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RESEARCH ARTICLE

A Software-Defined UAV Network Using Queueing Model

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ABSTRACT To increase the redundancy and to provide seamless connectivity of the conventional communication systems, an unmanned aerial vehicle (UAV) enabled on-demand forwarding base station approach can be a flexible and dynamic solution, particularly for emergency services. However, managing and controlling these UAVs in changing scenarios can be challenging specifically in large-scale network scenarios. As a promising method of administering these networks, software-defined networking (SDN) can be a good choice compared to traditional networking due to its automated, centralized, and intellectual controllability. Therefore, to meet the future sixth-generation wireless communication requirements with high network availability, improved communication convergence, and intelligent features, a software-defined UAV (SDUAV) networking framework is proposed in this work. To enhance the reliability and scalability, and to reduce the single-point failure issues of this network, a multi-SDN controller-based approach is also deployed in this newly designed architecture. Besides, to solve the load balancing and fault tolerance problems like controller overhead or cascading failure, an adaptive load balancing algorithm as well as a robust hybrid routing algorithm are developed, accordingly. In addition, to evaluate the performance of the proposed architecture, a mathematical model is proposed by using the M/M/1 and M/M/c queueing systems at the primary and secondary controllers, respectively. Simulation results show that the proposed model reduces the packet processing time by 60%, 44%, and 25% in terms of packet arrival rate, service rate, and utilization factor, respectively, compared to the existing control-domain adjustment algorithm.

INDEX TERMS 6G, adaptive load balancing algorithm, micro air vehicle link protocol, NFV, primary-secondary model, queuing model, robust hybrid routing algorithm, SDN, UAV.

I. INTRODUCTION

With the introduction of the fifth-generation public-private partnership (5G-PPP) initiative, the majority of network operators have been seeking an adaptable and dynamic network architecture instead of the fixed cell-based infrastructure that supports the backhaul, fronthaul, and Xhaul networks. Besides, to support the Internet of Things (IoT), Internet of Vehicles (IoV), industry 4.0, and the Internet of Everything (IoE) networks, the small cell, picocell, and femtocell infrastructure are not enough to meet the needs [1], [2]. In addition, a stable and seamless handover-based network topology is required for the deployment of sixth-generation (6G) communication systems, which can be managed and controlled very quickly and easily [2]. Therefore, to tackle the heterogeneous 6G connected devices with machine-to-machine (M2M), device-to-device (D2D), and machine-to-device (M2D) connectivity, the conventional macro base station (BS) based network infrastructure will not be able to support these links and hence, an alternative dynamic on-demand support-based

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networking system is required to support these future wireless networking [3].

Recently, significant efforts have been made to design, develop, and enhance the unmanned aerial vehicles (UAVs) based aerial networking system [4]. By carrying equipment like a wireless access point (WAP), receiver, and transmitter as payload, UAV can provide ubiquitous 3D connectivity and coverage where the traditional cannot cover [5]. Besides, these UAV-enabled aerial networks are extremely useful in emergencies such as post-disaster scenarios [6]. Therefore, to support the future 6G wireless networking, UAV can be one of the possible solutions as the backhaul infrastructure to create cell-free communication systems [7].

To support the recent trends like extended reality (XR), big data analysis, fog computing, and mobile edge computing the networking and internet research and development communities have come out with different futuristic ideas like programmable networking, named data networking (NDN), and software-defined networking (SDN). Among them, SDN is regarded as one of the most significant network structures for the years to come [8]. For several factors, SDN has drawn the attention of the majority of business, government, and intellectual figures as a future core network. Initially, it enables network operators to have a consolidated view of the network and administer it more efficient and flexible manner, making it easier to configure and control network components [9], [10]. Besides, it provides automation and programmability feasible, which may minimize the need for manual configuration tasks and human error, enhancing network security and efficiency. SDN additionally facilitates faster integration with cloud services and different revolutionary technologies like the IoT, computer vision, and artificial intelligence (AI) [11]. Furthermore, SDN offers optimized traffic control, network virtualization, and higher utilization of network bandwidth [12]. The adoption of open-source software and affordable commodity hardware is yet another manner that SDN is predicted to save enterprises revenue by eliminating the requirement for pricey proprietary solutions [13], [14]. Therefore, to support the 6G features like ultra-high speed with low-latency communication (uHSLLC), ubiquitous mobile ultra-broadband (uMUB), massive machine-type communication (mMTC), ultra-high data density (uHDD), SDN is the perfect solution because of its programmability, automation, and intellectual features [1], [15].

The queueing models, on the other hand, are an effective way of evaluating and improving the performance of wireless communication systems [16]. To satisfy the rising need for wireless connectivity and communication systems, these models provide many capabilities, including the capacity to simulate various traffic behavior patterns, such as burst and periodic traffic. As a result, researchers can comprehend how wireless networks regulate various types of information as well as how to enhance the effectiveness of networks. Queueing models can additionally be employed for determining the capacity of wireless networks, including the number of clients and data transmission rates, and traffic loads [16], [17].

In wireless networks, quality of service (QoS) characteristics like delay, packet loss, and throughput can also be predicted with the implementation of queueing models. Even, to satisfy particular QoS requirements, the network architecture and protocols can be designed and optimized accordingly by using this QoS-based information [18]. Additionally, wireless network reliability can be analyzed using queueing models in many different kinds of scenarios and environments. Hence, this could help to identify the possibilities of bottlenecks and enhance the performance of the networks. As a result, the queueing paradigm can be utilized in UAV networking to enhance their performance and capabilities.

Although SDN and UAV have received the majority of attention in several research studies such as their combination, deployment link, channel selection, and coverage improvement, none of these evaluations utilized the two technological advancements to develop a superior networking architecture based on the traffic analysis [19], [20]. We thereby develop an innovative comprehensive computational mathematical model based on the queueing theory to support the future 6G wireless networking demands and presented an SDN-enabled UAV network called software-defined UAV (SDUAV) networking. In order to enhance the reliability and adaptability of the proposed SDUAV networking framework, this work constructs a distinctive primary-secondary multi-SDN controller-based network platform, with SDN acting as the core network and UAVs serving as the backhaul infrastructure. At the same time, a macro air vehicle connection (MAVLink) is also employed for establishing a reliable and secure point-to-point (P2P) communication link between the controllers and UAV nodes, which can track the real-time traffic variations and network topology. Following that, a newly developed packet processing algorithm is introduced which can regulate the packet processing mechanism to minimize cognitions and avoid seemingly small problems from becoming severe bottlenecks. Besides, to ensure the efficient as well as equitable allocation of the network load across the secondary controller and the UAV nodes, a special adaptive load balancing algorithm based on queueing theory is also developed. Furthermore, a robust and dynamic routing scheme and a virtual router redundancy protocol (VRRP) are proposed in order to determine the most effective approach based on network topology and distance and enable the automatic failover mechanism procedure, respectively. Finally, M/M/1 and M/M/c queuing systems are employed at the primary and secondary controllers (where c is the number of servers) in order to develop a novel analytical model for tracking and predicting variations in packet arrival rate, service time, and network behavior that can help in designing and planning the networking infrastructure. The significant contributions of this research are summed up as follows:

- To support the 6G features like the uMTC, uHSLLC, uHDD, uMUB, and M2M communications, a holistic SDUAV networking system is proposed that provides centralized coordination and controllability to the UAV networks with the help of the SDN concept.
- For improving the scalability and reliability of the proposed SDUAV network, a primary-secondary controller-based approach is developed.
- By deploying the MAVLink in the SDUAV system, a lightweight P2P messaging protocol is proposed that can collect periodic information like the network topology, the number of active UAVs in the network, and traffic demand of the network to avoid congestions and ensure low-overhead communication.
- To control the flow of data packets between the SDN controllers and the UAVs effectively and efficiently, a unique packet processing algorithm is designed which is capable of minimizing the network congestion as well as managing the packets based on their priority.
- By utilizing the performance matrices of the forwarding elements like the traffic demands of each link and traffic capacities of each link a novel adaptive load balancing algorithm is developed which can dynamically allocate the traffic loads and responsibilities among the secondary controllers and the UAVs to maximize the resource usages and reduce the delays.
- In order to ensure an efficient and flexible management of the network's QoS requirements such as maximum throughput and low jitter and latency in a large-scale UAV network, a robust and dynamic routing scheme is presented that can select the best path based on network topology and distance.
- To keep track of the network topology and status as well as to implement the load balancing algorithm, make intelligent decisions, and facilitate the network automation mechanism, a novel holistic mathematical queueing model is proposed by using the M/M/1 and M/M/c for the primary and secondary controllers, respectively. By using this queueing model, the optimal number of UAV nodes and the number of secondary controllers to control and operate UAVs can be determined very swiftly and efficiently.

The remainder of the paper is structured as follows: The literature review in Section II covers the difficulties of large-scale UAV deployment, the drawbacks of utilizing a single controller, and the advantages of employing multi-controllers. It also includes an overview of relevant work in the fields of SDN and UAV networks. Then, the related concepts and terminologies employed in this research like UAV as BS and the importance of the queueing model in wireless communication are explained in Section III. Next, Section IV explores further into system paradigm, accompanying algorithms, and protocols for the primary-secondary multi-SDN controller-based SDUAV network. Following that, Section V describes the mathematical model of this proposed framework based on queueing theory, and the findings of this research are discussed in Section VI. The work is finally concluded in Section VII, which also offers further research suggestions.

II. LITERATURE REVIEW

The overview of the relevant work in the SDUAV network is illustrated in this session. Additionally, we have briefly described the benefits and limitations of existing solutions, such as the limitations of ubiquitous UAV deployment, the single controller strategy, and the advantages of deploying multiple SDN controllers. Finally, an overview of the gap the paper intends to solve.

A. RELATED WORK

Because of their potential to revolutionize wireless communications, SDUAVs have received a significant amount of interest in recent years. Compared to conventional wireless networks, the use of UAVs and SDN technology has several advantages, including improved network performance and increased flexibility [12]. However, due to the complexity and dynamic nature of SDUAV networks, performance evaluation brings new challenges. For addressing concerns with performance in wireless networks, queueing models have proven to be an effective technique.

In this context, queueing models can be used to examine the behavior of SDUAV networks and predict how they would operate in diverse circumstances. Thus, researchers aim to optimize SDUAV networks using AI, machine learning (ML), blockchain, and network function virtualization (NFV) to improve UAV movements, manage network resources, handle network changes, and enhance security.

To increase the adaptability and stability of the wireless network, some researchers have recently explored the combination of SDN and UAV communication technologies. In [21], Silva et al. propose SDN-based topology management for flying ad hoc networks for flying ad hoc Networks. To manage this topology and modify network architecture in response to changes in UAV deployment, their proposed approach makes use of a central SDN controller. On the other hand, Tan et al. [22] provide a solution for protecting critical drones in UAV networks. Their suggested method establishes a topology deception strategy using SDN technology that can conceal the positions of key UAVs in the network.

In order to achieve maximum network coverage and as well as throughput, the UAV's position is very crucial. Therefore, Rahman et al. [23] focused on enhancing the UAV location to increase the throughput in SDN-based disaster area communication networks. The authors suggest a method for positioning UAVs optimally to maximize the network performance, while also taking into consideration SDN-based network control and shifting network conditions. Then, to resolve the scheduling issues for UAVs, C. Zhang et al. present an approach for implementing SDN control in the context of the internet of UAVs [24]. Their proposed scheme optimizes

UAV scheduling at the network edge using Q-learning, a reinforcement learning algorithm.

Treating the SDN controller as the manager and the UAV nodes as the forwarding switch in [25] Vishal Sharma et al. design a management approach and handover scheme. Their experimental results show that the formulated approach is capable of reducing handover latency, end-to-end (E2E) delay, and signaling overheads. Meanwhile, Li et al. [26], provide a method for increasing network energy efficiency

in UAV-enabled air-ground integrated deployments. The proposed technique balances the load between terrestrial nodes and UAVs to maximize the network's energy efficiency.

To reduce the overall expense of the system, which includes the cost of computing on the vehicles, communication with UAVs, and UAV deployment, Zhao et al. [27] introduce a cost optimization technique for deploying UAVs as mobile computational offloading nodes in SDN environments. Their recommended cost optimization technique determines the task of offloading decisions and reduces the system's overall cost by taking into account the network circumstances, the task computation requirements, and the energy consumption of UAVs. While dealing with SDN's interaction mechanism with other existing networks, Ali et al. [28] develop a software-defined strategy for coexisting wireless fidelity (WiFi) networks with UAVs. In densely populated urban areas, where WiFi networks are overloaded and UAVs can offer additional communication capacity, the authors seek to solve the difficulties of offloading traffic to WiFi from UAVs. According to delay-oriented metrics, the suggested approach employs SDN to offload traffic from WiFi to UAVs.

Taking into account the SDN's security concerns, Hermosilla et al. [29], discuss the security issues with implementing SDN and NFV technology in UAV systems as well as offers a security orchestration and enforcement architecture to solve these issues. To guarantee the privacy, accuracy, and accessibility of UAV data and services, the framework incorporates security functions into the deployment process and upholds security regulations. In 5G-enabled softwarized UAV networks, Gupta et al. [30] recommend a strategy for data distribution. The authors create a data dissemination method in UAV networks by exploiting the benefits of blockchain, such as decentralization and immutability.

Some scholars also expanded the application of UAVs in various domains by leveraging the benefits of SDN. For example, A UAV-based approach to industrial deterministic networking is suggested by Guan et al. in [31]. The presented scheme creates a network with deterministic communication for industrial control systems employing softwarized UAVs. While L. Wan introduces a technique for industrial control systems employing softwarized UAVs. While L. Wan et al. introduce a technique for enumerating autonomous vehicle sources within the paradigm of the software-defined IoV [32]. To monitor and gather data about vehicular traffic, they suggest using non-cooperative UAVs fitted with wireless sensors. The UAVs employ ML methods to identify the source of the traffic after applying SDN technology to gather and process data for large-scale networks.

