CHAPTER I
INTRODUCTION

1.1 Background

The Internet has become an essential technology, serving not merely as a supporting facility but as a fundamental component of modern life. Various sectors, including personal communication, education, business operations, and public services, rely heavily on the availability of reliable Internet connectivity [1]. As dependence on Internet-based services continues to grow, the stability and quality of network access have become critical factors in ensuring effective operations. Consequently, network service providers are required to maintain reliable infrastructure capable of supporting the increasing demand for rapid and continuous information exchange [2].

Bandwidth management is one of the key approaches to addressing performance issues in Internet networks. In the absence of optimal configurations and well-defined management policies, bandwidth resources tend to be dominated by certain users, resulting in unequal allocation and reduced controllability. Such conditions can significantly degrade Quality of Service (QoS), particularly during periods of high user activity and increased network traffic [3]. QoS degradation may lead to higher delay, increased packet loss, and unstable throughput, all of which negatively affect network performance. As reported by F. Dwilaksono, these effects are especially noticeable in latency-sensitive applications such as real-time communication, online examinations, and other real-time services, ultimately reducing users' Quality of Experience (QoE) and overall productivity [4],[5].

These conditions highlight that bandwidth management is not merely a mechanism for limiting Internet access, but rather a strategy for allocating network resources efficiently and fairly among users [6]. For example, a study conducted by Migni Finces Manao et al. implemented a static bandwidth management policy using the Queue Tree method, in which bandwidth was allocated at fixed rates to specific divisions or user groups. Although the approach demonstrated stable performance under normal network conditions, it encountered limitations when dealing with dynamic traffic patterns and sudden traffic surges, reducing its effectiveness in environments characterized by fluctuating network demands [7]. This limitation arises because data usage patterns are often variable and asymmetric, making static systems less flexible and responsive to changing conditions. Consequently, there is a need for an adaptive bandwidth management system capable of automatically adjusting network resource allocation in response to real-time variations in traffic demand and user activity [8].

The unpredictable nature of network traffic requires a transition toward bandwidth management systems that are more adaptive and responsive to real-time network conditions, particularly in institutions with highly variable user demands [9]. When a specific user group suddenly generates a large volume of traffic, the absence of an adaptive control mechanism can significantly disrupt overall network stability and performance. Therefore, effective bandwidth management requires more than simple usage restrictions; it also necessitates dynamic resource allocation based on continuously monitored network conditions to ensure optimal performance and service quality [10].

To address these challenges, computational intelligence approaches such as the Fuzzy Inference System (FIS) can be employed to manage uncertainty in network traffic control. As demonstrated by M. F. Alwan et al., FIS utilizes linguistic variables such as low, medium, and high to represent conditions that cannot be precisely defined, enabling greater flexibility in handling dynamic network environments [11]. One of the most widely used FIS methods is the Sugeno Fuzzy model. Due to its ability to produce direct numerical outputs, the Sugeno approach is particularly well suited for control systems, allowing adaptive bandwidth limits to be determined based on real-time network conditions, such as the number of active users and current traffic levels [12].

The Sugeno Fuzzy method offers significant advantages in terms of computational efficiency, making it well suited for systems that require fast and dynamic decision-making. In contrast, modern machine learning approaches generally depend on model training, large volumes of historical data, and greater computational resources [13]. Sugeno Fuzzy operates using a deterministic rule base, enabling it to generate direct numerical outputs with a high degree of consistency. This characteristic allows decision-making processes to be performed efficiently while maintaining relatively low computational complexity. Consequently, the Sugeno Fuzzy approach is considered suitable for near real-time systems based on periodic feedback control and can be effectively implemented on embedded devices with limited computational resources [14].

On the other hand, the Per Connection Queue (PCQ) method in MikroTik has been shown to distribute bandwidth fairly among users by allocating network capacity based on the number of active connections. This mechanism ensures that each user receives an equitable share of available bandwidth, reducing the likelihood of resource domination by particular users and promoting fair network utilization [15]. However, the effectiveness of PCQ depends on bandwidth limits that are typically configured statically by network administrators. These limits are generally established during the initial network planning stage and do not account for changing traffic conditions over time [16]. Although scheduled adjustments can be implemented to modify bandwidth allocations periodically, such approaches still lack the adaptive capability required to respond dynamically to real-time traffic fluctuations.

Static bandwidth management systems, or open-loop control systems, do not consider subsequent changes in network conditions once configurations have been permanently applied. As a result, their policies may become ineffective when network traffic or the number of users increases significantly [17]. In contrast, dynamic bandwidth management systems based on closed-loop feedback control can automatically adjust their behavior according to current network conditions. This capability enables bandwidth resources to be allocated more efficiently while maintaining stability and fairness despite fluctuations in traffic load. Therefore, closed-loop control architectures are considered more effective for preserving network Quality of Service (QoS) than static approaches that rely on fixed configurations [18].

Although the potential of Fuzzy Inference Systems (FIS) in network optimization has been widely demonstrated, their implementation in previous studies has generally been limited to decision-making and prediction tasks. For instance, the study conducted by I. W. Lahiya and F. Arifin employed the Sugeno Fuzzy method to generate adaptive decisions; however, the execution of those decisions on network devices was performed separately and still required administrator intervention [19], Similarly, the research by M. F. Alwan et al. [11], focused on predicting bandwidth load without directly applying configuration changes to network devices. As a result, these approaches have not been able to provide fully adaptive and real-time bandwidth management through direct integration with network infrastructure.

