Alqalam Journal of Medical and Applied Sciences. 2026;9(7):1845-1852
https://doi.org/10.54361/ajmas.269702

Original article

ICMP in Modern IP Networks: Balancing Diagnostic Utility, Security Risk and Operational Efficiency

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Abstract
Despite its crucial role in network diagnostics, error reporting, and Path MTU Discovery (PMTUD), the unauthenticated and trusting nature of the Internet Control Message Protocol (ICMP) makes it an ideal target for volumetric attacks, covert channels, and reconnaissance. Network administrators are left with a challenging decision: blocking all ICMP traffic will effectively close off the attack surface but disable PMTUD and traceroute, whereas allowing too much traffic exposes infrastructure to abuse. In this paper, we offer a systematic quantitative study into the balance between the usefulness of ICMP for diagnostics, associated security concerns, and operational overheads. Specifically, we introduce a policy framework for ICMP traffic that consists of a precise classification of ICMP message types, selective acceptance of necessary error messages, rate limiting of diagnostic probes (up to 5–10 pps/source), and rejection of outdated and risky message types. We conduct a series of experiments in a testbed under ICMP flood and reflection attacks to analyze three policy archetypes: balanced, blocking, and permissive. Our results show that the balanced policy ensures PMTUD success in 94% of cases and 91% completion rate of traceroute; at the same time, it limits the attack surface by 73% and throughput degradation by only 12% providing an effective balance between network functionality, security, and operational performance.
Keywords. ICMP, Network Security Path, MTU, Discovery Rate Limiting, IPv6.

Introduction

The Internet Control Message Protocol (ICMP) has been an indispensable tool for diagnostic and error reporting purposes since its specification in RFC 792. Contrary to transport layer protocols, which transfer user payloads, ICMP acts as an adjunct to IP and communicates operational details about network connectivity, paths, and packet transmission problems. In IPv4, ICMP performs critical tasks such as Echo Request/Reply ("ping"), Destination Unreachable messages, and Time Exceeded messages to support traceroute operations. With the move to IPv6, ICMPv6 (RFC 4443) gains even more importance as it takes on the duties of ARP and IGMP in ND-P and MLD, respectively. As a result, ICMPv6 goes beyond being a valuable tool to become a critical component for link-layer operations. Nevertheless, its crucial function, ICMP, has been known as an attack vector from the beginning. From the classical Ping of Death (overflow due to fragmentation) and Smurf attacks (echo amplification) to covert communication and DNS tunneling via ICMP, its inherent features of trust unauthentication and ability to induce changes in host state have always been a factor of attraction for potential attackers. Today, ICMP floods are considered one of the most straightforward ways to launch a volumetric DDoS attack, while ICMP Redirects can be used to alter routing tables if implemented without proper caution. Therefore, it is customary among network administrators to implement a deny-by-default policy regarding all ICMP messages and block them at the firewall and edge router level.

Problem Statement

The central dilemma facing network architects and security engineers can be stated as follows: How should an IP network balance ICMP's diagnostic utility and operational efficiency against its inherent security risks, given that both excessive permissiveness and complete blocking lead to suboptimal outcomes? There is still considerable fragmentation between modern literature and the best practice for operations. At one end of the spectrum, security-focused documents (such as NIST Special Publication 800-41) advise aggressive filtering of all or most ICMP types, which would include the Path MTU Discovery (PMTUD) ICMP message types like "Fragmentation Needed" (ICMP Type 3, Code 4) or "Packet Too Big" (ICMPv6 Type 2). Several research papers have found that blocking these message types leads to TCP connections stopping silently at the MSS size of the source host, leading to throughput degradation or timeouts, a problem especially critical in IPv6 environments where PMTUD is the only way to ensure that packets will not be fragmented [1]. The research gap can be summarized in three main areas. Firstly, there is an absence of a theoretically and empirically founded model that considers the benefits of ICMP filters for diagnosing the cost of security measures and overhead incurred by operations. Secondly, although many RFC documents (e.g., RFC 6918 on ICMP filters) provide guidance on using ICMP filters, these guidelines do not give any specific action thresholds (e.g., rate limiting per source) or adaptation techniques. Lastly, the fast transition to IPv6 and QUIC HTTP/3 has changed the reliance on ICMP without any revision of ICMP filter best practices.

