# Systematic Management of Labels in Unified MPLS Environments

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**Abstract:** ***This article examines architectural principles of systematic label management in unified MPLS environments of multidomain transport networks. The study is conducted as a review-analytical synthesis of contemporary scientific and technical works, within which the label is interpreted not as a local forwarding identifier, but as an end-to-end architectural control element integrating routing, forwarding, and operational mechanisms. The analysis is based on publications addressing unified MPLS architectures, hierarchical label stacks, fast convergence mechanisms, and the extension of forwarding semantics through network actions. It is shown that the resilience and scalability of multidomain MPLS networks are determined not so much by the choice of individual protocols as by the degree of systematization of label management, including the separation of inter-domain and intra-domain levels, a predictable stack structure, and control over the scope of control-information interpretation. The synthesis of architectural solutions demonstrates that extending the label management model by incorporating network actions increases the expressiveness and controllability of forwarding, while simultaneously imposing strict engineering constraints related to stack depth and hardware header processing. Particular attention is paid to the role of controlled path selection and logical topology segmentation as prerequisites for aligning label stack structure with architectural management policies. It is shown that systematic label management is formed as a result of reconciling architectural, hardware, and operational constraints, rather than as a set of isolated protocol mechanisms. The article may be of interest to researchers in transport network architecture, network operators, and engineers involved in the design and evolution of scalable MPLS networks.***

**Keywords:** label management, MPLS architecture, hierarchical label stack, network actions, segment routing, multidomain networks

## 1. Introduction

The growth in the scale of operator and enterprise communication networks and the increasing complexity of data transmission requirements are leading to the transformation of multiservice transport network architectures. Modern networks are formed as a collection of autonomous domains with varying topology and routing rules, yet they are required to provide end-to-end traffic delivery with predictable characteristics [5]. Under these conditions, the label in Multiprotocol Label Switching ceases to be a local forwarding attribute and becomes a systemic control element integrating the transport layer, service functions, and operational procedures.

The relevance of the problem increases in large hierarchical networks, where traditional approaches based on expanding internal routing domains or manual configuration of signaling mechanisms lead to increased operational complexity and reduced resilience. Attempts to ensure end-to-end paths by enlarging domains overload the control plane, while excessive fragmentation complicates management and diagnostics [2]. As a result, a gap arises between physical network segmentation and the logic of end-to-end service delivery, manifesting in reduced predictability of label stack behavior and increased operational costs in the absence of a unified systemic approach to label management.

The aim of the study is to form a systemic understanding of label management in unified multiservice switching environments and to identify architectural principles ensuring coordinated distribution, hierarchical organization, and extensibility of the label stack in multidomain networks. To achieve this goal, the work addresses the following tasks:

- Analyze architectural mechanisms of unified multiservice switching;
- Systematize the roles and levels of labels in a hierarchical stack;
- Assess the extension of the label management model through the implementation of network actions.

The research hypothesis is that the resilience and scalability of unified multiservice networks are determined primarily by the degree of systematization of label management, including the separation of areas of responsibility, a predictable label stack structure, and the integration of fast failure recovery mechanisms, rather than by the choice of individual routing protocols. Testing this hypothesis is carried out through an architectural review-analytical synthesis oriented toward identifying stable structural invariants of label management in multidomain MPLS environments.

The scientific novelty of the work lies in forming an analytical framework within which label management is viewed as a holistic architectural function of a unified multiservice environment, combining distribution, hierarchy, processing, and label extension mechanisms, rather than as a collection of isolated protocol solutions.

The scope of the study is defined by a focus on architectural mechanisms of systematic label management in multidomain transport-layer MPLS environments. The work does not consider overlay architectures where forwarding control is implemented without using labels as a basic forwarding plane element, nor solutions oriented exclusively toward user or access network segments. The analysis does not include a detailed comparison of protocol implementations and configuration options, as the subject of research is the architectural organization of label management and its impact on network scalability, manageability, and operational predictability.

