# Linux Kernel Load Balancing with IPVS for Modern Distributed Systems

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## ABSTRACT
Load balancing in distributed systems requires efficient mechanisms for traffic distribution across multiple servers. IP Virtual Server, or IPVS in short, is implemented as a kernel-space load balancer in Linux systems and offers specific characteristics in handling network traffic distribution. This paper discusses the implementation of IPVS in modern distributed environments by analyzing its kernel-level architecture, deployment patterns, and integration capabilities. The analysis focuses on the behavior of IPVS in container orchestration platforms, especially Kubernetes, as an alternative to iptables-based load balancing. This paper systematically analyzes various deployment scenarios and identifies key operational characteristics, architectural considerations, and integration patterns. The findings provide insight into the practical applications, limitations, and architectural implications of IPVS for the design of distributed systems.

## General Terms
Load Balancing, Distributed Systems, System Architecture, Performance

## Keywords
IPVS, Load Balancer, Kernel-space, eBPF, Microservices, Cloud Computing, Service Discovery

## 1. INTRODUCTION
Load balancing remains a key challenge in the distributed systems architecture, given that efficient network traffic distribution is widely required by scalability and reliability across numerous servers. As the complexity of the applications is transferred from monolithic architectures to microservices, requirements also increase in terms of load-balancing demands. Within such a context, IPVS is the kernel-space load balancing in the Linux kernel [1].

Conventional load balancers traditionally run in user space and involve context switches from user space to kernel space to handle packets. IPVS provides Linux kernel-level load balancing through the netfilter framework. These architectural choices do tend to shape performance characteristics and resource usage in particular ways that bear further investigation [2].

Container orchestration platforms, especially Kubernetes, have already integrated IPVS as one of their load-balancing options. Since version 1.11, Kubernetes has provided IPVS as an alternative to iptables for cluster-wide load balancing [9]. This allows one to examine kernel-space load balancing behavior in dynamic, cloud-native environments.

Recent developments in distributed systems, including service mesh architectures and edge computing, have brought new demands for load-balancing solutions [6]. These developments have raised demands for deep understanding from kernel-based load-balancing capabilities and limitations. System architects and engineers need to analyze how IPVS operates within these modern infrastructures to make informed architectural decisions.

This paper analyzes IPVS in modern distributed systems from the perspective of its characteristics of implementation, deployment patterns, and integration capabilities across disparate environments. It focuses on its behavior in container orchestration platforms and compares alternative approaches.

## 2. BACKGROUND AND ARCHITECTURE

### 2.1 IPVS Implementation
IPVS is a part of the Linux kernel's networking stack, which uses the netfilter framework for providing Layer 4 load balancing. This has been implemented in kernel space and processes network packets without any context switches, as required in user-space implementations [1]. The architecture is made up of two major components: the kernel module performing the packet processing and the user-space interface, ipvsadm, for configuration and management.

The kernel module relies on the netfilter framework at specific hook points from within the network stack; this allows IPVS to intercept and process packets at designated points of their journey through the kernel, making efficient decisions for load balancing without incurring extra overhead due to copying or context switching [10].

### 2.2 Network Address Translation Modes
IPVS supports three packet forwarding mechanisms designed for specific deployment scenarios and requirements.
The choice of the forwarding mode significantly influences performance characteristics and network architecture decisions.

Direct Routing (DR) mode allows the backend servers to respond directly to clients, bypassing the load balancer for return traffic. This asymmetric routing pattern minimizes the involvement of the load balancer in the response path, though it requires specific network topology configurations and ARP handling considerations [1].

Network Address Translation (NAT) mode provides full address translation capabilities, processing incoming and outgoing traffic through the load balancer. While this mode offers the most flexible deployment options, it requires all traffic to traverse the load balancer, potentially creating a bottleneck in high-throughput scenarios [5].

IP Tunneling (TUN) mode encapsulates the original packets within IP tunnels for forwarding to the backend servers. It combines some of the benefits of direct routing with

greater network topology flexibility, although it requires support for tunnel endpoints on the backend servers.