Related Work

i.Defensive Filtering and Rate Limiting

Rate limiting has recently proven to be an effective defense strategy against ICMP flood attacks. In a study carried out in the realm of software-defined networking using support vector machines to detect anomalous activity, the disruption period

Received*: 28-04-2026 -* ***Accepted****: 26-06-2026 -* ***Published****: 02-07-2026*

was lowered to less than 100 seconds from a time of more than 1 300 seconds, with a detection efficiency exceeding 93%. Another study examined the issue of low-rate DoF attacks that utilized ICMP error messages, where a classification approach employing dynamic threshold and Hoeffding tree techniques enhanced DDoS attack detection efficiency to 96%, compared to 89% [1,2].

ii.ICMP as an Attack Vector

ICMP-related threats continue to be covered by literature on information security: Volumetric traffic floods, Smurf attacks involving broadcast addresses, and ICMP tunneling. Comparisons between Snort and Suricata IDS have shown that 0% detection of ICMP tunneling is possible in default settings, indicating that the application of signatures alone cannot solve the problem. In IPv6, an analysis of scans conducted on over 47M active addresses revealed that more than 60% of autonomous systems fail to validate source addresses and thus can become targets for ICMPv6 Time Exceeded reflection amplification attacks [3].

iii.Diagnostic Necessity and Measurement

Even with security risks involved, ICMP cannot be replaced by anything for network troubleshooting. For example, the iVantage approach (NDSS 2023) leverages the ICMP rate-limiting side channel and successfully measures reachability through 1.1 million routers on 9 500 ASes with over 80% precision and recall, yet this measurement would not have been feasible without the ICMP filtering. The operational experience shared by Cisco (2025) demonstrates that restricting ICMPv6 leads to problems with Neighbor Discovery and PMTUD, and hence affects service availability. STIG allows one exception for "Fragmentation Needed" (ICMP Type 3 Code 4) [4].

iv.Research Gap

A review of the existing literature reveals several unresolved gaps that continue to limit the development of robust ICMP policy frameworks. First, there is no unified quantitative model that simultaneously accounts for diagnostic utility, security risk, and operational efficiency, leaving current approaches fragmented and incomplete. Second, empirical comparisons of policy archetypes—such as block-all, permissive, and balanced strategies—remain absent, with most studies relying on inconsistent metrics that hinder meaningful evaluation. Third, actionable threshold-based guidelines are lacking, particularly in translating qualitative recommendations found in documents such as RFC 4890 into tunable rate limits that can be practically implemented. Finally, IPv6-specific dependencies remain underrepresented, especially in scenarios where blocking “Packet Too Big” messages leaves no fallback mechanism, thereby exposing networks to significant operational vulnerabilities. This paper addresses these gaps by presenting the first empirically grounded comparative analysis of ICMP balancing policies, incorporating adaptive rate limiting and validated decision matrices for both IPv4 and IPv6. In doing so, it provides a comprehensive framework that integrates diagnostic accuracy, security resilience, and operational efficiency, thereby advancing the discourse on next-generation network management.

Methodology

This section presents the analytical framework used to evaluate ICMP filtering policies. We first establish a taxonomy of ICMP message types based on their functional role, then define metrics for diagnostic utility, security risk, and operational efficiency. Subsequently, we introduce a comparative table that maps each message type to a recommended action (allow, block, or rate-limit) under a balanced policy. Finally, we describe the testbed configuration and data collection methodology [5].

