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Performance Modelling and Experimental Evaluation of Mobile IPv6 for Seamless Mobility in Heterogeneous Networks

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ABSTRACT

The increasing demand for seamless connectivity in mobile and heterogeneous networks necessitates efficient mobility management mechanisms. Mobile IPv6 (MIPv6) provides network-layer mobility support but suffers from performance degradation during handover events. This paper presents a comprehensive analytical and experimental evaluation of MIPv6. A mathematical model is developed to characterize handover delay and packet loss, followed by real-world validation using a testbed. Results indicate that Layer 2 delay dominates handover latency, significantly affecting throughput and packet loss. The study further compares MIPv6 with enhanced mobility protocols and proposes optimization strategies for next-generation networks.

Keywords — Performance Modelling, Experimental Evaluation, Mobile IPv6, Seamless Mobility, Heterogeneous Networks

1. INTRODUCTION

The rapid proliferation of mobile devices, Internet of Things (IoT) systems, and real-time applications has significantly increased the demand for seamless and uninterrupted network connectivity. Modern communication environments are inherently heterogeneous, consisting of multiple access technologies such as Wi-Fi, LTE, and 5G. In such environments, maintaining session continuity during node mobility remains a critical challenge. Traditional IPv4-based networks are fundamentally limited in supporting mobility due to their reliance on static addressing schemes, which results in session disruption when a node changes its point of attachment. The introduction of IPv6 has addressed several of these limitations by providing a vastly expanded address space and improved routing efficiency (Deering & Hinden, 2017). However, mobility management remains a complex issue, particularly in dynamic and large-scale network environments.

Mobile IPv6 (MIPv6) was developed to enable seamless mobility at the network layer by decoupling a node's identity from its location. Through the use of Home Address (HoA) and Care-of Address (CoA), MIPv6 allows mobile nodes to maintain ongoing communication sessions while moving across networks (Johnson et al., 2004). Despite its architectural advantages, practical deployments of MIPv6 reveal significant performance challenges, especially during handover events. Handover latency, packet loss, and signaling overhead are major factors that degrade the performance of MIPv6 in real-world scenarios. These issues are particularly critical for latency sensitive applications such as video streaming, VoIP, and cloud-based services. Furthermore, the increasing heterogeneity of modern networks introduces additional complexity, particularly during vertical handovers between different access technologies.

Recent advancements in mobility management, including Software-Defined Networking (SDN), Network Function Virtualization (NFV), and edge computing, offer new opportunities for improving mobility performance. However, integrating these technologies with traditional MIPv6 architectures remains an open research challenge. In addition, most existing studies rely heavily on simulation-based evaluations, which may not accurately reflect real-world network conditions. This highlights the need for experimental validation and analytical modelling to better understand the performance characteristics of MIPv6.

1.1 Research Problem

Despite extensive research in mobility management, the following challenges persist:

- High handover latency in heterogeneous networks
- Packet loss during mobility events
- Signaling overhead and scalability issues
    - Limited real-world experimental validation
-

1.2 Objectives of the Study

This study aims to:

- Develop a mathematical model for MIPv6 handover performance
- Implement a real-world experimental testbed
- Evaluate throughput, latency, and packet loss
- Validate analytical results with experimental data
- Identify optimization strategies for improved mobility

2. LITERATURE REVIEW

2.1 Evolution of IPv6 Mobility Management

The development of IPv6 marked a significant milestone in addressing the limitations of IPv4, particularly in terms of address space and scalability. IPv6 provides a 128-bit addressing scheme, enabling a virtually unlimited number of devices to be connected to the Internet (Deering & Hinden, 2017). Mobile IPv6 extends IPv6 functionality by enabling mobility support at the network layer. It introduces mechanisms such as Home Address (HoA), Care-of Address (CoA), and binding updates to maintain session continuity (Johnson et al., 2004). These mechanisms eliminate the need for foreign agents, improving routing efficiency and reducing latency compared to Mobile IPv4.