## 2. Materials and Methods

The study is based on peer-reviewed scientific publications from 2022–2025 dedicated to multiservice transport network architectures and label management mechanisms. The analysis included works viewing the label as an architectural control element influencing network scalability, resilience, and operational predictability, rather than merely as a local forwarding identifier. Publications related to the transport and core network levels, where label stack management exerts a systemic influence on end-to-end traffic delivery, were considered.

The study is conducted in the format of an architectural review-analytical synthesis, oriented not toward aggregating quantitative indicators, but toward identifying structural principles and invariants of label management in unified MPLS environments. Methodologically, the work belongs to the class of systematized conceptual reviews, in which the object of analysis is architectural solutions and component interaction models, rather than individual experimental implementations or protocol optimizations.

Source selection was carried out based on predefined criteria. Publications satisfying the following conditions were included:

- Investigation of architectural or protocol mechanisms using labels in the forwarding or control process;
- Analysis of multidomain or hierarchical network structures;
- Consideration of scalability, convergence, or forwarding function extensibility issues;
- Publication in a peer-reviewed journal, preprint server, or as industry-grade technical documentation.

Works focused exclusively on local QoS optimization, overlay control mechanisms not using labels as a basic forwarding element, and studies limited to access or user networks without architectural generalizations were excluded from the analysis.

The selection procedure was conducted in stages. At the first stage, a primary search for publications on thematic areas of label management, unified multiservice switching architectures, fast convergence mechanisms, and forwarding semantics extension was performed. At the second stage, selection based on abstracts and keywords was carried out, excluding irrelevant works. At the third stage, full texts were analyzed to identify the architectural role of labels, their distribution method, position in the stack, and scope. The final set of sources was formed after eliminating architecturally duplicate works, ensuring conceptual compactness and analytical integrity of the corpus.

To ensure reproducibility and conceptual rigor of the analysis, a single analytical framework was applied to all selected sources. Within this framework, each architecture was examined according to a fixed set of dimensions: the functional role of the label in the architecture, its distribution method and scope, position in the stack hierarchy, nature of interaction with path selection mechanisms, and influence on convergence and operational management processes. Using a unified set of analytical dimensions allowed for comparing architectures based on different protocol premises without reducing the analysis to a comparison of individual technologies.

The present study does not cover architectures where forwarding control is implemented exclusively through overlay mechanisms or centralized controllers without using labels as a basic forwarding plane element. Access networks and user segments where label stack management does not exert a systemic influence on end-to-end traffic delivery and transport network architectural stability remain outside the analysis scope.

In the study by Barkalov et al. [1], the label is viewed not merely as a forwarding identifier, but as a transport mechanism supporting differentiated flows in service-aware routing models. The authors show that binding labels to service characteristics allows managing traffic behavior at the transport network level; however, this model is mainly oriented toward intra-domain scenarios and does not touch upon systemic label stack coordination in multidomain environments. Chen and Pan [2] analyze label switching in optical packet networks, paying special attention to label recognition reliability and header processing mechanism stability under high transmission speeds, emphasizing the dependence of MPLS architectural solutions on physical and hardware constraints. The Cisco technical guide [3] summarizes practical mechanisms for configuring and operating label stacks in carrier-grade multiservice networks. This source captures established engineering approaches to separating inter-domain and intra-domain management, hierarchical stack organization, and localization of control information distribution scope, but does not formalize these solutions into a single architectural model. The work by Du et al. [4] shows the use of label stacks for local route recovery under high failure dynamics, where stack operations act as a key mechanism for accelerated convergence without control plane involvement. Dudczyk et al. [5] view labels as a transport layer element in software-defined architectures, emphasizing their role in ensuring traffic management flexibility while maintaining network scalability. Huin et al. [6] propose scalable constraint-based routing where path selection is performed without changing the forwarding plane, highlighting the possibility of logical route management while maintaining an unchanged transport mechanism structure. In the study by Ihle and Menth [7], the label is formalized as a carrier of network actions extending forwarding semantics considering hardware constraints on header parsing depth and processing speed. Jia et al. [8] analyze control plane load reduction in software-defined networks, demonstrating the limitations of approaches not using systemic label management as a forwarding architecture element. In the work by Kao et al. [9], a mechanism for accelerated forwarding rule installation in reactive architectures is proposed; however, path and forwarding state management remains predominantly centralized. Finally, Kułacz et al. [10] demonstrate expanded path manageability through logical segmentation of intra-domain topologies in segment routing networks, creating prerequisites for aligning path selection with management policies and label stack structure. Collectively, the reviewed works form a fragmented view of the role of labels in forwarding management, justifying the need for their systemic analysis within unified MPLS architectures.