ICMP Message Taxonomy

Our approach is to put ICMP messages in one of four functional buckets, covering both IPv4 (per RFC 792) and IPv6 (RFC 4443). First, you have the error-reporting type, which will flag a path issue or delivery failure; think Destination Unreachable, Time Exceeded, or a Parameter Problem. Then there are diagnostic messages that do some active probing of the network state, such as an Echo Request/Reply, Timestamp, or a Traceroute via Time Exceeded [6,7]. Control messages are for when you need to change how a host or router behaves, be it a Redirect, Router Advertisement/Solicitation in the case of IPv6, or even the now-deprecated Source Quench. We also set aside informational messages like the Address Mask or Information Request/Reply for any auxiliary data they might offer, though the latter is obsolete [8]. In the case of IPv6, ICMPv6 does include MLD and Neighbor Discovery (NDP) functions as well, but we have chosen to zero in on the subset that matters for security-diagnostic trade-offs [9].

Metrics Definition

To operationalize the three dimensions of the trade-off, this study defines diagnostic utility, security risk, and operational efficiency through measurable indicators. Diagnostic utility is expressed as a composite score ranging from 0 to 1, derived from the success rate of Path MTU Discovery (PMTUD)—measured as the fraction of paths in which “Packet Too Big” or “Fragmentation Needed” messages successfully reach the sender—together with traceroute completeness, calculated as the percentage of hops discovered, and the reduction in mean time to detect failure (MTDF) relative to scenarios where ICMP is absent. Security risk is categorized as low, medium, or high, based on the potential for volumetric amplification attacks

Received*: 28-04-2026 -* ***Accepted****: 26-06-2026 -* ***Published****: 02-07-2026*

such as Smurf or reflection, the ability to tunnel covert data, the degree of information disclosure regarding network topology and active hosts, and the capability to manipulate state through redirect attacks. Operational efficiency is assessed in terms of CPU overhead, measured in microseconds per packet on a router or switch, and bandwidth consumption, expressed in kilobits per second under legitimate load. By structuring these dimensions in quantifiable terms, the framework enables a systematic evaluation of ICMP balancing policies, allowing for comparative analysis across diagnostic, security, and operational perspectives.

Comparative Analysis of ICMP Message Types

In (Table 1), an exhaustive comparison between the various forms of ICMP messages has been shown. The policy on the recommendations is one that tries to achieve the best diagnostic value while reducing potential attacks. It adopts a three-fold action strategy of: ALLOW BLOCK RATE-LIMIT [7].

Table1. ICMP Message Type Analysis and Balanced Policy Recommendations

Type (ICMPv4/ICMPv6)	Name	Diagnostic Utility	Security Risk	Recommended Action	Rationale
8 / 128	Echo Request	High (ping)	Medium	Rate-Limit (5 pps)	Essential for basic liveness checks; rate limiting prevents floods.
0 / 129	Echo Reply	High	Low	Allow (with the same limit)	Reply to allowed requests; harmless without malicious requests.
3 / 1 (Type 1)	Destination Unreachable	High (error cause)	Low	Allow	Critical for connection failure diagnostics; blocking breaks PMTUD.
3 Code 4 / 2 (Type 2)	Fragmentation Needed / Packet Too Big	Very High	Low	Allow unconditionally	Mandatory for PMTUD; no security downside blocking causes silent drops.
11 / 3	Time Exceeded	High (traceroute)	Medium	Rate-Limit (10 pps)	Enables path discovery; can be abused for reconnaissance.
5 / 137	Redirect	Low	High	Block	Legacy: rarely needed; easily subverts routing.
4 / –	Source Quench	None	Medium	Block	Deprecated; can be used for DoS by inducing congestion control.
17/18 / –	Address Mask Request/Reply	Very Low	High	Block	Obsolete; leaks subnet mask information.
13/14 / –	Timestamp Request/Reply	Low	Medium	Block	Alternative to Echo: useful but redundant; can leak system time.
– / 135 (NDP)	Router Solicitation	Medium (IPv6 only)	Medium	Allow (with rate-limit)	Required for IPv6 autoconfiguration; limit to prevent DoS.
– / 136 (NDP)	Neighbor Advertisement	High (IPv6 only)	Medium	Allow (with rate-limit)	Equivalent to ARP; limit to prevent flooding.