The objective of this research on SDUAV networks is to develop solutions to the problems and constraints of conventional UAV networks in handover management, improve the throughput, and virtualization. However, none of the recent studies has concentrated on the network's scalability and dependability by investigating its traffic system using a queueing model. Thus, the motivation for conducting a study on the topic of SDUAV wireless networks is undoubtedly being driven by the growing use of UAVs in the communication field. By combining SDN with UAV technology, it is possible to provide flexible and effective management of network resources, improving UAV networks' performance as well as their security and scalability.

B. CHALLENGES OF LARGE-SCALE UAV NETWORK

UAV deployment on a large scale can increase wireless capacity, enabling more devices to connect and interact at once as illustrated in Fig. 1. In addition, load balancing can improve resource efficiency and lessen the need for complicated infrastructure [33]. Moreover, by eliminating the requirement for redundancy infrastructure, this strategy can also increase network stability, spectrum usage, changeover management, and energy efficiency [34]. Dense UAV networks, however, are constrained by factors including regulation, communication, power, coordination, security, privacy, and weather. For deployment and operation to be successful, these limitations must be overcome [35]. Again, creating a trustworthy and effective communication link between multiple UAVs and ground control stations is another significant challenge. Furthermore, power limitations and coordination difficulties can also be an issue [36]. On the other hand, security threats like hacking and jamming, as well as privacy concerns with data collection, also need to be addressed [35], [37].

C. LIMITATIONS OF SINGLE SDN CONTROLLER

An automated management system that abstracts and administers the underlying physical network infrastructure is termed as SDN controller. It regulates and supervises data flow within a network, enabling more flexible network configuration and modification options as well as more insight into network activities and performance [38]. The SDN controller, which is described as the brain of the entire network, functions as an intermediary between the network and higher-level applications and services. However, there are limitations to using a single SDN controller in a network. The use of a single SDN controller in a network may lead to various performance issues, potential downtime, and a loss of connectivity and services if the controller fails [39]. Furthermore, the single controller may not be able to handle the scale of a large, complex network or manage a network that spans multiple geographic locations. In addition, it also can be difficult to manage and maintain, especially in large

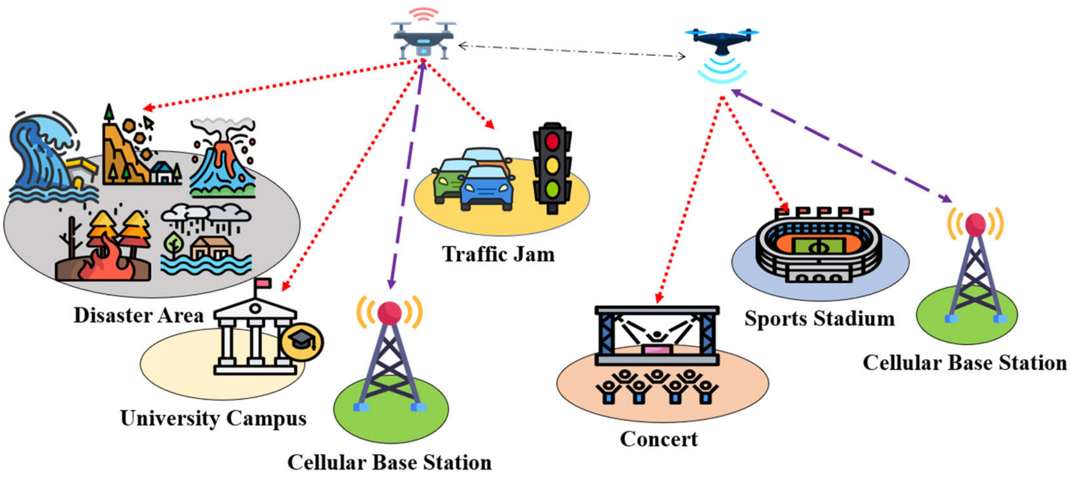


FIGURE 1. A typical UAV-based aerial base station scenario.

and dynamic environments, and has no redundancy in case of failure.

D. ADVANTAGES OF MULTI-SDN CONTROLLER

The limitations of a single SDN controller, including scalability, fault tolerance, and complexity, can be overcome by using multiple SDN controllers. Multiple controllers provide benefits such as increased control, scalability, flexibility, and network visibility, as well as improved network performance and reliability [40]. The use of multiple controllers can also allow for better network abstraction, decision-making, and efficient traffic management, and can provide different tenants with more control over their network [41]. In summary, the following are the most important merits of multi-SDN controllers:

- Better performance and more effective use of network resources are made possible by the use of multiplex controllers, which can handle a larger volume of network traffic and resources. Additionally, having multiple controllers helps simplify network management and upkeep.
- Multiple controllers provide fault tolerance and redundancy in the event of a controller failure, allowing the network to continue to function even if one controller fails.
- Multiple controllers can be used to monitor and control a network that covers multiple geographical locations, providing for more efficient network resource use and improved visibility into network activities and performance. In addition, the network also can be configured and modified with greater flexibility if there are multiple controllers, and different policies and rules can be applied to various network segments.
- For better decision-making and more effective use of network resources, multiple controllers can offer a more thorough view of the network. Furthermore, by splitting the network up into smaller, more manageable pieces, several controllers can abstract the network more effectively.
- Different tenants can each have their controllers owing to the multi-controller design, giving them more control over their network and services. By prioritizing and scheduling traffic according to established policies and rules, the usage of a primary-secondary queueing architecture enables the effective control of traffic needs in the network.
- Utilizing an SDN controller makes it possible to abstract from the underlying physical network infrastructure, which can make network management easier and enable more adaptable network architecture. With numerous controllers, they may work together to coordinate decisions that are
- Intelligent and adaptable to shifting network conditions, including congestion and weather.

III. BACKGROUND

In the area of information and communication technology (ICT), UAV has become one of the most widely studied topics in recent years. The queuing model, On the other hand, is also considered one of the most effective methods for network analysis and has been extensively employed in the context of wireless communication. Therefore, in this section, we have first provided a brief explanation of how a UAV can function as a wireless base station (WBS) and how it can be deployed in the SDN framework. Besides, the primary-secondary multi controller-based UAV network is also discussed. After that, we discussed the importance of queueing model in wireless communication and which queueing system is suitable for the proposed SDUAV model.

A. UAV AS A BASE STATION

UAVs consist of an airframe, propulsion, navigation control systems, payload, and a power source. Interestingly, a UAV can act as a WBS by carrying communication equipment and infrastructure onboard, such as antennas and

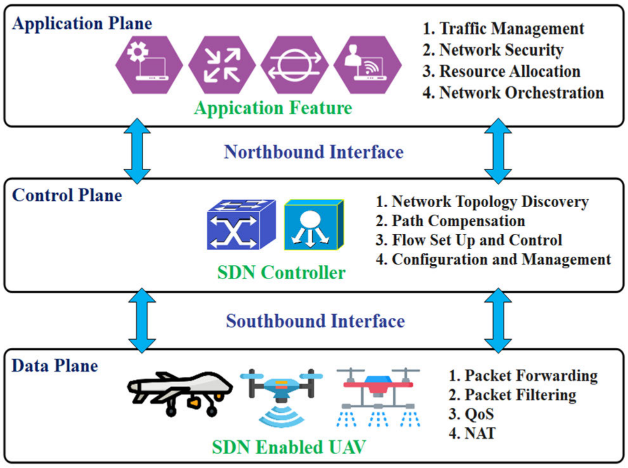


FIGURE 2. The architecture of the proposed SDUAV framework.

radio transceivers, to establish a temporary network and provide coverage and connectivity to devices in the area [42]. To ensure a stable and efficient operation, the UAV also requires additional features like power management systems, global positioning system (GPS) navigation, and collision avoidance management systems. The communication equipment is integrated into the UAV as a payload and works with its flight control and navigation systems to provide wireless coverage [43]. The payload can be used as a WBS by adding communication equipment, such as modems, routers, and antennas. This makes the UAV act as a flying cell tower, providing wireless coverage and connectivity in areas with limited infrastructure or during emergencies [44]. Therefore, UAVs can be deployed to remote areas to provide permanent connectivity and overcome physical barriers, making them a flexible solution for expanding wireless coverage with the help of the SDN platform as demonstrated in Fig. 2.