Comparison of individual study results was carried out not by implementation level or specific mechanism efficiency, but by the degree of their architectural integration into forwarding management. Such an approach allowed abstracting from differences in simulation environments, hardware platforms, and load scenarios to focus on structural properties determining scalability and behavior predictability as network complexity grows.

Applying this method allowed transitioning from describing individual architectural solutions to identifying recurring structural patterns and architectural invariants of label management preserved across various Unified MPLS implementation variants. These invariants served as the basis for subsequent generalization and formulation of the systemic label management model presented in the results section.

Source analysis was performed using comparative architectural synthesis. For each study, the following analytical units were identified: the label's role in the architecture, its distribution mechanism, position in the stack hierarchy, scope, and influence on convergence and operation processes. Obtained characteristics were compared to identify recurring architectural patterns and structural differences. Separate attention was paid to hardware implementation constraints and their influence on permissible label stack depth and functional saturation. Analysis results were used to build a generalized model of systemic label management in unified multiservice environments.

## 3. Results

The Unified MPLS architecture describes the organization of a multidomain MPLS network with function separation between inter-domain and intra-domain label management levels [3]. Within the conducted analysis, the object of study is the label management scheme, including procedures for distribution, binding, and processing of label stacks at domain boundaries. The analysis examines methods for forming end-to-end transmission paths while maintaining internal routing domain isolation and limiting the control information distribution scope.

In the analyzed architecture, a combination of inter-domain delivery based on labels distributed via BGP and intra-domain delivery based on LDP is used [3]. This scheme is applied to form end-to-end transmission paths without merging internal routing domains and without distributing global topological information to all network segments. Such an approach aligns with architectural routing models oriented toward limiting control data scope in networks with scalable requirements [6]. Table 1 examines the main architectural components of systematic label management in Unified MPLS.

**Table 1:** Systematic management of labels in the unified MPLS architecture (Compiled by the author based on source [3])

| Aspect | Architectural solution | Label management mechanism | Characteristic |
|---|---|---|---|
| End-to-end forwarding paths | Hierarchical MPLS structure | BGP-LSP + LDP-LSP | Inter-domain and intra-domain delivery |
| Label distribution | BGP IPv4 with Label | Exchange of prefixes and labels | Limited distribution scope |
| Network segmentation | Independent IGP domains | Next-Hop-Self on ABR | Localization of routing information |
| Label stack management | Multi-level label stack | Service / BGP / LDP | Hierarchical label structure |
| Fast convergence | BGP PIC | Pre-installed backup entries | Local switching |
| Multipath information | BGP Add-Path | Advertisement of multiple paths | Support for redundancy |
| Local protection | LFA / rLFA | Dynamic label stacking via LDP | Intra-domain recovery |

Area Border Routers (ABRs) in Unified MPLS function as inline route reflectors with next-hop replacement. The ABR role is described as localizing the visibility scope of inter-domain labels and for recursive route resolution at domain boundaries. When transitioning between domains, inter-domain label rebinding associated with next-hop change is applied, whereas intra-domain labels are added and removed in accordance with LDP rules [3]. In the packet forwarding process, label stack operations include pushing a new label upon domain entry, swapping the top label when transitioning between levels, and popping the label upon domain exit. These operations are implemented as label push, swap, and pop depending on the node role and the packet's current position in the domain hierarchy.