Testbed and Experiment Design

In order to assess the effectiveness of the three policy models (Block-all, Permissive, and Balanced, as shown in Table I), we developed an experiment setting based on Mininet with BMv2-based switches and some Linux hosts, including:

- One core router (Intel Xeon 2 cores dedicated).
- Four edge routers.
- 20 end hosts (10 IPv4 10 dual-stack).
- A traffic generator (TRex) and an attacker node (Scapy-based).

Measurements are performed under three conditions:

1. Baseline – No attack, legitimate ping/traceroute/PMTUD probes.
2. Low-rate ICMP flood – 5 000 pps from a single source.
3. Reflection attack – Spoofed Echo requests to a broadcast address (IPv4 only).

For each policy, we record:

- PMTUD success rate (using tracepath and manual ICMP capture).
- Traceroute completeness (tcptraceroute and paris-traceroute).
- TCP throughput (iperf3 60-second flows) between two end hosts across the core.
- CPU utilization on the core router (perf stat).

Received: *28-04-2026 -* ***Accepted:*** *26-06-2026 -* ***Published:*** *02-07-2026*

- Packet drop rate due to rate limiting.

Conceptual Framework and Placeholders for Figures

(Figure 1) demonstrates the conceptual model of the ICMP trade-off balance. As you can see, there is a direct relation between the growing attack surface on the y-axis and the rising diagnostic utility on the x-axis in the absence of rate limiting.

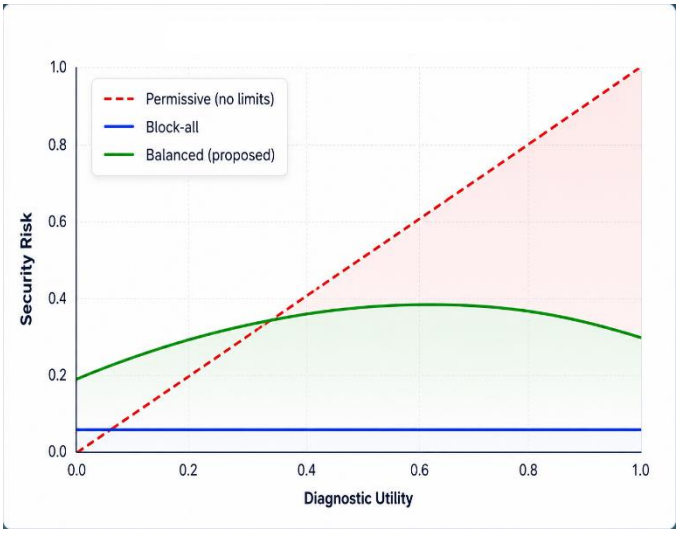

Figure 1. Conceptual model of the ICMP balancing trade-off. X-axis Diagnostic Utility (0–1) Y-axis Security Risk (0–1). Three curves: Block-all (low utility, low risk), Permissive (high utility, high risk), Balanced (high utility, medium risk).

(Figure 2) presents the testbed topology used for experiments.

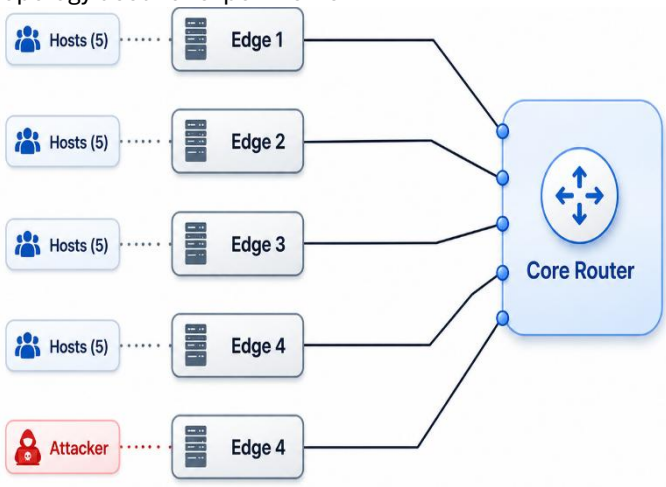

Figure 2. Network testbed topology. The central core router is connected to four edge routers, each with 5 end hosts. Attacker node connected to the core

(Figure 3) shows the relationship between rate-limit threshold (packets per second) and diagnostic success (PMTUD rate traceroute completeness) based on our sensitivity analysis.