The average time a request spends in the UAV system (T_u) can be formulated as

$$T_u = \frac{L_u}{\lambda_o} \tag{1}$$

For a wide range of applications, including emergency aid, rural connectivity, military operations, emergency services, temporary events, campus area networking, agricultural monitoring, and traffic jam, UAVs can serve as WBS with the help of the SDN platform as indicated in Fig. 3. In addition, locations where the conventional communication equipment is harmed, disconnected, or unavailable, these UAVs can provide wireless communication networks, providing a flexible and scalable solution for communication requirements [45].

In the proposed model as demonstrated in Fig. 3, the controller of SDN can be divided into a primary controller and a secondary controller, with the secondary controller managing particular regions and the primary controller serving as the network's central management unit [46], [47].

Hence, adaptability and reliability can be enhanced by this distributed architecture [48]. With this architecture, it's easier to scale the network by adding additional secondary controllers at the control plane for growing network traffic. On the other hand, in the SDN-based UAV architecture, the

Packet_in and Packet_out messages, which request and transmit data about network packets, improve communication between the SDN controller and UAVs. The controller uses Packet_out messages to instruct the UAVs on how to handle packets, and the UAVs use Packet_in messages to request assistance as described in Fig. 4.

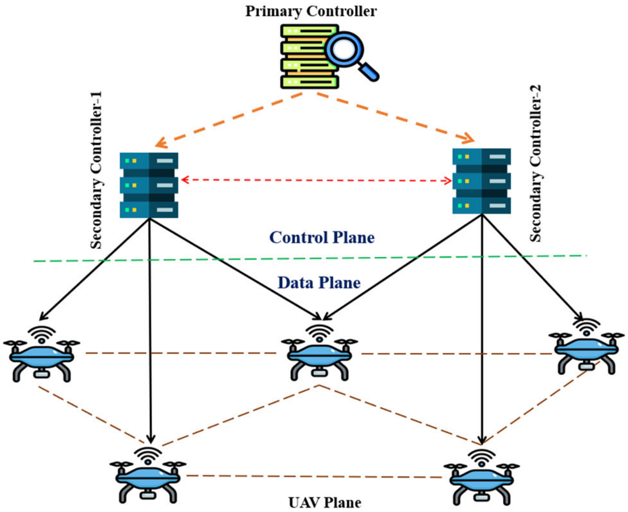


FIGURE 3. Communication links between the SDN controllers and UAVs.

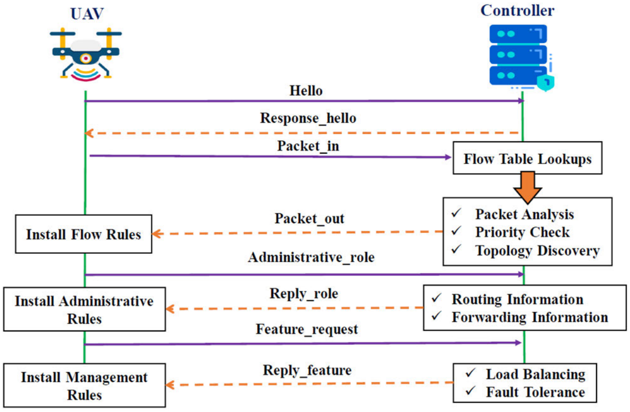


FIGURE 4. Communication flow diagram between controller and UAV.

B. QUEUEING MODEL FOR WIRELESS NETWORKING

With the use of a queueing model, the performance of systems with the queues, such as communication networks, can be mathematically assessed. By considering the arrival rate, service rate, and available resources, it can define the behavior of the system and can help by allocating resources, managing traffic, and controlling congestion [49]. Besides, the queueing model can be utilized to assess the performance of SDUAV networks for primary-secondary SDN controllers' scenarios. The network's performance under different traffic loads and the consequences of congestion can be explained by this analytical model. So, queueing models can play a crucial role in an SDUAV network.

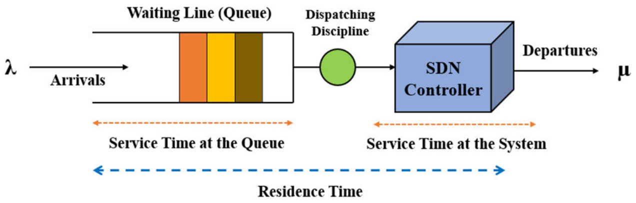


FIGURE 5. Queueing mechanism of the proposed framework.

The essential factors of the queueing model, including service time at the queue, service time at the system, queue length, system length, and utilization, need to be taken into account in the context of this proposed methodology as described in Fig. 5. The service time at the queue refers to how long a request must wait in the queue before the system may handle it. Service time at the system, on the other hand, is the sum of a request's time spent in the SDN controller, including time spent in the queue and time spent being processed. The quantity of requests in the queue is sometimes referred to as the queue's length. Again, the total number of requests in the system, including both those in the queue and those being handled, is referred to as the system length. Utilization, meanwhile, is the percentage of the system's overall processing capacity that is being used to handle requests. So, it is determined by dividing the average number of requests being handled by the system's overall processing capacity [50].

The choice of system modeling for the queueing model is very crucial for performance analysis. There are different models available such as M/M/1, M/D/1, M/G/1, and M/M/c, but their suitability depends on the network characteristics and goals of the analysis. The choice of the queueing model is just one aspect of the performance analysis and other factors such as traffic patterns and performance metrics must be considered. The M/D/1 model can be used if the service time is known and constant, but it assumes exponential inter-arrival times which may not be accurate. The M/G/1 model is suitable to analyze non-exponential service time distributions, but it has limited ability to model systems with multiple servers. Besides, the M/G/1 model expects that each request is handled in the same amount of time. The service time, however, is often random and follows a statistical distribution in a real-world SDUAV network. Consequently, the M/G/1 and M/D/1 models are not suitable for the SDUAV networks.