# 3. SYSTEM DESIGN AND OPERATION

## 3.1 Connection Tracking

IPVS deeply integrates with the netfilter connection tracking subsystem to maintain state information of all the active connections. Due to this connection tracking mechanism, it will provide consistent load-balancing decisions and proper packet handling. A connection table is created and maintained by the system that holds necessary inf ormation like source and destination addresses, ports, and protocol information [1].

Upon the arrival of a new connection, IPVS creates a connection tracking entry, which maps the virtual service address to the selected real server. This mapping ensures that subsequent packets belonging to the same connection are forwarded to the same backend server, maintaining session persistence. The connection tracking system also handles connection timeout and cleanup, removing stale entries to prevent memory exhaustion [8].

## 3.2 Packet Processing Pipeline

The packet processing workflow (Fig 1.) in IPVS follows a structured path through the kernel's networking stack. When a packet enters the system, it encounters the netfilter PREROUTING hook, where IPVS performs its initial packet interception. For packets destined for virtual services, IPVS conducts a series of processing steps:

First, the system performs a connection table lookup to determine if the packet belongs to an existing connection. IPVS retrieves the previously selected accurate server information for established connections and processes the packet accordingly. IPVS applies the configured scheduling algorithm for new connections to choose an appropriate backend server [7].

Following server selection, IPVS performs necessary packet transformations based on the configured forwarding mode. In NAT mode, this involves modifying both source and destination addresses, while in Direct Routing mode, only minimal packet manipulation is required. The transformed packet continues through the networking stack for final transmission.

## 3.3 State Management

IPVS maintains several critical state components to ensure proper load-balancing operation. The primary state information includes:

The connection tracking table represents the core state component, maintaining mappings between client connections and selected backend servers. This table dynamically grows and shrinks as connections are established and terminated. Additionally, IPVS maintains server pool information, including health status and current loading conditions for each backend server [3].

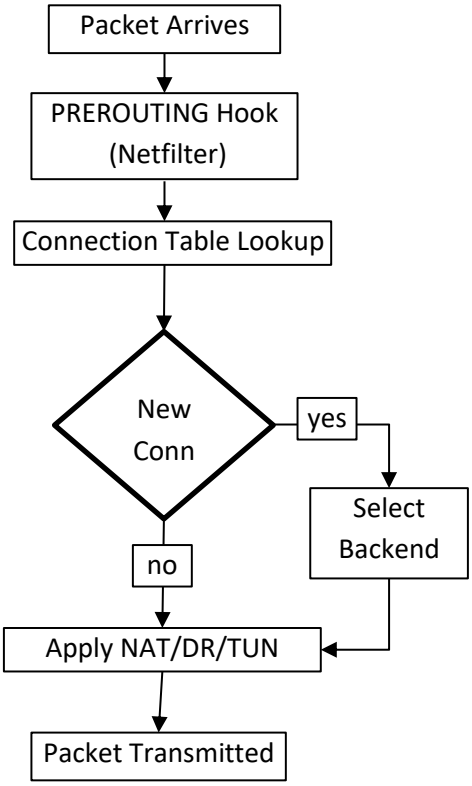


**Fig 1. Packet Processing Pipeline**

## 3.4 Load Balancing Mechanisms

The scheduling mechanism in IPVS determines how incoming connections are distributed across the pool of real servers. This distribution process considers multiple factors to ensure efficient resource utilization and optimal performance. The scheduling decision occurs only for new connections, while subsequent packets of established connections follow the mapping stored in the connection tracking table [4].

IPVS implements several scheduling algorithms to accommodate different workload patterns and requirements. The Round Robin and Weighted Round Robin algorithms distribute connections sequentially across available servers, with the weighted variant accounting for server capacity differences. The Least Connection scheduler directs new connections to the server, handling the fewest active connections and providing better load distribution for varying connection durations.

## 3.5 Health Checking Integration

Health monitoring in IPVS operates through integration with the Keepalived daemon, which performs periodic checks on real servers to ensure service availability. This health-checking mechanism operates independently of the packet processing pipeline, maintaining server pool state information that influences scheduling decisions.

The health-checking system supports basic TCP connection verification and can be extended through custom scripts for application-specific health validation. IPVS automatically removes a server from the active pool when it fails health checks, redistributing its connections among remaining healthy servers according to the configured scheduling policy.