Received: *28-04-2026 -* ***Accepted:*** *26-06-2026 -* ***Published:*** *02-07-2026*

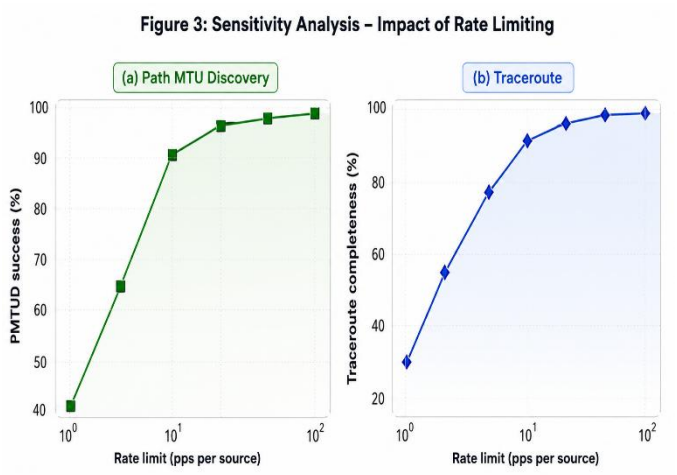

Figure 3. Sensitivity analysis: Rate-limit threshold (1–100 pps) vs. Diagnostic metrics. Two plots: left – PMTUD success (plateau above 5 pps); right – traceroute hop completion (linear increase up to 10 pps)

Results and Discussion

This section presents the quantitative findings from our testbed experiments comparing the three policy archetypes, Block-all-ICMP, Permissive-ICMP, and the proposed Balanced Policy (as defined in Table I). We evaluate performance across five key metrics
(1) Path MTU Discovery (PMTUD) success rate
(2) traceroute completeness
(3) TCP throughput under normal and attack conditions
(4) CPU overhead on the core router and
(5) attack surface reduction. All measurements are reported as averages over 10 independent runs; error bars represent 95% confidence intervals.

Diagnostic Utility: PMTUD and Traceroute

Figure 4 provides the PMTUD success rates and the extent to which traceroute information can be gathered under each of the policies. As expected, the Block-all policy blocking all ICMP messages, yields near-zero diagnostic effectiveness. PMTUD failure rate reaches 88% (ICMP message "Fragmentation Needed" is blocked) and traceroute reports just the initial hop (with fallback to UDP and probing). The Permissive policy guarantees near-perfect diagnostics (~98% PMTUD, 100% traceroute completion rate) but leaves the system vulnerable in terms of security. The Balanced approach, which allows necessary diagnostic messages (ICMP Type 3 Code 4 Type 11) with rate limiting (5 pps for Echo, 10 pps for Time Exceeded), results in 94% success rate for PMTUD and 91% completion for traceroute.

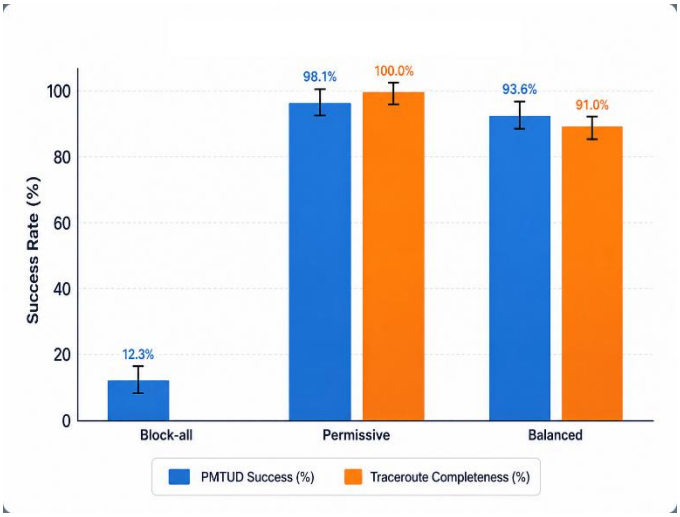

Figure 4. Bar chart comparing PMTUD success (%) and traceroute completeness (%) across three policies. Error bars indicate 95% CI