The analysis recorded a three-level label stack structure including a service label, an inter-domain label, and an intra-domain label [2]. Operations of adding, removing, and replacing labels correlate with the node role and its position relative to domain boundaries. Similar work with the label stack is described in failure bypass mechanisms based on segment routing, where the route is encoded as an ordered list of labels. Constraints on label stack depth and processing are formalized in studies of MPLS network actions, where limit sizes and hardware header parsing requirements are set [7]. Intra-domain routing management using logical topology variants is fixed in works on segment routing with an extended path computation model.

During the analysis of MPLS architectures, an extension of the label management model was recorded, wherein the label is used as a forwarding identifier and a carrier of formalized packet processing instructions. In the investigated MPLS architecture, network actions are encoded directly in the label stack and processed during forwarding without recourse to external signaling mechanisms [7]. This approach complements the classic transport label model previously described for hierarchical MPLS architectures with separated inter-domain and intra-domain management levels [3].

The extended model is implemented by including a network action sub-stack placed within the MPLS stack. The sub-stack consists of an indicator and a set of stack elements containing network action codes and accompanying processing parameters [7]. For each network action, a scope is defined determining the set of nodes on which the corresponding operation is performed. This scheme aligns with architectural principles of control data localization and interpretation scope limitation previously recorded in scalable routing and forwarding management models [6], and with inter-domain label distribution mechanisms in Unified MPLS. Table 2 examines the main parameters of the extended label management model characterizing engineering constraints on network action stack design and hardware processing.

Table 2 – Key characteristics of MNA and P4-MNA (Compiled by the author based on source [7])

| Parameter | Value |
|---|---|
| Maximum number of network actions | 32 |
| Maximum size of the network action sub-stack | 17 stack entries |
| Maximum header parsing depth | 51 stack entries |
| Supported action scopes | hop-by-hop, ingress-to-egress, select |
| Implemented use cases | loss measurement, network slicing |
| Processing throughput | 400 Gb/s per port |
| Additional per-hop latency | ≈13 ns |
| Packet loss under load | not observed |
| Hardware platform | ntel Tofino™ 2 |

The presented parameters describe the upper complexity bounds of the extended label stack. Constraints on sub-stack size and header parsing depth fix the permissible number of instructions processed in the hardware forwarding path [7]. These constraints correlate with previously described requirements for managing hierarchical label stack depth in MPLS networks and with results of studies dedicated to reducing control plane load by transferring functions to the forwarding plane.

Hardware implementation of network action processing is described using a programmable switch example, where extended label stack processing is performed at line rate without recording packet losses. Measured processing time characteristics are comparable to parameters of local route recovery mechanisms using label stack manipulations under high failure dynamics. Within the conducted analysis, the extended label management model is fixed as a formalized addition to the MPLS transport level integrated into existing architectural forwarding schemes.

The conducted analysis allows recording a number of architectural invariants preserved across various Unified MPLS environment implementations. Such invariants include hierarchical label stack organization, localization of control information interpretation scope, separation of inter-domain and intra-domain management levels, and alignment of stack structure with fast convergence mechanisms and hardware header processing. The presence of these invariants determines the architectural resilience of multidomain MPLS networks as scale and functional complexity grow.

## 4. Discussion

Systematic label management in Unified MPLS cannot be reduced exclusively to correct label distribution and rebinding based on BGP and LDP. These mechanisms form the basic transport framework but do not set manageability for path selection within a domain. Under conditions where the label stack is used as a carrier of service semantics and policies, the lack of managed route selection leads to a gap between stack formation logic and actual traffic flow through the network. In such a scenario, the label remains correct from a signaling perspective but loses connection with architectural management intent.