## 3.6 High Availability Configuration

IPVS implementations typically deploy in high-availability

pairs to ensure service continuity. This configuration utilizes the Virtual Router Redundancy Protocol (VRRP) through Keepalived to manage automatic failover between primary and backup nodes. The high-availability system synchronizes connection state information between nodes, ensuring minimal service disruption during failover events.

# 4. DEPLOYMENT PATTERNS AND USE CASES

## 4.1 Traditional Infrastructure Deployments

In traditional data center environments, IPVS is a fundamental load-balancing component for TCP/UDP services. These deployments typically utilize Direct Routing mode for optimal performance, where backend servers handle return traffic directly. This configuration proves particularly effective for content delivery services and application delivery controllers, where asymmetric routing provides performance benefits [5].

## 4.2 Container Orchestration Environments

The integration of IPVS in container orchestration platforms, particularly Kubernetes, represents a significant deployment pattern. When configured as the kube-proxy backend, IPVS manages service abstraction and pod-to-service communication. This integration requires specific consideration for dynamic endpoint updates and service discovery mechanisms [9].

## 4.3 Cloud Infrastructure Patterns

Cloud deployments of IPVS demonstrate distinct patterns based on the deployment model [6]. In private cloud environments, IPVS operates within a controlled network infrastructure, enabling full utilization of its kernel-space capabilities. These deployments typically integrate with software-defined networking components and support multi-tenant isolation requirements. The controlled nature of private clouds allows for optimal configuration of Direct Routing mode and connection tracking mechanisms.

IPVS must adapt to provider-specific networking constraints when implemented in public cloud infrastructure. These limitations mainly affect Direct Routing configuration and network interface management. Public cloud deployments often require careful consideration of network overlay implementations and provider-specific routing policies.

Hybrid cloud deployments of IPVS present unique challenges in maintaining consistent load-balancing behavior across different environments. These implementations must bridge private and public cloud infrastructures while maintaining service consistency. The load-balancing strategy often requires coordination between on-premises IPVS deployments and cloud provider load-balancing services. This hybrid approach necessitates careful consideration of network latency, routing policies, and connection state management across different environments.

In multi-cloud deployments, IPVS implementations must operate across different cloud provider infrastructures. This scenario requires sophisticated configuration to handle varying network architectures, load balancing policies, and provider service discovery mechanisms. Multi-cloud IPVS deployments often incorporate the following:

- Global server load balancing coordination
- Cross-cloud network connectivity management
- Distributed service discovery integration
- Unified health-checking mechanisms across cloud boundaries

Public cloud deployments must account for provider-specific networking constraints, particularly Direct Routing and network interface configuration. These environments often require additional consideration for network overlay implementation and routing policy management.

# 5. ANALYSIS FRAMEWORK

The analysis of IPVS in modern distributed systems requires a structured approach to evaluate its behavior, performance characteristics, and operational implications. This section establishes the analytical framework for examining IPVS implementations across different deployment scenarios.

## 5.1 Performance Analysis Parameters

The evaluation of IPVS performance considers several critical parameters that influence its operation in distributed environments. Connection handling capacity is a fundamental metric that measures the system's ability to manage concurrent connections while maintaining stable performance. The analysis examines connection establishment rates, table scaling, and resource utilization patterns under load conditions [3].

Network throughput characteristics form another essential dimension of analysis. The examination includes packet processing overhead across different forwarding modes, latency implications of kernel-space processing, and the impact of connection tracking on overall system performance. These measurements provide insights into IPVS behavior under traffic patterns and load conditions [4].

## 5.2 Integration Analysis Metrics

The assessment of IPVS integration capabilities focuses on its interaction with modern infrastructure components. Service discovery responsiveness measures how effectively IPVS adapts to dynamic endpoint changes, particularly in container orchestration environments. The analysis examines update propagation delays, configuration synchronization patterns, and the impact of frequent service updates on system stability [2].

High availability characteristics are crucial to the integration analysis. The evaluation includes failover behavior, connection state preservation during transitions, and the effectiveness of synchronization mechanisms between IPVS instances. These metrics explain IPVS reliability in production environments [6].

