Architecture Design and Performance Analysis of MPLS VPN in Meteorological Wide-Area Networks

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Abstract: ***The continuous advancement of meteorological observation technologies has led to an exponential growth in data volume, necessitating highly efficient and robust data transmission networks to improve forecasting accuracy and timeliness. Concurrently, meteorological services are undergoing a strategic shift towards intensification and structural flattening to enhance operational responsiveness. However, the conventional three-tier (provincial-municipal-county) tree-structured network architecture has emerged as a critical bottleneck, characterized by inherent latency and single points of failure that impede data flow and service agility. To address these limitations, this paper proposes and describes the implementation of a Multi-Protocol Label Switching (MPLS) Virtual Private Network (VPN) architecture to reconstruct the foundational meteorological network. This modernized design establishes a secure, three-layer mesh network that enables logical direct connectivity between any two nodes across the administrative hierarchy. The results demonstrate that this MPLS VPN-based mesh topology significantly enhances the stability, reliability, and data transmission efficiency of the meteorological private network. By facilitating seamless, low-latency communication and providing robust traffic engineering capabilities, this network transformation effectively supports the evolving demands of data-intensive and time-sensitive modern meteorological operations, paving the way for more advanced and reliable weather prediction services.***

Keywords: MPLS VPN; Meteorological Network; Network Architecture; Data Transmission; Weather Forecasting; Mesh Network; Network Stability.

1. INTRODUCTION

With continuous advances in observation technology, meteorological observation has evolved from isolated, single-point measurements to an integrated three-dimensional, ground–air–space gridded system employing aircraft, satellites (CMA), and other advanced equipment. To obtain finer-grained gridded observational data, the number of stations keeps increasing, sampling frequencies keep rising, and data volumes keep expanding. Meanwhile, the ever-higher demands for forecast timeliness and accuracy place enormous pressure on data-transmission speed. Building an efficient and rapid meteorological data-transmission network has thus become a key component of meteorological modernization.

An efficient meteorological data-transmission network is a fundamental requirement for meteorological modernization. As forecast services move toward intensification and flattening, the hierarchical distinctions among province, city, and county are weakening, and interactions among them are increasing—especially cross-regional forecast cooperation between neighboring counties and cities. The traditional tree-structured wide-area network places heavy loads on provincial and municipal nodes; failure of a provincial (or municipal) node can disrupt the meteorological data-transmission network for the entire province (or city).

Based on MPLSVPN mesh networking, any two nodes in the network can be directly connected while ensuring the confidentiality, integrity, and availability of data transmission. It offers advantages such as low cost, ease of management, and high flexibility. This paper will provide a detailed account of the research on applying MPLS VPN technology in the provincial meteorological wide-area network.

In the field of 3D vision, Peng, Zheng, and Chen (2024) proposed a dual-augmentor framework for domain generalization in 3D human pose estimation[1], building upon prior work by Peng et al. (2023) on black-box domain adaptation via input and network regularization[2]. Similarly, Pinyoanuntapong et al. (2023) addressed self-aligned domain adaptation for mmWave gait recognition[3], while Zheng et al. (2025) introduced a motion-aware diffusion framework for video-based human mesh recovery[4]. Beyond core vision tasks, AI is increasingly applied in finance; Wang et al. (2025) conducted an empirical study on AI-enhanced financial risk control in multinational supply chains[5], and Tian et al. (2025) developed a cross-attention multi-task learning model for ad recall in digital advertising[6]. In healthcare, Chen et al. (2023) presented a generative vision-language pretraining method for unified medical image segmentation[7]. Recruitment processes are being transformed by Li et al. (2025), who optimized resume-job matching using transformer and graph neural networks[8]. Financial and environmental applications are also prominent, with Zhang, Li, and Li (2025) leveraging deep learning for carbon market forecasting[9], and Tong et al. (2024) creating a hybrid ML-DL framework for credit approval prediction[10]. Tan et al. (2024) combined deep transfer learning with ensemble classifiers for damage detection from limited data[11]. Zhuang (2025) analyzed the digital transformation of real estate marketing strategies[12], while Han and Dou (2025) designed a multimodal knowledge graph-based recommendation method[13]. Zhang et al. (2025) applied AI-driven sales forecasting in the gaming industry[14], and Cheng et al. (2025) explored the link between executive human capital and stock price volatility[15]. Li, Wang, and Lin (2025) proposed a GNN-enhanced sequential model for cross-platform ad campaigns[16]. Further applications include generative urban design by Xu (2025)[17], intelligent 5G network testing by Tu (2025)[18], real-time industrial monitoring by Xie and Liu (2025)[19], automated system reliability engineering by Zhu (2025)[20], self-supervised ad optimization by Zhang Yuhan (2025)[21], and low-cost 3D content creation by Hu (2025)[22].