The M/M/1 model, on the other hand, is simple to analyze and understand and can be deployed to model a system with a single server and unlimited buffer space. Besides, this model can provide useful insights into system performance and capacity. Moreover, it follows a Poisson distribution, and consequently that packet service times follow an exponential distribution. In addition, this technique works effectively if there is a single server accessible to serve packets and the traffic demand is unpredictable events. As a result, this model can be very low to moderate with a lot utilized to calculate the maximum number of UAVs that can be controlled by a single primary controller in a UAV network. While the arrival process and service time follow the same distributions as the M/M/1 model, the M/M/c model indicates that c identical servers are available to serve the packets. This approach works efficiently in circumstances where there is a high traffic volume and multiple servers are needed to process the packets. As a result, the M/M/1 and M/M/c models are suitable for the SDUAV network since they enable the evaluation of both the primary and secondary controllers as well as their interactions.

IV. SYSTEM MODEL

In the system model portion of this paper, the design and the architecture of a network for UAVs are described. This includes the communication link between the UAV and the SDN controller, packet processing, routing, and switching algorithms, load balancing scheme between primary-secondary controllers, and fault tolerance mechanisms when the secondary controller plays the primary controller's role. In addition, this section also offers a thorough overview of the system's major components as well as their functions and how they operate together to maintain the UAV network's efficient functioning in different scenarios.

A. ARCHITECTURE

The architectural structure of a primary-secondary controller-based SDUAV network typically includes the following components as shown in Fig. 6.

1) PRIMARY CONTROLLER

The primary controller is the governing point of the entire SDUAV network. As a result, it holds the responsibility for regulating the network topology, allocating the resources, providing a global network view, managing traffic, enforcing policies, providing failover and redundancy, and coordinating with secondary controllers. Furthermore, it supervises the UAV network to optimize its performance, enforces policies for the UAV nodes, and coordinates with secondary controllers to ensure efficient UAV network administration.

2) SECONDARY CONTROLLERS

The secondary controllers are in charge of directing and coordinating the assigned UAVs. Additionally, they take instructions and tasks from the primary controller and prioritize and carry out these activities using the queueing paradigm. Even, they give the primary controller input on the UAVs' status so that they can make necessary adjustments to keep the network running smoothly.

3) UAVs

UAVs are aerial vehicles that have wireless sensors and communication equipment so they can connect to a network and provide information to the primary and secondary controllers.

4) NETWORK INFRASTRUCTURE

The network infrastructure includes channels for communication as well as the routers, switches, and gateways that are required to link the controllers and UAVs together [47].

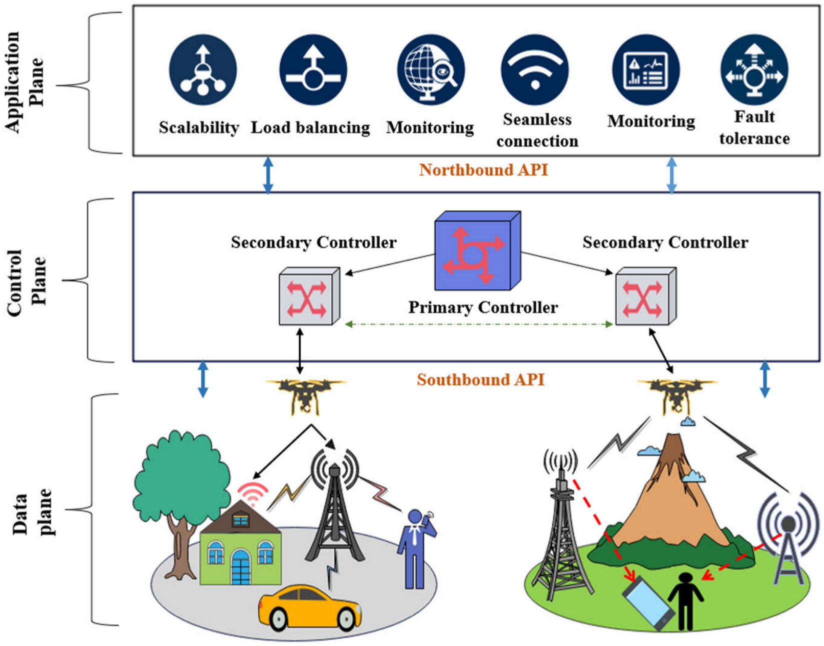


FIGURE 6. An architectural structure of the proposed model.

5) DATABASE

The primary controller can access the information required to make choices and to update the queueing model because the network employs a database to store the data produced by the UAVs, secondary controllers, and the primary controller.

6) MANAGEMENT AND MONITORING SYSTEM

The management and monitoring system has the responsibility of keeping track of the network's performance and giving the primary controller data that can be utilized to optimize the network's performance and make choices [51].

7) USER INTERFACE

The user interface enables the human operator to communicate with the network, issue commands, and tasks, and keep track of the network's efficiency [51]. As the primary controller can assign the resources and prioritize tasks according to their importance and urgency, and because the queueing model offers a framework for modeling and analyzing the performance of the network, this architecture enables the effective use of the resources and coordination of the UAVs in the network. Hence, a multi-controller SDN architecture is designed in this framework, assuming N is the number of controllers and U number of UAVs.

Thus, the number of nodes (V) can be described as [52]

$$V = N + U \tag{2}$$

The connection between the UAVs and the controller (Ω) is described as,

$$\Omega = N \times U \tag{3}$$

where Ω donates the binary matrix.

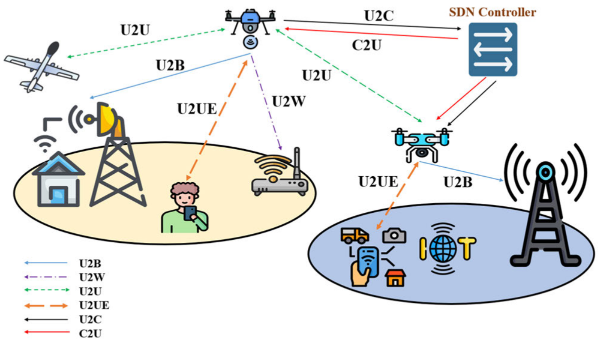


FIGURE 7. MAVLink protocol for communication link establishment.

The SDN controller's load measurement is also crucial. A controller's total load is made up of Hello packets, Echo packets, and Packet_in messages from the data plane. Hence, the overall load of the controller (L_c) is calculated as [52]

$$L_c = \sum_{i=1}^{N} L_{u_i} \tag{4}$$

where $\boldsymbol{L_{u_i}}$ donates the load of the $\boldsymbol{i^{th}}$ controller.

