networks, cross-domain communication may involve different routing protocols, and it is necessary to ensure that these protocols are interoperable and compatible to ensure smooth cross-domain communication [11-13].

3 Proposed Technical Solution

The SRv6 deterministic network scheme proposed in this paper is mainly used to provide end-to-end reliable network paths in heterogeneous network scenarios.

(i) According to the current heterogeneous network scenario, the heterogeneous network domains are abstracted into a domain (Domain), respectively. Different domains have independent controllers to manage the intra-domain network and collect detailed topology information and related network SLA information (e.g., bandwidth, latency, packet loss, etc.) within the domain. Controllers in different domains are accessible to each other and exchange topology boundary connection information and aggregation routing information within the domain. Eventually, each controller generates the entire network topology information (detailed topology information within the domain and connection and aggregation routing information with other domains). The organization is shown in the following figure: Domain1 and Domain3 are SRv6 networks, and Domain2 is a heterogeneous MPLS network (this scheme applies to various heterogeneous networks, and only MPLS networks are used here as an example).

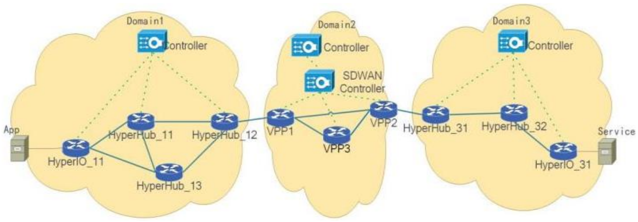

Figure 1 SRv6 heterogeneous network networking diagram

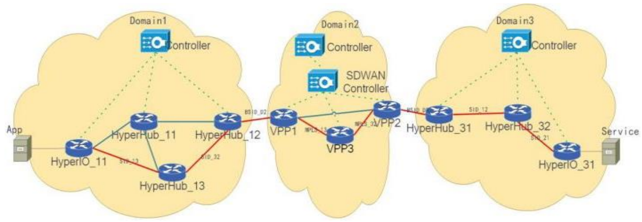

Figure 2 Schematic diagram of the arithmetic path

(ii) The service requests a service that meets the end-to-end SLA (delay, jitter, packet loss, etc.) from the controller in this domain. The controller requests end-to-end SLAs (delay, packet loss, etc.) using a cascading call method to request an end-to-end path to satisfy the SLA service, and the path includes. The specific processes are as follows:

1) The business application (app) applies to the header domain controller (Controller) for a service that meets the SLA quality requirements. This domain controller calculates the optimal SRv6 path within the domain (the domain directly connected to the device of the tail node of the optimal path is the next domain) and carries the new SLA requirements (subtracting the SLA consumption of this domain, such as the latency of this domain) to the next level of the domain controller cascade application;
2) The domain controllers at each level operate identically until the tail domain (the domain that provides the service Service).
3) After the tail domain finishes calculating the optimal SRv6 path in the domain, it occupies the path resources (e.g., bandwidth), and it returns the request SRv6 path information to the previous domain controller (the BSID represents an SRv6 path);
4) at each level, the domain controller receives the application result returned by the next domain. If the application succeeds, the domain occupies the path resources; if the application fails, the optimal path is recalculated within the domain (by deleting the tail node of the original optimal path). If the optimal SRv6 path cannot be computed within the domain, a failure is returned to the previous domain controller.
5) The header domain controller, which applies for an end-to-end path that satisfies the SLA through a cascading call, returns it to the business application (app);

The final end-to-end path is calculated as shown in the following figure: the red path is the absolute path.

(iii) The controller installs end-to-end SRv6 deterministic paths in the equipment accessed by business applications. The traffic of business applications is forwarded in strict accordance with the end-to-end SRv6 deterministic path to ensure SLA service quality.

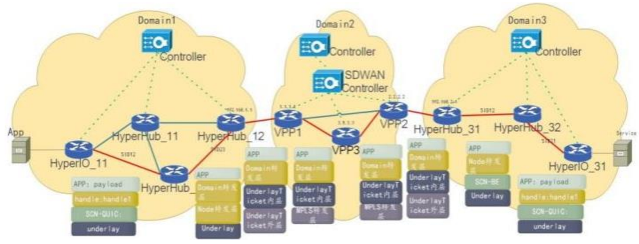

Figure 3 Traffic forwarding diagram

(iv) Failure Scenarios

Failure scenarios are mainly categorized into intra-domain failures and inter-domain failures.

When an intra-domain failure occurs, the controller in the domain senses it and re-calculates the path that meets the SLA conditions in the domain. If it can compute a new path, it switches to the new path directly, and the upstream does not sense it; if it cannot compute a new path, it notifies the upstream controller of the failure and triggers the upstream controller to recompute the path.

When an inter-domain failure occurs, the boundary device senses it to notify the domain controller in which it is located, and the upstream controller triggers the recalculation.

4 Validation Results

As the core network solution of our self-developed computing network operating system, this solution connects the cloud-side end through the SRv6 deterministic network to provide end-to-end deterministic service for business. It has successfully passed the laboratory validation on the CENI test network.