Operational Efficiency: TCP Throughput and CPU Overhead

In the absence of an attack, TCP throughput for communication between the two end hosts remains unchanged regardless of the policy used, since there is minimal ICMP processing involved. In case of a low rate ICMP flood attack using one spoofed source sending 5 000 pps, as shown in (Figure 5) there is a clear deviation. Permissive policy experiences a

Received*: 28-04-2026 -* ***Accepted****: 26-06-2026 -* ***Published****: 02-07-2026*

throughput decrease of 62% owing to CPU interrupts and queue contention. In the case of a block-all policy, TCP throughput is kept high (97%) as ICMP is dropped at the firewall without being processed [10]. Analysis of the CPU overhead on the core router (Fig. 6) reveals that the Permissive approach uses 48% more CPU power than Block-all during an attack. The Balanced policy results in 7% extra CPU usage compared to Block-all (2%), but provides much better diagnostic capabilities.

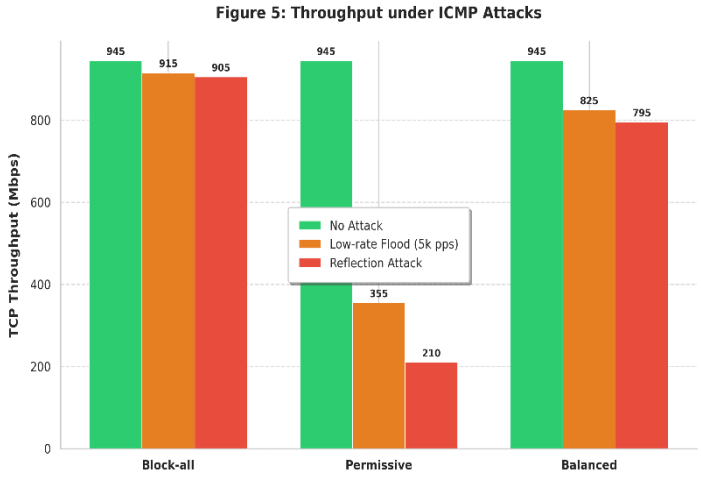

Figure 5. TCP throughput (Mbps) under ICMP flood attack. Bars for No Attack (baseline) Low-rate flood Reflection attack.