B. COMMUNICATION LINK BETWEEN THE UAV AND THE CONTROLLERS

UAVs and the primary-secondary controllers are connected through an extremely lightweight P2P messaging protocol called the micro air vehicle link (MAVLink) communication protocol, which is designed for low-overhead connection as well as used in UAVs, aircraft, and between onboard drone components [53]. A contemporary hybrid publish-subscribe and point-to-point design pattern are used by MAVLink, while configuration sub-protocols like the mission protocol

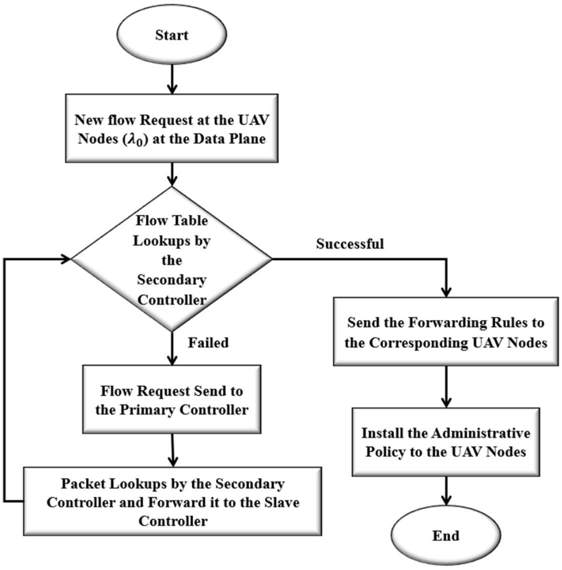


FIGURE 8. Flow chart of the proposed packet processing algorithm.

or parameter protocol are point-to-point. The UAVs have wireless communication devices (e.g., wifi or cellular) to connect to the network and are assigned an internet protocol (IP) address by a dynamic host configuration protocol (DHCP) server as illustrated in Fig. 7. When the UAV joins the network, it sends a message to the primary controller for permission. The primary controller assigns the UAV to a secondary controller based on network conditions and task priority. The UAV and secondary controller then communicate through the IP protocol, with the secondary controller forwarding data packets to the primary controller for use in the queueing model and routing decisions, resulting in efficient resource use and effective coordination of UAVs in the network. Therefore, through the MAVlink protocol, the SDUAV network can create a wireless communication link. The controller enables the UAV to create a direct data link with the BS, wifi network, user equipment (UE), and other adjacent UAVs. In contrast, UAVs build a payload data link as a downlink with the controller as an uplink, while SDN establishes a control and management link with UAVs as an uplink. Thus, all the periodical information from the forwarding elements such as traffic demand of each node, traffic loads on each node, and network topology status can flow from the UAV to the or from controller to UAV to the controller.

C. PACKET PROCESSING MECHANISM

The data packets are transmitted effectively and efficiently using the packet processing method, which also helps the network to run as efficiently as possible. As shown in Fig. 8, the packet processing mechanism controls the flow of data packets between the UAVs and the primary-secondary controllers. Initially, the UAVs produce data packets, which are then transmitted through Packet_in messages to the appropriate secondary controller. Next, the data packets are transmitted to the secondary controller, which only forwards the necessary rules for the UAVs if it is aware of the flow. Therefore, the secondary controller then utilizes the queueing model to determine the priority of the packet, the resources needed to process it, and the resources required to process it. Hence, the secondary controller controls the network's local traffic in this manner. However, if the incoming flow is new or a new session begins, the secondary controller sends the data packet to the primary controller. The primary controller then assesses the data packet's priority and the resources needed to handle it using the queueing model after receiving it. Additionally, the primary controller updates the queueing model and makes the routing decisions using the data in the packet. Whether it is another UAV or a higher-level system, the primary controller then passes the data packet to its target in a Packet_out format.

QoS, on the other hand, enables the primary controller to designate various priorities to various data packet types and guarantee that they are processed in the correct sequence.

To avoid network overload and guarantee that high-priority packets are transmitted effectively, the primary controller can employ the congestion management measures, such as discarding or delaying low-priority packets when the network is congested. Thus, the queueing model-based packet processing mechanism in a primary-secondary controller-based SDUAV network is key to the network's functionality since it makes it possible for the efficient and effective transmission of data packets and coordination of the network's UAVs. The Packet Processing Algorithm, also known as algorithm 1, is specifically designed to handle new packet arrivals at UAV nodes in an SDN architecture. This algorithm takes in the new packet arrival rate at the UAV nodes and outputs the installation of administrative policy. The algorithm is composed of several steps that include a new flow request at the UAV nodes, a flow table lookup by the secondary controller, sending forwarding rules to the corresponding UAV, and installing administrative policy at the UAV nodes. If the flow request fails, it is then sent to the primary controller for the packet lookup, then forwarded to the secondary controller, and repeated step 2 until successful. Finally, the algorithm ends, providing an efficient solution for the packet processing as well as the administrative policy installation at the UAVs in an SDUAV framework.

Thus, based on the utilization (ρ_p), the average number of requests in the queue at the primary controller (l_p) is expressed as

$$l_p = \frac{\rho_p^2}{1-\rho_p} \tag{5}$$

The average number of requests in the queue at the secondary controller (l_s) is expressed as

$$l_s = \frac{\lambda_o^2}{c\mu_s\left(c-\lambda_o\right)} \tag{6}$$

D. ROUTING AND SWITCHING ALGORITHM

The best routing and switching protocol for a primary-secondary multi-SDN controller based large-scale UAV

```
Algorithm 1 Packet Processing Algorithm
Input: New packet arrival rate at the UAV nodes ($\lambda_o$).
Output: Administrative policy installation at the UAV nodes.

Step 1: New flow request at the UAV nodes ($\lambda_o$) at the data plane.
Step 2: Flow table lookups by the secondary controller.
Step 3: If successful then send forwarding rules to the corresponding UAV.
Step 4: Install the administrative policy on the UAV nodes.
Step 5: If fail then the flow request sends to the primary controller.
Step 6: Packet lookups by the primary controller and forward it to the secondary controller.
Step 7: Repeat step 2.
Step 8: End.
```

network using a queueing model would likely be OpenFlow. OpenFlow is a commonly used protocol in SDN and allows for centralized control and management of network traffic through the use of a separate controller. This allows for the efficient and flexible management of network resources, particularly in large-scale and dynamic environments like a UAV network. Additionally, by using a queueing model, the network can effectively manage and prioritize traffic to ensure stable and reliable communication. Therefore, in the model, a robust hybrid routing algorithm is applied that can improve the performance of a multi-SDN controller enabled dense UAV network by combining the strengths of different routing algorithms and adapting to changing network conditions.

A robust hybrid routing algorithm combines different routing algorithms to create a more robust and efficient routing scheme for a primary-secondary multi-SDN controller based large-scale UAV network. The basic idea is to use different routing algorithms for different situations or network conditions. In addition, the robust hybrid routing algorithm might use shortest path routing for normal network traffic, but switch to link state routing when network congestion is detected [54]. This can help to reduce delay and improve network efficiency when the network is operating normally, while also ensuring that the network can adapt to changing conditions and still provide good performance. This algorithm uses link state routing for high-priority traffic but switches to flooding for low-priority traffic. This can help to ensure that high-priority traffic is given priority over low-priority traffic, while also ensuring that all packets are delivered. Based on the waiting time at the queue, the controller sets priority modeling whether the packet is linking state or flooding traffic.

The average waiting time in the queue (w_p) at the primary controller is expressed as

$$w_p = \frac{\rho_p}{\mu_p - \rho_p} \tag{7}$$

The average waiting time in the queue (w_s) at the secondary controller is expressed as

$$w_s = \frac{\rho_s}{c\mu_s - \lambda_o} \tag{8}$$

This proposed algorithm can also use a combination of routing algorithms based on the number of requests in the system to make routing decisions. For example, it can use the Link State Routing to determine the best path based on the network topology and distance, while using the QoS-based routing to determine the best path based on the traffic's requirements.