As shown in Table 1, validation results include delay validation, packet loss validation, and performance validation.

a) Latency validation: the validation results show that the scheme can provide network latency below 100 ms.

b) Packet loss validation: the validation results show that the scheme can provide 99.999% network reliability.

c) Performance validation: The validation results show that the solution can support network bandwidth of more than 100Gbps.

The delay from the Yangtze River Delta region to the Beijing-Tianjin-Hebei regional network via the SRv6 deterministic network is within 100ms, and the jitter is under 10ms, which meets the higher real-time requirements of the application.

Table 1 Validation Results of the proposed SRv6 deterministic network

Download	Packet loss	Upload	Packet loss	RTT (ping)
1010.68kbps/200,00kbps	0.00%	316 68kbps/200.00kbps	0.00%	87.1ms
1,02Mbps/200,00kbps	0.00%	308,64kbps/200,00kbps	0.00%	91.1ms
1,02Mbps/20000kbps	0.00%	112.24kbps/20000kbps	0.00%	94.4ms
1,02Mbps/200,00kbps	0.00%	331,98kbps/200,00kbps	0.00%	88.8ms
1,04Mbps/200,00kbps	0.00%	327,55kbps/200,00kbps	0.00%	95.0ms
1007,05kbps/200,00kbps	0.00%	328 90kbps/200,00kbps	0.00%	87.5ms
951,22kbps/200,00kbps	0.00%	321.54kbps/200,00kbps	0.00%	91.6ms
1,04Mbps/200,00kbps	0.00%	341,51 kbps/200/00kbps	0.00%	91.1ms
988,03kbps/200,00kbps	0.00%	319,43kbps/200,00kbps	0.00%	95.0ms
977.82kbps/200,00kbps	0.00%	3,04kbps/200,00kbps	0.00%	90.6ms

5 Additional Insights and Future Directions

5.1 Dynamic SLA Adaptation

Whereas the proposed scheme has made an attempt at computing end-to-end paths for the meeting of predefined SLAs, coming with mechanisms for dynamic SLA adaptation could be worked upon as one of the future research areas. Using these network conditions and service requirements, the controllers dynamically adjusted the path parameters at real-time for optimizing performance and resource utilization at the given instance and ensuring adaptive SLA fulfillment.

5.2 Considerations of Security and Privacy

In any heterogeneous network environment, security and privacy considerations remain top. The SRv6 Deterministic Networking framework makes it possible for strong security elements such as authentication, encryption, and access control to be incorporated. Such security elements under the SRv6 Deterministic Networking architecture may go a long way in ensuring that sensitive data remains secure during transmission as well as making it hard for security threats that could emanate from various domain networks.

5.3 Cross-Domain Traffic Engineering

By enabling or exercising effective traffic engineering across the disparate network domains, optimum resource utilization and resultant better performance of the networks are envisaged. Future enhancements to the proposed scheme can involve benign traffic engineering algorithms that will make intelligent routing, congestion control, load sharing across interworked domains resulting in gaining better overall network efficiency.

5.4 Integration with Emerging Technologies

Integration of SRv6 Deterministic Networking with ever-emerging network architectures like Artificial Intelligence (AI), Machine Learning (ML) as well as Software-Defined Networking (SDN) will bring in new abilities and functionalities. Predictive network analytics through the AI/ML algorithms and centralized network management and orchestration by SDN are a good combination towards agile, scalable, and intelligent heterogeneous network deployments.

6 Conclusions

In conclusion, this paper presented a strong scheme using SRv6 Deterministic Networking that deals with the complexities concerning building the end-to-end reliable paths in a heterogeneous network domains' environment. Using a hierarchical approach and cascading path computation, the scheme ensures intact inter-domain communication following strict Service Level Agreement (SLA).

This is validated in the laboratory on the CENI test network where the proposed scheme delivers network latency below 100 milliseconds and network reliability of 99.999% with training of network bandwidths exceeding 100 gigabits per second. Incredibly, the scheme achieves an excellent performance from the Yangtze River Delta region to the Beijing-Tianjin-Hebei regional network while meeting varieties of applications with demanding real-time requirements where latency is within 100 milliseconds and jitter under 10 milliseconds.

This research adds to the frontier of Deterministic Networking (DN) - bridging across heterogenous networks and provisioning reliable end-to-end paths. The restatement of SRv6 technology opens new eyes for implementation through hierarchical management, hence creating the new pathway for resolving dynamically evolving problems of modern network infrastructures.

If feasible, other promising future research in this domain may include using optimization techniques that further improve path computation with respect to efficiency, scalability, and flexibility towards dynamic network conductivity. Further from a different angle, real-world deployment and validation of the above scheme across multiple networks environment would aid in understanding the applicability and effectiveness of the same in practical deployment.

This is another major stride to the quest for a deterministic and reliable networking solution, whose potential application lies in the realm of telemedicine, autonomous driving as well as industrial automation among other.

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