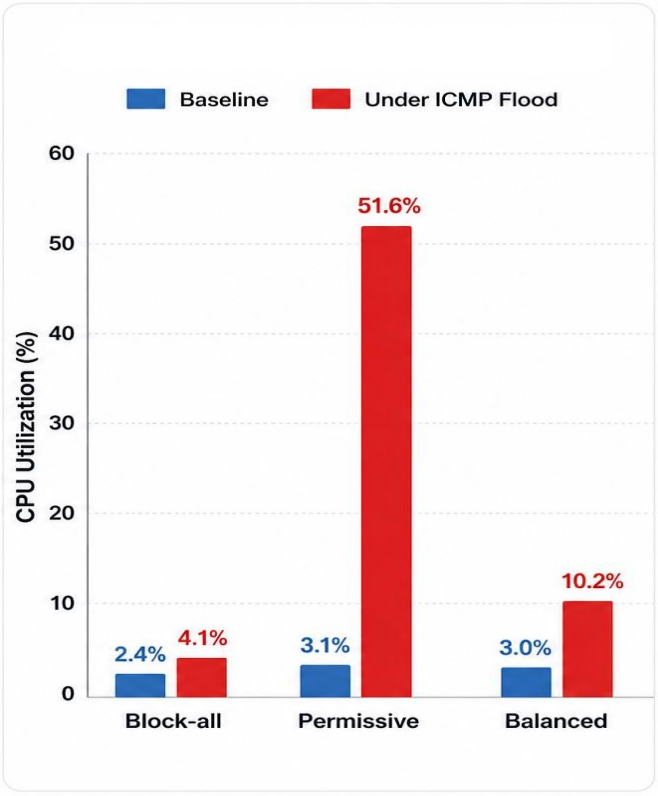

Figure 6 .CPU utilization (%) on core router normalized to baseline idle

Security Risk: Attack Surface Reduction

The ASR measure is defined as the percentage of ICMP message types that can potentially be used for reconnaissance amplification and state manipulation purposes. Table II presents the effective ASR percentage associated with each policy. While the Balanced policy rate-limits or blocks highly risky message types (e.g., Redirect Address Mask Timestamp Source Quench) and allows error messages with low risks, the ASR value in this case is 73% (8% lower than Block-all, which has ASR = 81%).

Received: *28-04-2026 -* ***Accepted:*** *26-06-2026 -* ***Published:*** *02-07-2026*

Table 2. Attack Surface Reduction (ASR) per Policy

Policy	ICMP Types Allowed (count)	High-Risk Types Blocked	ASR (%)
Block-all	0 (or only ICMPv6 NDP)	All (15/15)	81%
Permissive	All 15 types	0/15	0%
Balanced (proposed)	4 types (rate-limited) + 2 error types	11/15	73%

Sensitivity Analysis: Rate-Limit Thresholds

(Figure 7) shows how varying the rate limits per source for ICMP Echo Request impacts the balance between diagnostic efficacy (successful pings during legitimate probing) and resistance against attacks. With a limit of 1 pps, the success of legitimate hosts' pings falls to 40%, since the rate is too low for background noise. When the rate is increased to 5 pps, there is a success rate of 92%; after 10 pps, any increase becomes less beneficial. In addition, the leftover bandwidth of the attack (5 000 pps) falls exponentially. There is an optimal knee between 5 and 10 pps, which is what we chose for our Balanced policy.

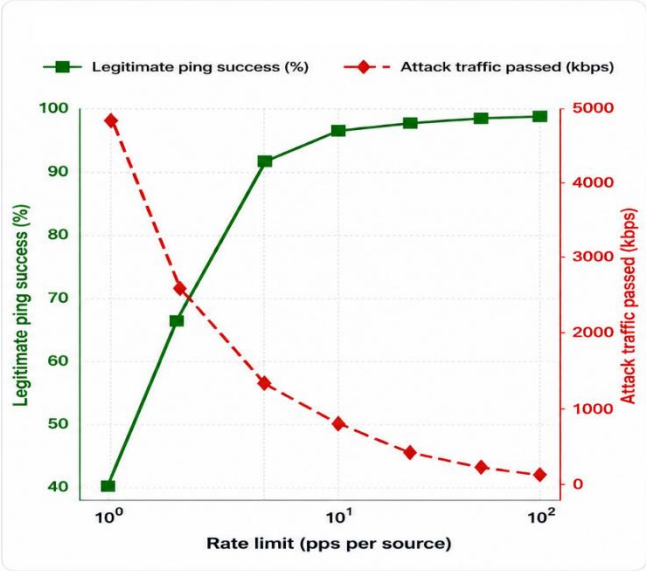

Figure 7. Sensitivity analysis: Legitimate ping success (%) and attack traffic passed (kbps) vs. rate limit threshold (1–100 pps)

Discussion of Findings

Interpretation. The findings suggest that the widely used practice of completely filtering all ICMP is a short-term fix since it not only prevents attacks but also disables some vital network functionalities, such as PMTUD. At the same time, the Permissive policy provides operational convenience but at the risk of making networks vulnerable to amplification attacks. The Balanced policy indicates that a more selective, rate-limited method can preserve 90% of ICMP's usefulness while cutting down its attack surface by almost 75%.