The average number of requests (L_p) at the system at the primary controller is denoted as

$$L_p = \frac{\rho_p}{1 - \rho_p} \tag{9}$$

The average number of requests (L_s) at the system at the secondary controller is denoted as

$$L_s = \frac{\lambda_o^2}{\mu_s\left(c - \lambda_o\right)} \tag{10}$$

For M/M/1 queueing model, the packet processing time (W_p) for the primary controller is formulated as

$$W_p = \frac{1}{\left(\mu_p - \Lambda_p\right)} \tag{11}$$

where Λ_p represents the overall packets entering into the primary controller.

For M/M/c queueing model, the packet processing time for the secondary controller (W_s) is formulated as

$$W_s = \frac{1}{\left(c\mu_s - \Lambda_s\right)} \tag{12}$$

where Λ_s represents the overall packets entering into the secondary controller.

For n number of servers, the probability $P(n)$ in a certain state is formulated as

$$P(n) = \frac{\lambda_o^n e^{-\lambda_o}}{n!} \tag{13}$$

E. LOAD BALANCING BETWEEN THE PRIMARY-SECONDARY CONTROLLERS

The method of load balancing in this proposed scheme involves dividing up responsibilities and communications among the many secondary controllers and UAVs in the network to maximize resource usage and reduce delays as demonstrated in Fig. 9. The primary controller assigns each task to the appropriate secondary controller and UAV after using the queueing model to assess the priority and resources needed for each one. Additionally, each secondary controller and UAV's workload and status are tracked by the primary controller, which uses this data to make any necessary adjustments to keep the network working smoothly.

In this developed framework, the adaptive load balancing algorithm (ALBA) as described in algorithm 2 offers

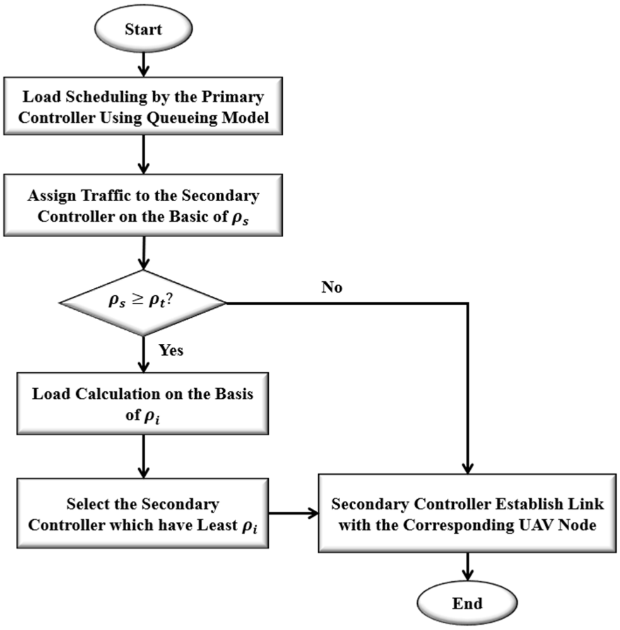


FIGURE 9. **Flow chart of the proposed adaptive load balancing algorithm.**

```
Algorithm 2 Adaptive Load Balancing Algorithm
Data:
$\rho_s$ = utilization of the secondary controller.
$\rho_t$ = Threshold utilization of the corresponding secondary controller.
$\rho_i$ = Utilization of the $i^{th}$ secondary controller.
Input: Utilization of the secondary controller ($\rho_s$)
Output: Selection of the secondary controller based on $\rho_s$
Step 1: Load scheduling by the primary controller by using the queueing model.
Step 2: Assign traffic to the secondary controller on the basic of $\rho_s$
Step 3: Check $\rho_s \geq \rho_t$
Step 4: If no then the secondary controller establish a link with the corresponding UAV node.
Step 5: If yes then load calculation based on of $\rho_i$
Step 6: Select the secondary controller which have the least $\rho_i$
Step 7: End.
```

a dynamic load balancing that may be accomplished by employing a queueing model. According to the secondary controllers' current workload, the primary controller serves as a scheduler in this architecture and distributes the incoming traffic to them accordingly. Each secondary controller's performance metrics, such as the CPU and memory use, and the number of active connections, are periodically collected by the primary controller. Then these parameters are used by the primary controller to determine the load index for each of the secondary controllers. The primary controller modifies the traffic allocation among the secondary controllers based on the recognized controllers to balance the load. If a secondary controller is overloaded, for instance, the primary controller may divert some of that secondary controller's traffic to one that is underloaded. To adjust to shifting network conditions, the primary controller periodically performs the aforementioned procedures. The traffic inside each of their designated regions is managed by the secondary controllers in turn.

The system utilization for the primary controller (ρ_p) is denoted as

$$\rho_p = \frac{\lambda_o}{\mu_p} \tag{14}$$

where λ_o and μ_p represent the packet arrival rate at the data plane and service rate of the controller, respectively.

The system utilization for the secondary controller (ρ_s) is denoted as

$$\rho_s = \frac{\lambda_0}{c\mu_s} \tag{15}$$

where μ_c represents the service rate at the data plane and service rate.

The load distribution among different secondary controllers based on utilization of the secondary controller (ρ_i) is expressed as

$$\rho_i = \frac{\lambda_i}{\mu_i} \tag{16}$$

where λ_i and μ_i represent the arrival rate and the service rate of the i^{th} secondary controller, respectively.

This strategy can help to ensure an effective and equitable distribution of burden among the controllers by monitoring traffic patterns and modifying the assignments as necessary, which will improve network performance. Additionally, the primary controller in this adaptive load-balancing method continuously analyzes the network circumstances and modifies the job allocation in real-time. This method can help to ensure that the network is always running at its highest level of efficiency and can be more successful at reacting to changing network conditions, such as changes in the availability of resources or the arrival of new tasks. In a primary-secondary controller-based SDUAV network, load balancing ultimately aims to ensure that activities are executed effectively and efficiently by preventing congestion and decreasing the time and resources needed to complete each task as shown in Fig. 9. The algorithm also takes into account the UAV network's QoS requirements such as throughput, jitter, and latency. So, this can be accomplished by giving various traffic kinds, including video, audio, and data, distinct weights and routing them to the most appropriate secondary controller by their QoS requirements.

F. SECONDARY AS PRIMARY CONTROLLER AND FAULT TOLERANCE MECHANISM

In the case that the primary controller becomes unavailable, a failover mechanism is a system that instantly shifts control from the primary controller to a secondary controller. If the primary controller in a multi-SDN controller-based UAV network is unable to function, then the secondary controller can step in and manage load balancing using a queueing paradigm. This is often accomplished by using a failover mechanism if the primary controller becomes unavailable, automatically transfers control to the secondary controller. The secondary controller subsequently takes over as the primary controller and uses the queueing paradigm to govern the network, including load balancing. This makes sure that network traffic is distributed effectively and that the failure of the primary controller won't have an effect on network performance. The failover technique is often implemented in a multi-SDN controller-based UAV network using a protocol like the hot standby router protocol (HSRP) or the virtual router redundancy protocol (VRRP). Regarding the supported features, scalability, compatibility, and performance in the specific context of the UAV network and the employed queueing model, both of them exhibit different characteristics.