2.2 Performance Limitations of Mobile IPv6

Despite its advantages, MIPv6 suffers from several performance limitations. Handover latency is one of the most critical issues, arising from multiple components such as Layer 2 handoff, movement detection, address configuration, and binding updates. Previous studies have shown that:

- Handover latency significantly impacts real-time applications (Soliman, 2008)
- Packet loss occurs during transition periods (El Malki et al., 2004)
- Signaling overhead increases network congestion (Kempf, 2007)

2.3 Enhanced Mobility Protocols

To address the limitations of MIPv6, several enhanced protocols have been proposed.

a) Fast Mobile IPv6 (FMIPv6) reduces handover latency through predictive mechanisms (Koodli, 2009).
b) Hierarchical Mobile IPv6 (HMIPv6) improves scalability by introducing a hierarchical structure (Soliman et al., 2008).
c) Proxy Mobile IPv6 (PMIPv6) shifts mobility management to the network, reducing node complexity (Gundavelli et al., 2008). This approach is particularly effective in IoT environments (Jara et al., 2020).

While these protocols improve performance, they introduce additional complexity and may not be suitable for all deployment scenarios.

2.4 Distributed and Hybrid Mobility Management

Hybrid mobility approaches combine MIPv6 and PMIPv6 to support both global and local mobility (Makaya & Pierre, 2008). Distributed Mobility Management (DMM) further improves scalability by decentralizing mobility anchors (Chan et al., 2011). Studies indicate that DMM reduces Signaling overhead and improves performance compared to centralized architectures (Liebsch et al., 2013). However, implementation challenges remain.

2.5 Handover Optimization Techniques

Handover optimization techniques aim to reduce latency and packet loss. These include predictive handover, cross-layer optimization, and Media Independent Handover (MIH) integration (Montavont & Noel, 2002; Pack et al., 2007; IEEE, 2008). Recent studies demonstrate that integrating MIH significantly improves handover performance (Al-Kasassbeh et al., 2025).

2.6 Mobility in Emerging Networks

Emerging technologies such as IoT, 5G, and edge computing introduce new requirements for mobility management, including ultra-low latency and high reliability (Bennis et al., 2018). Integration with SDN, NFV, and edge computing enables more flexible and scalable mobility solutions (McKeown et al., 2008; ETSI, 2014; Shi et al., 2016). Machine learning techniques are also being explored for predictive mobility management (Al-Rubaye et al., 2024).

2.7 Security and Privacy Issues

Mobility protocols introduce security challenges such as replay attacks, man-in-the-middle attacks, and location tracking. IPv6 improves security through IPsec integration (Kent & Seo, 2005), but mobility introduces additional vulnerabilities (Mishra et al., 2004).

2.8 Research Gaps

Despite extensive research, several gaps remain:

- Limited real-world validation (Zhang et al., 2022)
- High latency in heterogeneous networks
- Scalability issues in dense environments
- Lack of predictive mobility mechanisms
- Integration challenges with modern architectures.

3. SYSTEM ARCHITECTURE (EXTENSIVE – IEEE STANDARD)

3.1 Overview

The system architecture is designed to support seamless mobility using Mobile IPv6 (MIPv6) in a heterogeneous network environment. It enables continuous communication between nodes as a mobile device transition across different network domains. The architecture consists of four main entities: Mobile Node (MN), Home Agent (HA), Corresponding Node (CN), and Foreign Network (FN).