2. INTRODUCTION TO MPLS VPN TECHNOLOGY

MPLS (Multi-Protocol Label Switching) is a label-based, high-speed, and efficient data-transmission technology on public communication networks. “Multi-protocol” means MPLS not only supports multiple network-layer protocols but also accommodates various data-link-layer protocols at Layer 2. Positioned between OSI Layers 2 and 3, it enables interworking between the two layers. Proposed by the Internet Engineering Task Force (IETF), MPLS was designed to solve network issues and increase forwarding speed. Compared with traditional IP [3] routing, MPLS only needs to analyze the IP packet header at the network edge, generate labels according to algorithms, and then forward packets inside the MPLS network based solely on those labels—without re-parsing the IP header at every hop—thereby improving forwarding efficiency. For example, when CE1 communicates with CE2, the packet is first received by PE1, which generates a label using the MPLS algorithm and encapsulates the packet into an MPLS frame. Acting as an LER (Label Edge Router), PE1 also computes the LSP (Label Switched Path) to CE2. The packet is then forwarded along this LSP through the MPLS network to PE2, which decapsulates the MPLS frame, strips all labels, restores the original IP packet, and delivers it to CE2.

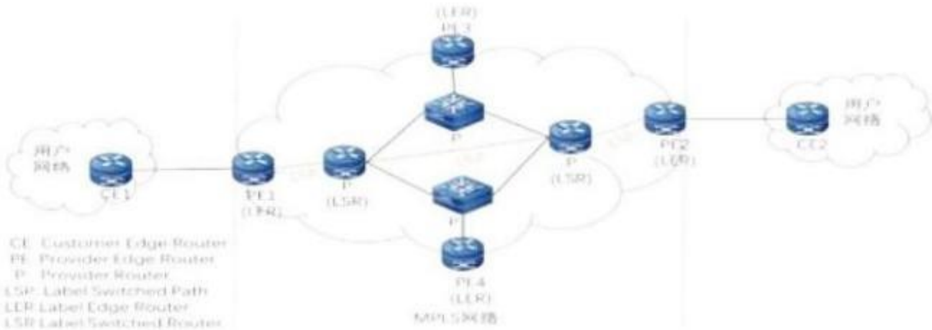

Figure 1: Schematic of data transmission in an MPLS network

MPLS VPN is a VPN built on an MPLS network. VPN [4] (Virtual Private Network) is a private network overlaid on an existing physical network using tunneling technologies to provide secure connectivity. Traditional VPNs typically employ tunneling protocols such as GRE (Generic Routing Encapsulation), L2TP (Layer 2 Tunneling Protocol), PPTP (Point-to-Point Tunneling Protocol), and IPSec [5]. An MPLS-based VPN interconnects the branches of a private network via LSPs, forming a unified network that transports private traffic across the public network.

3. APPLICATION OF MPLS VPN IN THE PROVINCIAL METEOROLOGICAL WIDE-AREA NETWORK

The MPLS VPN backbone adopts a mesh topology in which any two nodes can be logically connected. A two-tier national–provincial mesh has been established between the China Meteorological Administration and each provincial meteorological bureau, enabling intercommunication among all provincial nodes. The following focuses on the upgrade of the provincial meteorological service network using MPLS VPN.

3.1 Overall Network Planning

Following the MSTP [6] + MPLS VPN hot-standby integration plan, construct the provincial backbone network system. The provincial meteorological service private network must have primary and backup links; to ensure redundancy, the two links are provided by different carriers. The original provincial service private network's primary and backup networks both used an MSTP tree topology. The provincial MSTP aggregation adopts a 1:1 point-to-point model without sub-interfaces; each city-level meteorological department connects to the provincial WAN via a separate physical link, and the provincial router provides an independent physical interface for each city's link, reducing inter-link dependency and improving system stability and manageability.