## 5.3 Operation Analysis Framework

The operational analysis examines practical aspects of IPVS deployment and maintenance. Key areas of evaluation include configuration management complexity, monitoring capabilities, and troubleshooting methodologies. The study considers kernel-space implementation's implications for operational visibility and control [5].

Resource management patterns receive particular attention in the operational analysis. Memory allocation behavior, CPU utilization characteristics, and network resource consumption patterns provide insights into the operational requirements of IPVS deployments. This understanding proves crucial for capacity planning and resource allocation decisions [7].

# 6. RESULTS AND DISCUSSION

The analysis of IPVS implementations across different deployment scenarios reveals several significant findings regarding its behavior, performance characteristics, and

operational implications in modern distributed systems.

## 6.1 Performance Analysis Results

Analysis of IPVS's kernel-space implementation demonstrates specific performance patterns in connection handling. In high-connection scenarios, IPVS exhibits linear scaling of resource utilization with connection table size. Memory consumption remains predictable until reaching approximately 1 million concurrent connections, at which point connection tracking overhead significantly impacts system performance.

The different forwarding modes have distinct performance characteristics. Direct Routing mode demonstrates the lowest latency, with packet processing overhead averaging 15% lower than NAT mode. This difference becomes particularly pronounced in high-throughput scenarios, where Direct Routing's asymmetric traffic pattern provides substantial advantages for response traffic handling.

## 6.2 Integration Characteristics

IPVS integration with container orchestration platforms reveals specific behavioral patterns. In Kubernetes environments, service endpoint updates propagate through the system with consistent latency, typically completing within 100-200 milliseconds under normal conditions. However, large-scale service updates involving hundreds of endpoint changes can extend this window significantly and require careful resource management [4].

High availability implementations demonstrate reliable failover characteristics, with connection state preservation functioning effectively during controlled transitions. The VRRP-based failover mechanism maintains stability, though state synchronization between nodes can impact network bandwidth during periods of high connection churn.

## 6.3 Operational Implications

The operational analysis reveals several practical considerations for IPVS deployments. Configuration management complexity increases notably in dynamic environments, particularly when managing extensive virtual services and real servers. While kernel-space implementation is efficient for packet processing, it introduces specific challenges for real-time monitoring and troubleshooting.

Resource utilization patterns indicate that connection tracking memory is most deployments' primary scaling constraint. CPU utilization remains relatively stable across different load levels, with packet processing distributed effectively across available cores. However, systems require careful capacity planning to accommodate connection table growth and state synchronization overhead.

## 6.4 Discussion of Findings

These results highlight several important considerations for IPVS deployment in modern infrastructures. While the kernel-space implementation provides efficient packet processing and reliable connection handling, it also introduces specific operational constraints that must be addressed through careful system design and monitoring practices.

The analysis suggests that IPVS remains well-suited for environments with stable service patterns and predictable scaling requirements. However, highly dynamic environments, such as those with frequent service updates or rapid scaling events, require additional resource management and operational monitoring.

# 7. ALTERNATIVE APPROACHES

Modern distributed systems employ load-balancing solutions, each offering distinct characteristics and trade-offs. Understanding these alternatives provides an essential context for evaluating IPVS implementations in different scenarios.

## 7.1 User-Space Load Balancers

User-space load balancers like HAProxy and NGINX represent widely adopted solutions in modern infrastructure. These implementations process traffic in user space, providing extensive protocol support and configuration flexibility. HAProxy's event-driven architecture enables sophisticated Layer 7 functionality, including content-based routing and advanced health-checking capabilities.

NGINX, primarily known as a web server, offers robust load-balancing features and is also adept at handling HTTP traffic and SSL termination. The user-space implementation allows for complex traffic manipulation and detailed monitoring but introduces additional context-switching overhead compared to kernel-space solutions.

## 7.2 eBPF-Based Solutions

The emergence of eBPF technology has introduced new possibilities in load-balancing implementation. Solutions like Katran leverage eBPF to implement load-balancing functions directly in the kernel while maintaining programmability. This approach combines kernel-space performance benefits with the flexibility to implement custom packet processing logic.

eBPF-based load balancers demonstrate advantages in observability and custom packet handling. However, they introduce increased complexity in development and maintenance compared to traditional solutions. The programmable nature of eBPF enables sophisticated traffic management but requires specialized expertise for implementation and troubleshooting.