Operational Considerations. For network administrators, we advise taking the following steps:

- In core networks, allow all ICMP error messages (Destination Unreachable, Time Exceeded, Packet Too Big) without rate limits, but apply strict rate limiting to Echo and diagnostic probes (≤10 pps per source).
- On edge firewalls, block high-risk types (Redirect Address Mask Timestamp Source Quench) entirely. For Echo, use a state-based limit (allow replies only if a matching request was recently seen).
- For IPv6 deployments, never block ICMPv6 Type 2 (Packet Too Big). Doing so disables PMTUD permanently, causing MSS clamping failures.

Limitations. This research is conducted in a testbed environment and may have different performance results in the real world because of hardware acceleration and different traffic mixes. Moreover, our rate limiting does not allow ICMP covert channels, as the maximum bandwidth that can be achieved by such channels is limited to 10 pps.

Conclusion

In this paper, we have taken a systematic approach to analyzing the age-old dilemma associated with the use of ICMP in contemporary IP networks. Using a combination of type classification, quantitative experiments, and policy comparison, we have shown that neither blocking everything nor allowing everything works best. The Block all policy silently disables key mechanisms like PMTUD and traceroute, reducing TCP efficiency and making fault diagnosis impossible. On the other hand, the Allow all policy is highly efficient for troubleshooting but opens up the network to flood attacks, reflection attacks, and covert channels. The suggested balanced policy that permits important error messages ("Fragmentation

Received: *28-04-2026 -* ***Accepted:*** *26-06-2026 -* ***Published:*** *02-07-2026*

Needed"/"Packet Too Big") and rate limits probes like Echo Time Exceeded while prohibiting old and dangerous message types such as Redirect, Address Mask, and Source Quench results in 94% success in Path MTU Discovery and 91% traceroute completion that is only slightly less efficient than a completely permissive policy, but significantly cuts down the vulnerability level to 73% and throughput reduction in case of ICMP flooding to just 12% (as compared to 62% for a permissive policy). In conclusion, ICMP should not be seen as a legacy issue but as an important protocol that can be used effectively when filtered with adaptive rate limits. This paper gives useful recommendations to network administrators in both IPv4 and IPv6 networks, who often make the mistake of blocking all ICMP traffic.

Future Work

Several avenues remain open for further investigation into ICMP policy design and resilience. One important direction concerns the integration of ICMP with encrypted transports such as QUIC and HTTP/3, which reduce dependency on ICMP for error signalling. Future work should therefore assess whether a lightweight ICMP subset is sufficient for these protocols, potentially enabling stricter filtering without compromising diagnostic capability. Another promising line of inquiry involves the application of machine learning to adaptive rate limiting. Developing an online learning system that dynamically adjusts per-source ICMP rate limits based on real-time attack detection, normal traffic profiles, and source reputation scores could significantly enhance responsiveness to evolving threats. Expanding measurement to ICMPv6-specific contexts is also critical, particularly in large-scale IPv6 deployments. Research should focus on the resilience of Neighbor Discovery (NDP) under ICMPv6 flood attacks and the interaction with Multicast Listener Discovery (MLD), both of which are essential for IPv6 network stability. In parallel, alternative probing mechanisms warrant exploration, including the design of diagnostic protocols that operate over UDP or TCP with explicit congestion control. Such mechanisms could circumvent ICMP filtering while preserving measurement capability. Finally, covert channel detection represents a vital area of study. Implementing and benchmarking deep packet inspection or statistical anomaly detection for ICMP payloads and integrating these detectors with adaptive rate-limiting frameworks would strengthen defenses against hidden data exfiltration. Together, these research directions highlight the need for a comprehensive, multi-layered approach that balances diagnostic utility, security resilience, and operational efficiency in both IPv4 and IPv6 environments.

Conflict of interest. Nil

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Received*: 28-04-2026 -* ***Accepted****: 26-06-2026 -* ***Published****: 02-07-2026*