3.2 Network Architecture Design

Both provincial and city levels deploy two routers each to access MSTP and MPLS VPN links. Dynamic routing and high-availability redundancy enable hot standby between MSTP and MPLS VPN links. To ensure device compatibility, both routers are the same model. Firewalls provide boundary access control between routers and the provincial/city LANs.

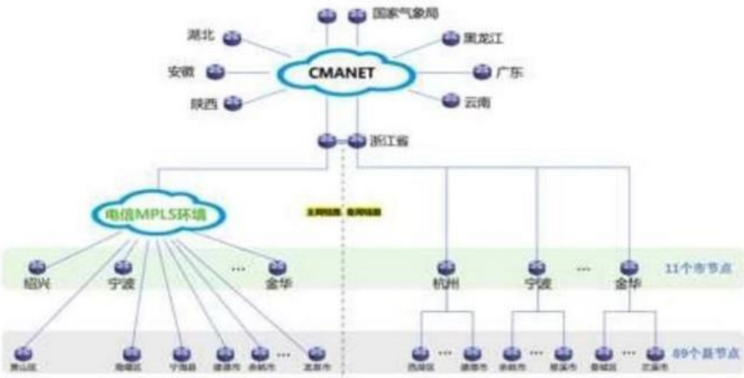

Figure 2: Province-wide WAN topology of MPLS VPN + MSTP

Provincial, city, and county meteorological network access nodes communicate using the EBGP [7] routing protocol. City and county meteorological departments advertise their full local IP address ranges on both MSTP and MPLS VPN routers; the provincial broadband firewall performs traffic diversion and access control. In the MSTP network, the router's Loopback0 address serves as the BGP neighbor source. EBGP peering between city/county MSTP routers and the provincial MSTP (backup) router is established via directly connected routes.

3.3 Route Optimization

During provincial WAN construction, involving the province-wide service network and LANs of all meteorological departments, route advertisement and path selection must be simulated and verified in advance to ensure rapid fault location and troubleshooting during cutover.

(1) Route Advertisement

The provincial meteorological WAN mesh is built on the carrier's existing CN2 network. When provincial, city, and county meteorological departments advertise their LAN service subnets via BGP, carrier limits apply: provincial nodes may advertise 100 routes, city nodes 50, and county nodes 20. Therefore, LAN route information must be aggregated before advertisement to reduce the number of routes.

(2) Route Selection

When the primary link is normal, all WAN traffic traverses the primary communication link, as shown in Figure 3; When the primary link fails, ensure that bidirectional traffic between provincial, city, and county meteorological departments follows the same path; otherwise, traffic will be blocked by various levels of meteorological intercepted by the security device in front of the meteorological department's LAN. Main analysis is as follows:

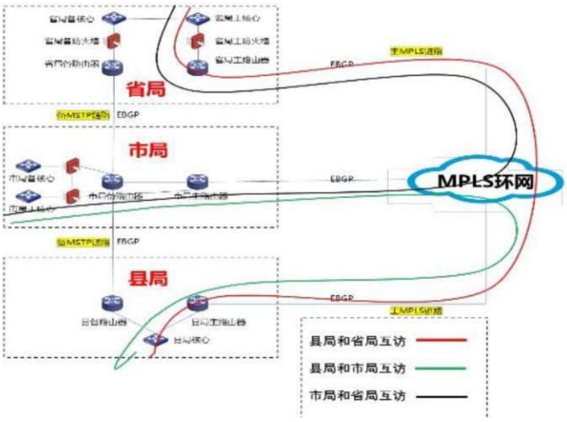

Figure 3: Service traffic path

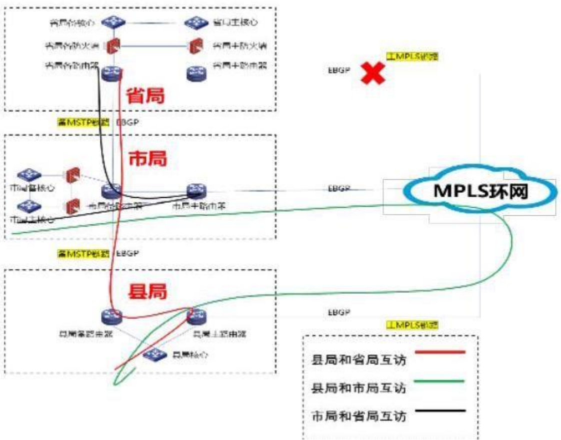

Figure 4: Provincial primary link failure

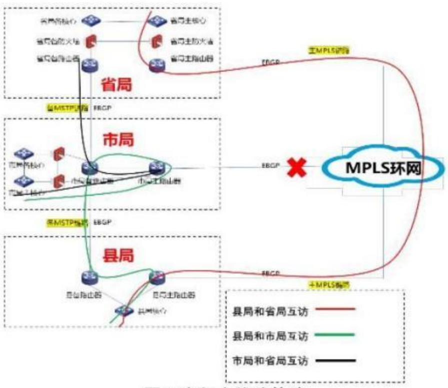

图 5 市级主线路故障

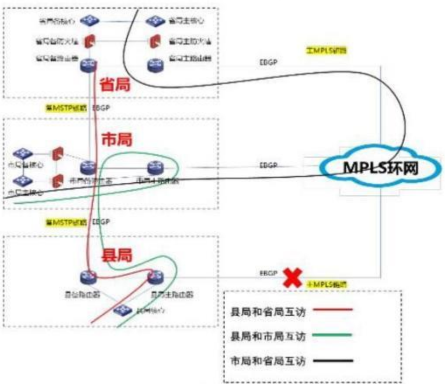

Figure 6: County-level primary link failure

Provincial primary link failure: the provincial primary link's routing information shows as unreachable in the primary link; at this time, municipal and county meteorological departments access provincial services via the backup link, while municipal-county mutual access uses the primary link, with traffic paths shown in Figure 4. Municipal primary link failure: the municipal primary link's routing information shows as unreachable in the primary link; provincial-municipal and municipal-county mutual access both use the backup link, while provincial-county mutual access uses the primary link, with traffic paths shown in Figure 5. County primary link failure: the county primary link's routing information shows as unreachable in the primary link; provincial-municipal mutual access is unaffected and continues via the primary link; municipal-county and provincial-county mutual access use the backup link, with traffic paths shown in Figure 6.

3.4 Network Cutover

Meteorological services are real-time; during network cutover, service continuity must be ensured while maintaining high implementation efficiency. A cutover plan is devised on a city-by-city basis, with all local cities executing simultaneously. Specific cutover steps are as follows:

Step1: Enable the BGP routing protocol on the provincial WAN router and import the provincial LAN's OSPF routes into BGP to facilitate subsequent MPLS connectivity tests with municipal and county meteorological bureaus.

Step2: At the municipal meteorological bureau, replace old equipment with new while keeping the OSPF configuration unchanged, and switch the backup link to use the BGP routing protocol.

Step3: At the county meteorological bureau, replace old equipment with new while keeping the OSPF configuration unchanged, and switch the backup link to use the BGP routing protocol. After the backup link test succeeds, switch the county bureau's MSTP primary link to the MPLS line and enable the BGP routing protocol.

Step4: After all county meteorological bureaus in the city have completed the above steps, switch the municipal bureau's MSTP primary link to the MPLS line and enable the BGP routing protocol.

Step5: After all 11 prefecture-level cities in the province have completed the switchover, shut down the provincial MSTP circuits and disable the province-wide OSPF routing process, thereby completing the full network migration.

4. SUMMARY:

Through research on MPLS VPN technology, a provincial meshed meteorological WAN based on MPLS VPN has been built, enabling direct interconnection (logical direct connection) among provincial, municipal, and county meteorological departments. County-level units can access the provincial center without transiting through the municipal bureau, and municipal bureaus can communicate with each other without passing through the provincial center, improving the efficiency and stability of information communication and laying the foundation for the future "cloud + edge" service model. Future work will focus on security protection for the MPLS VPN-based mesh network to further enhance the security of the meteorological intranet.

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