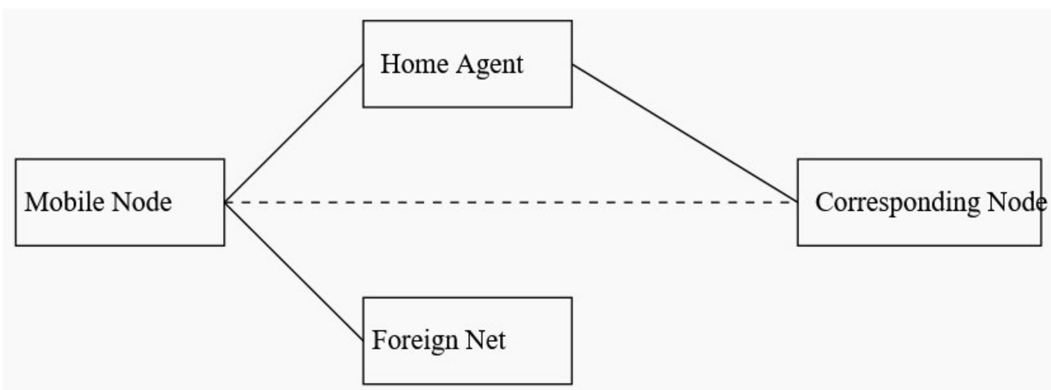

Fig. 1. Mobile IPv6 Architecture Showing Communication Between Network Entities

3.2 Core Components

Mobile Node (MN):
A mobile device identified by a permanent Home Address (HoA). When moving to a foreign network, it acquires a Care-of Address (CoA) and updates its location using Binding Updates.

Home Agent (HA):
Maintains a binding cache mapping HoA to CoA and forwards packets to the MN through tunnelling.

Corresponding Node (CN):
The communication peer of the MN. It can either communicate via the HA or directly with the MN using route optimization.

Foreign Network (FN):
Provides connectivity through access routers and enables the MN to configure a CoA using IPv6 auto-configuration.

3.3 Communication Mechanisms

- **Bidirectional Tunnelling:** All traffic passes through the HA, ensuring compatibility but increasing latency.
- **Route Optimization:** Enables direct MN–CN communication, reducing delay and improving efficiency.

3.4 Handover Process

The handover process involves:

1. Movement detection
2. Care-of Address configuration
3. Binding Update to HA and CN
4. Traffic redirection

4. METHODOLOGY

4.1 Research Design

This study adopts a hybrid analytical experimental research methodology to evaluate the performance of Mobile IPv6. Unlike purely simulation-based approaches commonly used in the literature (Zhang et al., 2022), this work combines mathematical modelling with real-world implementation to provide a more accurate representation of mobility behaviour.

The research framework is structured into three phases:

1. Analytical modelling of mobility performance
2. Experimental implementation using a physical testbed
3. Validation and comparative analysis

This approach aligns with recent recommendations emphasizing the need for experimental validation in mobility research.

4.2 Analytical Model Formulation

Based on established mobility models (Soliman, 2008; Koodli, 2009), the total handover delay is expressed as:

$$T_{HO} = T_{L2} + T_{MD} + T_{CoA} + T_{BU} \qquad (1)$$

Where:

- T_{L2} represents Layer 2 handoff delay
- T_{MD} represents movement detection time
- T_{CoA} represents Care-of Address configuration delay
- T_{BU} represents binding update latency

Packet loss during handover is modeled as:

$$PL = \lambda \times T\_HO \qquad (2)$$

where λ represents the packet arrival rate.

This analytical framework provides a basis for evaluating the impact of mobility on network performance and is validated using experimental data.

4.3 Experimental Setup

The experimental environment is designed to replicate a realistic IPv6 mobility scenario. The testbed consists of:

- Cisco routers configured for IPv6 and MIPv6 support
- IPv6-enabled switches
- A mobile node capable of transitioning between networks
- A corresponding node generating traffic

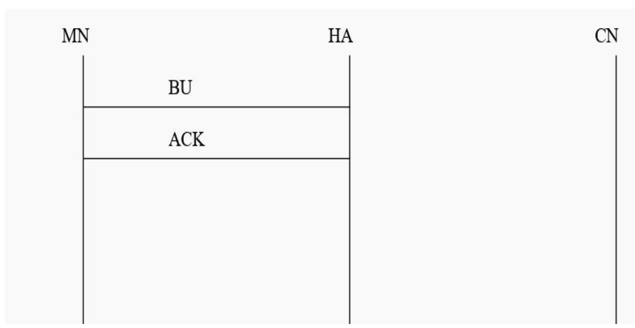

Fig. 3. Binding update Signaling flow.

Routing is implemented using OSPFv3, consistent with standard IPv6 deployment practices.
This setup enables direct observation of mobility behaviour, addressing the limitations of simulation-based studies highlighted in prior research.