The novelty of this research lies in two key contributions that have not been addressed in previous studies. First, the Sugeno Fuzzy approach is implemented not merely as a simulation-based decision-making mechanism, but as an active controller that directly modifies pcq-rate parameters on a MikroTik router through the RouterOS API within a closed-loop control framework. Second, the proposed system adopts a multi-output architecture in which a single inference cycle simultaneously generates three bandwidth allocation decisions for traffic classes with different priority levels, namely Real-time, Streaming, and Bulk traffic.

Based on this concept, the proposed system is evaluated in the SCR (Smart Systems and Robotics) Laboratory of the Faculty of Computer Science, Universitas Pembangunan Nasional "Veteran" Jawa Timur. The SCR Laboratory represents a network environment characterized by dynamic traffic patterns, particularly during class sessions, research activities, and concurrent student usage. Variations in the number of active users and the diversity of traffic types make this laboratory a suitable and representative environment for evaluating the effectiveness of the proposed adaptive bandwidth management system.

Based on the considerations outlined above, this research aims to address the gap in network automation technologies through a study entitled **"Design and Implementation of an Adaptive Bandwidth Management System Using Fuzzy Sugeno and Per Connection Queue (PCQ)."** The proposed system is designed not only to overcome unequal bandwidth allocation but also to operate autonomously and responsively in maintaining network service stability. By integrating adaptive decision-making with automated bandwidth control, the system is expected to improve resource utilization and sustain Quality of Service (QoS) under dynamic network conditions.

1.2 Problem Formulation

Based on the background presented above, the research problems addressed in this study are as follows:

1. How can an adaptive bandwidth management system based on Sugeno Fuzzy logic and Per Connection Queue (PCQ) be designed using a closed-loop control mechanism with traffic classification on a MikroTik router?
2. How can the proposed system be implemented autonomously using a Python-based controller through the MikroTik API to provide near real-time bandwidth management in the SCR Laboratory network at Universitas Pembangunan Nasional "Veteran" Jawa Timur?
3. How effective is the proposed adaptive bandwidth management system in improving the stability of Quality of Service (QoS) parameters under dynamic network traffic conditions?

1.3 Research Objectives

Based on the research problems that have been identified, the objectives of this study are as follows:

1. To design an adaptive bandwidth management system based on Sugeno Fuzzy logic and Per Connection Queue (PCQ) using a closed-loop control mechanism with traffic classification (Real-time, Streaming, and Bulk) on a MikroTik router.
2. To implement the proposed adaptive bandwidth management system autonomously using a Python-based controller integrated with a MikroTik router through the MikroTik API in a near real-time environment.
3. To analyze the impact of the proposed system on network service quality by evaluating Quality of Service (QoS) parameters before and after the implementation of the adaptive bandwidth management system.

1.4 Research Benefits

From a theoretical perspective, this research contributes to the advancement of Sugeno Fuzzy applications in traffic-aware bandwidth management within a single-subnet network environment. The integration of Sugeno Fuzzy as a computational decision-making mechanism, a MikroTik API–based automation system, and Per Connection Queue (PCQ) as the bandwidth distribution mechanism is expected to enrich the body of knowledge related to network automation and QoS-aware control systems that can adapt to dynamic network conditions.

From a practical perspective, this research is expected to provide an implementable solution for the SCR (Smart Systems and Robotics) Laboratory, Faculty of Computer Science, Universitas Pembangunan Nasional "Veteran" Jawa Timur, in managing bandwidth automatically according to user service requirements. By prioritizing critical traffic and regulating bulk traffic during periods of network congestion, the proposed system can support fairer, more stable, and more efficient bandwidth allocation that aligns with the characteristics of user activities within the laboratory environment.

1.5 Research Limitations

To ensure that the research remains focused and feasible, the following limitations are defined:

1. This research is conducted within the network environment of the SCR (Smart Systems and Robotics) Laboratory, Faculty of Computer Science, Universitas Pembangunan Nasional "Veteran" Jawa Timur. Therefore, the findings are specific to the characteristics of this environment and cannot be directly generalized to networks with significantly different infrastructure scales or topological complexities.
2. The proposed bandwidth management system employs only the Sugeno Fuzzy method as the decision-making mechanism, implemented using the Python programming language. Comparisons with other artificial intelligence approaches, such as Neural Networks, Genetic Algorithms, or related methods, are beyond the scope of this study.
3. The input variables of the Sugeno Fuzzy system are limited to the number of active users and network traffic parameters, namely Receive (RX) and Transmit (TX). Additional factors, such as router CPU utilization, external ISP latency, and deep packet inspection analysis, are not considered.

4. System integration is limited to MikroTik devices as the bandwidth control executor, with bandwidth distribution performed using Per Connection Queue (PCQ). Implementations involving other networking platforms, such as Cisco devices, OpenWRT, or Software-Defined Networking (SDN) architectures, are not discussed.
5. Communication within the closed-loop control system between the Python controller and the MikroTik router is performed exclusively through the MikroTik RouterOS API. Advanced transport-layer security mechanisms, including SSL/TLS certificate-based encryption and network hardening techniques, are outside the scope of this research.
6. System performance evaluation is limited to Quality of Service (QoS) metrics, including throughput, delay, packet loss, and jitter, based on the TIPHON standard. Network security, dynamic routing management, and physical-layer optimization are not included in the evaluation.