In operational scenarios of large transport networks, this discrepancy manifests given the simultaneous need for domain isolation, path manageability, and forwarding semantics extension. Under these conditions, the hierarchical label stack is used to encode service context, inter-domain delivery, and intra-domain path selection, while additional stack elements are applied for monitoring and logical segmentation without control plane involvement. Such a configuration emphasizes that label management becomes an element of architectural design, not an auxiliary forwarding setting.

Within Unified MPLS, label management acquires a systemic character only given the presence of mechanisms allowing label distribution to be aligned with controlled path selection within a domain. Classic IGP mechanisms ensure deterministic convergence but are limited to a single metric and do not support logical topology segmentation. This limitation becomes critical when using hierarchical label stacks and transitioning to rule-based management models where the transmission path is included in a managed context and is not a byproduct of shortest path calculation.

Using Segment Routing in an MPLS domain extends manageability through explicit path encoding, yet without additional logical segmentation, SR remains tied to a single domain topology. In this configuration, label stack management complicates as the same topology is used for diverse service requirements. FlexAlgo eliminates this limitation by introducing multiple logical topologies within a single domain, each formed based on its own metric and set of constraints [10]. Prefix-SIDs distributed via IGP link path selection to a specific logical topology, simplifying the alignment of routing policy and label stack structure. Figure 1 examines the comparative level of manageability and path selection flexibility in classic intra-domain routing protocols, segment routing schemes with explicit path definition, and the FlexAlgo model based on logical topology usage.

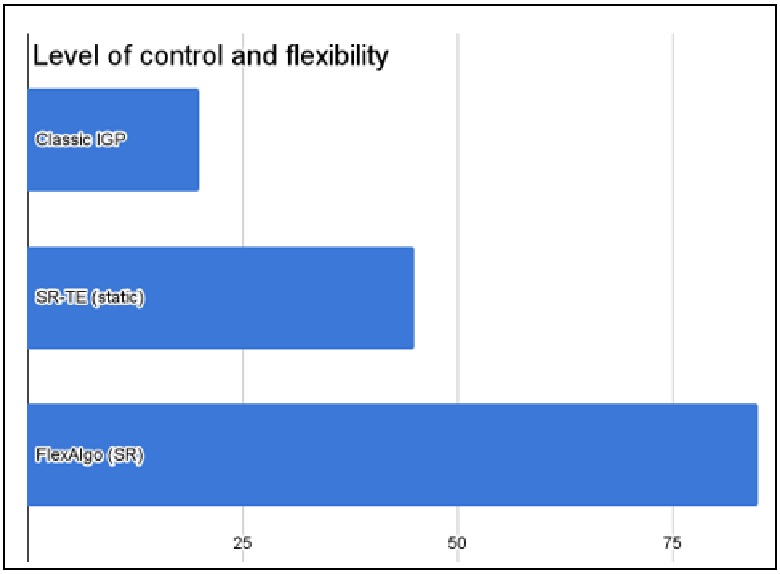


**Figure 1:** Level of control and flexibility: Classic IGP vs SR-TE vs FlexAlgo (Compiled by the author based on source [10])

The data presented in the diagram demonstrate differences in path manageability levels between the considered architectural approaches. For classic IGPs, a low indicator of 20 reflects a model where route selection is determined by a single topology and shortest path algorithm, and control capabilities are limited to link weight tuning. For SR-TE, level 45 indicates extended control through explicit segment sequence definition, while retaining dependence on the general domain topology and the need for static path description. The indicator 85, corresponding to FlexAlgo, characterizes a significantly higher level of manageability achieved through using multiple logical topologies with independent metrics and constraints, expanding the set of permissible routes and simplifying the alignment of path selection with management policies and label stack structure.