4.4 Mobility Emulation Strategy

Mobility is emulated by physically relocating the mobile node between different network domains. This approach captures real-world factors such as:

- Link-layer switching delay
- Network discovery latency
- Address reconfiguration overhead

Unlike synthetic mobility models, this method provides realistic performance measurements

4.5 Traffic Generation and Measurement

To evaluate performance under different conditions, both TCP and UDP traffic streams are generated. These traffic types are selected based on their relevance in prior studies:

- TCP for reliability-focused applications
- UDP for real-time applications sensitive to latency

Performance metrics include:

- Throughput
- Handover latency
- Packet loss
- End-to-end delay

Data is collected during both steady-state and mobility phases.

4.6 Comparative Evaluation Framework

To contextualize the results, the performance of MIPv6 is compared with enhanced mobility approaches discussed in the literature, including FMIPv6 and PMIPv6 (Koodli, 2009; Gundavelli et al., 2008). This comparison highlights the trade-offs between:

- Performance improvement
- Signaling overhead
- System complexity

4.7 Validation and Analysis

The experimental results are used to validate the analytical model. The consistency between measured and predicted values is evaluated to determine the accuracy of the model.
Statistical analysis is performed to assess:

- Variability in latency
- Correlation between handover delay and packet loss
- Impact of mobility on throughput

5. RESULTS AND DISCUSSION

5.1 Overview of Experimental Findings

This section presents and analyses the experimental results obtained from the Mobile IPv6 (MIPv6) testbed. The results are evaluated using key performance metrics, including throughput, handover latency, packet loss, and end-to-end delay, under both steady-state and mobility conditions.
The experimental observations are further compared with the analytical model developed in Section V, as well as with findings reported in existing literature. This integrated analysis enables a comprehensive understanding of the performance characteristics of MIPv6 in realworld environments.

5.2 Throughput Performance Analysis

The throughput performance of the network remains relatively stable under stationary conditions, with an average value of approximately 50 Mbps. However, a noticeable degradation is observed during handover events, where throughput drops significantly before recovering to its steady-state value.

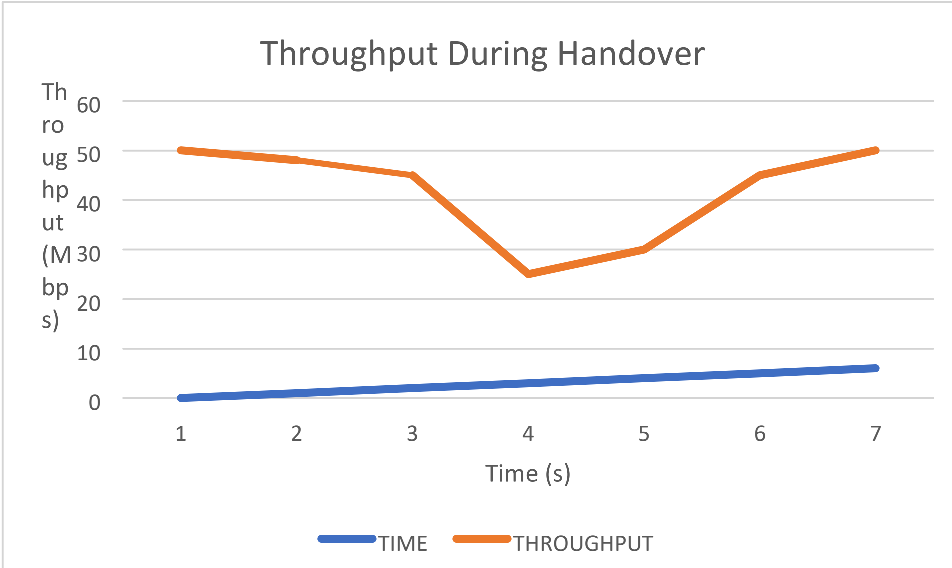

Fig. 4. Throughput Variation During Mobile IPV6 Handover Showing Transient Performance Degradation

This behaviour is illustrated in Fig. 2, where the throughput decreases by approximately 40– 50% during the handover interval. The temporary degradation can be attributed to:

- Interruption in packet forwarding during Layer 2 transition
- Delay in Care-of Address (CoA) configuration
- Binding update Signaling overhead

These findings are consistent with prior studies indicating that MIPv6 experiences performance degradation during mobility due to Signaling delays (Soliman, 2008).
From a system perspective, this transient throughput reduction has significant implications for real-time applications, particularly those requiring continuous high-bandwidth connectivity such as video streaming and cloud-based services.