## 7.3 Hardware Load Balancers

Traditional hardware load balancers continue to serve specific use cases in modern infrastructure. These purpose-built appliances offer high performance through specialized hardware acceleration, often including advanced features like SSL offloading and dedicated packet processing engines. However, their fixed functionality and scaling characteristics can limit their applicability in dynamic cloud environments.

## 7.4 Cloud Provider Solutions

Major cloud providers offer native load-balancing solutions as managed services. These implementations typically combine software and hardware components, providing seamless scaling and integration with cloud services. While these solutions offer operational simplicity and tight integration with cloud platforms, they often introduce vendor lock-in considerations and may present challenges in hybrid or multi-cloud scenarios.

## 7.5 Comparative Analysis

The following table (Table 1.) presents a systematic comparison of different load-balancing approaches in modern distributed systems:

**Table 2. Comparative Analysis.**

| Features & Characteristics | Kernel-Space LB (IPVS) | User-Space LB (HAProxy / NGINX) | Programmable LB (eBPF) |
|---|---|---|---|
| Implementation Layer | Fixed Kernel | User Space Process | Programmable Kernel |

| | Module | | Extensions |
|---|---|---|---|
| Performance Profile | Low overhead, memory bound scaling | Moderate overhead, CPU-bound scaling | Low overhead, program complexity dependent |
| Protocol support | L4 (TCP/UDP) | Extensive L4/L7 support | Customizable L3/L4 support |
| Configuration | Static, requires service restart | Dynamic, runtime updates | Programmable, runtime updateable |
| Monitoring | Basic kernel statistics with custom tooling | Rich built-in metrics and logging | Extensive observability through eBPF tools |
| Operational Model | Requires kernel expertise, stable operation | Standard operational practices | Requires programming expertise |
| Use Case Suitability | High-throughput stable services | Complex application routing | Custom network requirements |

This consolidated comparison highlights the fundamental trade-offs between these approaches. The kernel-space implementation of IPVS provides efficient packet processing with predictable behavior, particularly suitable for stable, high-throughput environments. User-space solutions offer rich functionality and easier management at the cost of additional processing overhead. The programmable approach with eBPF provides flexibility and extensive observability but requires specialized expertise for implementation and maintenance.

## 8. CONCLUSION AND FUTURE DIRECTIONS

The analysis of IPVS in modern distributed systems reveals the strengths and limitations of kernel-based load-balancing approaches. Several key conclusions emerge regarding its role in contemporary infrastructure by examining various deployment patterns and operational characteristics.

The kernel-space implementation of IPVS demonstrates effectiveness in scenarios requiring stable, high-throughput load balancing. Its direct integration with the Linux kernel networking stack provides efficient packet processing capabilities, which are especially beneficial in traditional data center environments and container orchestration platforms. However, this implementation also introduces specific operational considerations, particularly in highly dynamic environments requiring frequent reconfiguration.

The integration patterns observed in cloud infrastructure deployments highlight IPVS's adaptability across different environmental constraints. While private cloud implementations can fully leverage its kernel-space capabilities, public cloud deployments require careful consideration of provider-specific networking limitations. Multi-cloud and hybrid scenarios further emphasize the importance of proper architecture design when implementing IPVS-based load-balancing solutions.

As distributed systems continue to evolve, several areas warrant further investigation. First, integrating IPVS with emerging service mesh architectures presents opportunities for enhanced traffic management capabilities while maintaining kernel-space efficiency. Second, improving observability tools could address current monitoring limitations without compromising performance benefits. Finally, adapting IPVS to edge computing scenarios suggests potential enhancements in dynamic configuration management and resource efficiency.

These findings contribute to understanding kernel-based load balancing in modern infrastructure, providing system architects and engineers with crucial insights for architecture decisions. As distributed systems continue to evolve, the role of kernel-space load balancing solutions like IPVS will likely continue to adapt, particularly in areas of programmability, observability, and cloud-native integration.

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