At a conceptual level, FlexAlgo forms the missing manageability layer between label distribution and their interpretation during forwarding. In such a model, the label stack ceases to be universal for the entire domain and becomes context-dependent, tied to the selected logical topology. This creates a basis for systemic label management wherein transport, service, and policy aspects of traffic processing are coordinated within a single architectural scheme, and path management becomes a structure-forming rather than auxiliary function of Unified MPLS.

Practical implementation of systemic label management in Unified MPLS forms under the simultaneous influence of architectural requirements and physical network equipment constraints. In an operational environment, the MPLS stack includes service, inter-domain, and intra-domain labels, and additional elements related to forwarding function extension. This structural complexity directly reflects on header parsing depth and fast packet processing path stability [3].

One of the main sources of design constraints is the growth of label stack depth and density. Combining service labels with BGP and LDP labels, supplemented by network action elements, increases the number of header analysis operations and intensifies the dependence of forwarding behavior on hardware parsing limits. Limited parsing depth and fixed processing logic in specialized chips require strict control over label push, swap, and pop order. Without such control, an excessive stack leads to reduced packet processing predictability and increases the probability of traffic deviation from the fast path.

A substantial role in forming trade-offs is played by including fast convergence mechanisms in the label management loop. Using pre-calculated backup next-hop and label bindings allows reducing forwarding recovery time during failures, but requires maintaining a consistent state between domains and control planes. Under such conditions, label management ceases to be a local task and acquires a distributed character, where any inconsistency in label distribution or rebinding can disrupt fast switchover correctness.

Extending MPLS functionality by supporting monitoring, logical segmentation, and telemetry forms a separate group of design risks. Including network actions in the label stack increases management model expressiveness but simultaneously expands the potential processing error surface and load on the header parsing mechanism [7]. Controlling the scope of such elements becomes critically important, as incorrect distribution or interpretation of actions outside the specified context complicates operation and increases network sensitivity to configuration errors.

Overall, the discussed trade-offs show that systemic label management in Unified MPLS evolves at the intersection of requirements for stack depth, failure reaction speed, and forwarding function extensibility. Architectural solutions in this area form not as a set of independent optimizations, but as a result of reconciling hardware, protocol, and operational constraints determining the permissible boundaries of multidomain MPLS network development.

## 5. Conclusion

The work shows that label management in unified MPLS environments should be conceptualized not as a collection of protocol mechanisms, but as an independent architectural function of the transport network. With this approach, the label acts as a connecting element between routing,


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forwarding, and operational management, and network resilience and scalability depend on the degree of systematization of label stack structure and processing, rather than on the choice of individual protocols.

The obtained results confirm that separating inter-domain and intra-domain label management levels, hierarchical stack organization, and controlling control information distribution scope allow forming end-to-end transmission paths without enlarging routing domains. This creates a predictable architectural basis for multidomain networks requiring a combination of isolation, manageability, and fast failure recovery.

From an architectural perspective, the obtained results shift the focus of MPLS network design from selecting individual routing mechanisms to forming a managed label stack structure as the primary object of architectural control. In this formulation, the design task lies not in optimizing individual protocols, but in aligning label interpretation levels, their scopes, and permissible stack depth with path management logic and operational requirements. This allows viewing the label stack as a stable architectural construct whose behavior can be predicted and limited in advance, rather than as a byproduct of independent protocol solution interaction.

It is shown that extending label semantics through network actions moves MPLS environment management to a new level where the label stack is used as a carrier of formalized packet processing instructions. However, such a model requires explicit consideration of hardware constraints and strict control of stack depth and composition, as these parameters determine the applicability boundaries of extended functions in real networks.

Overall, systematic label management in Unified MPLS forms as a balance between architectural expressiveness, hardware feasibility, and operational resilience. The presented analytical framework allows viewing this balance as an object of purposeful design and can be used in the development and evolution of transport networks oriented toward long-term scalability and predictable behavior.

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