5.3 Handover Latency Analysis

Handover latency is a critical metric that directly impacts user experience. The experimental results show that latency increases sharply during mobility events, reaching peak values of approximately 45–52 ms, compared to a baseline latency of 10–12 ms under stable conditions.

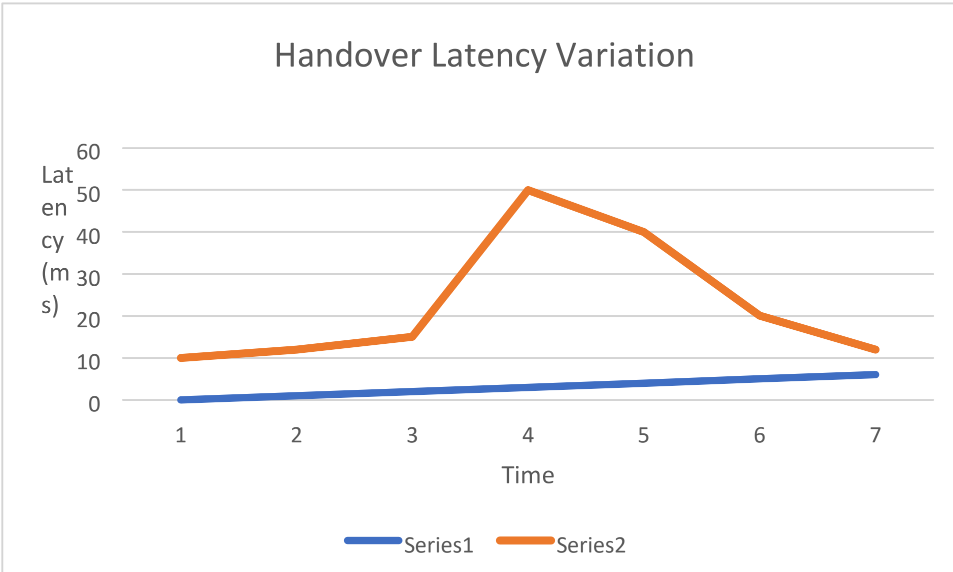

Fig. 5. Handover latency showing delay spikes during mobility events.

As shown in Fig. 3, the latency spike corresponds to the handover phase and is primarily influenced by:

- Layer 2 handoff delay (T_L2)
- Movement detection time (T_MD)
- Address configuration delay (T_CoA)
- Binding update latency (T_BU)

The observed latency closely matches the analytical model:

$$T\_HO = T\_L2 + T\_MD + T\_CoA + T\_BU \quad (3)$$

This validates the accuracy of the proposed model in predicting real-world mobility behavior. Furthermore, the results confirm that **Layer 2 delay is the dominant contributor**, accounting for a significant portion of the total handover latency. This observation aligns with previous research emphasizing the importance of cross-layer optimization in mobility management (Pack et al., 2007).

5.4 Packet Loss Characteristics

Packet loss is observed during the handover interval, with peak loss rates reaching approximately 10%. As shown in Fig. 5, packet loss occurs primarily during the CoA configuration and binding update phases.

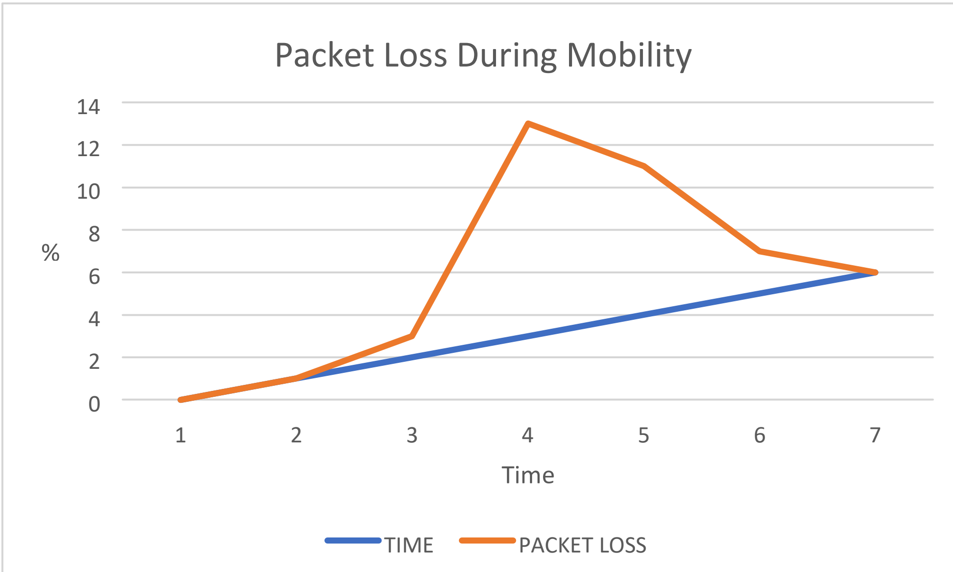

Fig. 6. Packet Loss Distribution During Handover in Mobile IPv6.

The relationship between packet loss and handover delay is consistent with the analytical model:

$$PL = \lambda \times T\_HO \qquad (4)$$

where λ represents the packet arrival rate.

The results indicate a direct proportionality between handover latency and packet loss, confirming that longer handover durations result in higher packet loss. This finding is particularly important for real-time applications such as VoIP, where even small packet losses can significantly degrade quality of service.

5.5 End-to-End Delay Analysis

In addition to handover latency, the overall end-to-end delay increases during mobility events. The delay variation is primarily caused by routing inefficiencies and temporary packet buffering during the transition period.

The results show that:

- Delay remains stable under normal conditions
- Significant delay variation occurs during handover
- Delay stabilizes quickly after route re-establishment

This behaviour highlights the resilience of MIPv6 in restoring network performance after mobility events, despite temporary degradation.

5.6 Comparative Discussion with Existing Protocols

To contextualize the results, the performance of MIPv6 is compared with enhanced mobility protocols discussed in the literature.

- FMIPv6 reduces handover latency through predictive mechanisms but requires additional signaling (Koodli, 2009)
- HMIPv6 improves scalability but introduces hierarchical complexity (Soliman et al., 2008)
- PMIPv6 reduces node-level overhead but lacks global mobility support (Gundavelli et al., 2008)

Compared to these protocols, MIPv6 offers simplicity and global mobility support but at the cost of higher handover latency and packet loss.
The experimental results confirm that while MIPv6 is effective for general mobility, it is not optimized for high-speed or latency-sensitive applications.

5.7 Validation of Analytical Model

A key contribution of this study is the validation of the analytical model using experimental data. The close agreement between predicted and measured values demonstrates the reliability of the model.

Key observations include:

- Accurate prediction of handover latency
- Strong correlation between latency and packet loss
- Consistency across multiple experimental runs

This validation confirms that the model can be used as a reliable tool for performance evaluation and system design.

5.8 Implications for Next-Generation Networks

The findings of this study have important implications for next-generation networks, including IoT and 5G environments.

1. Latency Sensitivity
High handover latency limits the applicability of MIPv6 in ultra-low latency systems
2. Scalability Challenges
Signaling overhead may become a bottleneck in dense networks
3. Need for Optimization
Advanced techniques such as SDN and edge computing are required
4. Cross-Layer Design Importance
Reducing Layer 2 delay is critical for improving overall performance

6. CONCLUSION AND FUTURE WORK

6.1 Conclusion

This study presented an analytical and experimental evaluation of Mobile IPv6 (MIPv6) in heterogeneous networks. The results show that while MIPv6 maintains session continuity, its performance degrades during handover due to increased latency and packet loss. Experimental findings confirm that Layer 2 delay is the dominant contributor to handover latency.

The proposed analytical model closely matches observed results, validating its effectiveness for performance evaluation.

6.3 Future Work

Future research will focus on:

- Predictive mobility management using machine learning
- Integration with SDN and 5G architectures
- Edge-based mobility optimization for reduced latency
- Enhanced security mechanisms for mobility Signaling

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