In this proposed model, the VRRP protocol enables automatic failover in the network by establishing a virtual router with a fictional IP address [55]. A virtual router is shared by the primary and secondary controllers, with the primary acting as the active router and the secondary in standby mode. When the primary fails, the secondary standard protocol VRRP, which encourages interoperability. Among the routers configured with the same virtual IP address, the VRRP protocol selects a primary router and checks on its availability, switching to a different primary router if necessary.

In a primary-secondary SDN-multi controller scenario, a queueing model for VRRP would require simulating the packet arrival and service rates at the primary and secondary controllers as well as the likelihood of failover between the controllers. The average number of packets in the system is related to arrival and service rates by Little's Law, a notion from queuing theory that can be used to accomplish this. Additionally, Markov chain analysis can be used to model the probability of failover. Nonetheless, there won't be any service interruptions for customers as a result of the failover procedure because all traffic can be automatically diverted to the new primary controller. The failover system also has a method for keeping track of the primary controller's availability and switching back to it when it becomes available once more. By doing this, it is made possible for the network to quickly recover from a failure and restore normal operations.

G. WORKING FLOW PROCESS

The primary controller is in charge of orchestrating the operations of the secondary controllers and the UAVs they control in an SDUAV network based on primary-secondary controllers. As seen in Fig. 10, the primary controller employs a queueing model to govern the movement of tasks and communications between the UAVs and the controllers. This strategy, as illustrated in Fig. 10, enables excellent resource management and network-wide coordination of UAVs since the primary controller would assign resources and assign tasks based on significance and urgency. The primary controller in this system serves as the central coordinator in charge of overseeing the operations of the secondary controllers and the UAVs they command. To effectively prioritize tasks and distribute resources, the primary controller employs a queueing model to govern the movement of tasks as well as the communications between the UAVs and the controllers. This strategy enables excellent resource management and network-wide coordination of UAVs since the primary controller would assign resources and assign tasks based on significance and urgency. In this framework, the secondary controllers and the UAVs they operate are under the control of the primary controller, which acts as the system's central coordinator. Besides, the primary controller can implement a queueing model to efficiently prioritize the tasks and distribute the resources.

When any task is received from the higher-level system, it is added to a queue, where the primary controller calculates its priority and the resources needed to accomplish it. Consequently, the appropriate secondary controller and UAV are then given the assignment by the primary controller, and they cooperate to do the task. Coordinating any required communication between the UAVs and controllers is another responsibility of the primary controller. Following completion of the task, the primary controller receives feedback and modifies the queueing model as necessary. In this process of the task, the primary controller receives feedback and of the task, the primary controller receives feedback and modifies the queueing model as necessary. This process allowed effective coordination of the UAVs in the network and efficient resources use. The following brief description summarizes the working flow process of the proposed framework:

- The primary controller receives an assignment or command from a higher-level system or human-machine interface.
- The task that was received is placed in a queue by the primary controller.
- The queueing model is used by the primary controller to decide which tasks are of the highest priority and which tasks demand the most resources to finish.
- The appropriate secondary controller and UAV are assigned the task by the primary controller.
- To perform the task, the UAV nodes and the secondary controllers cooperate with the primary controller and always send their current status.
- Following the task completion, the secondary controllers and UAVs provide feedback to the primary controller.
- Based on the feedback, the primary controller modifies the queueing model.

As the primary controller can distribute resources and assign tasks depending on their priority and timeliness, this method enables good coordination of the network's UAVs and efficient resource use. Such a system's design and performance analysis can include assessing factors like network capacity, network delay, and network throughput.

V. QUEUEING MODEL

The queueing model controls the flow of tasks and communications between UAVs and controllers, establishes the task

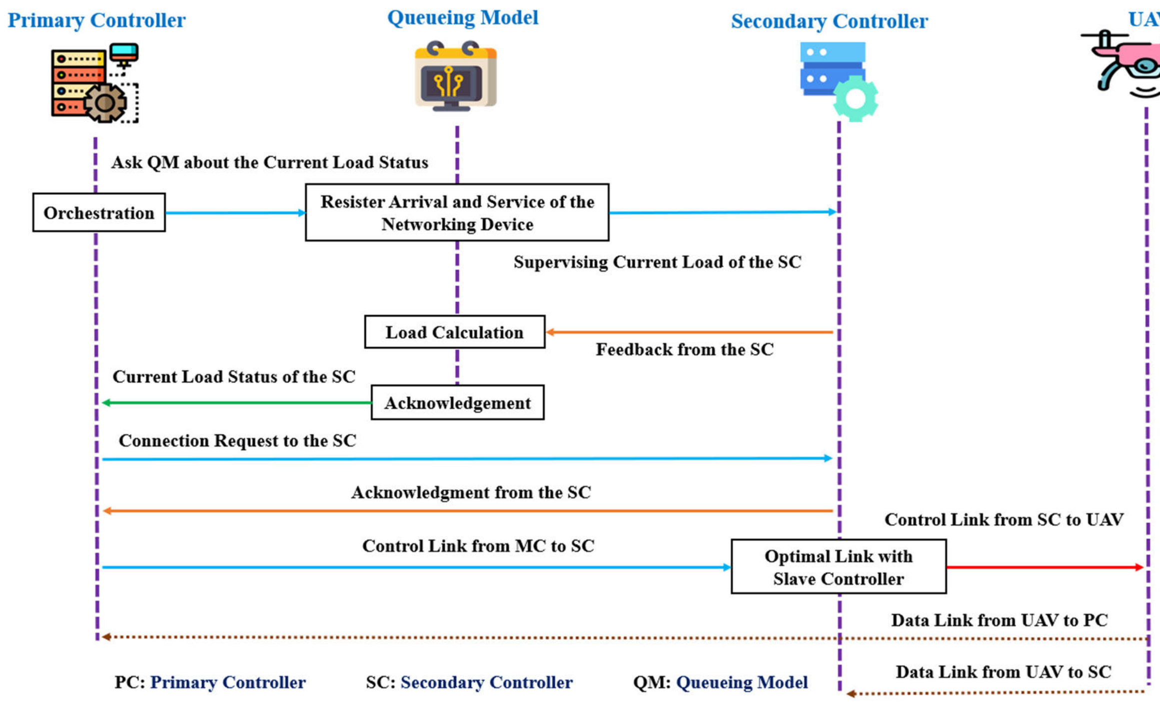


FIGURE 10. Working flow diagram of the proposed framework.

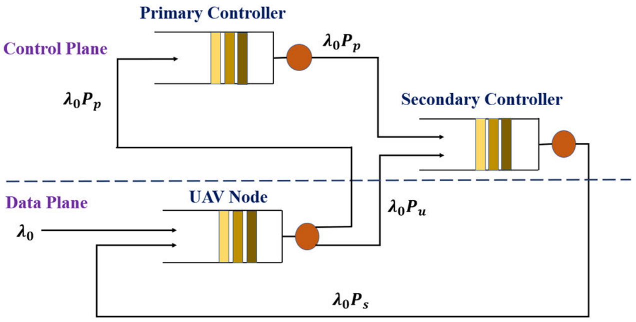


FIGURE 11. Queueing model of the proposed architecture.

priority and resource need, assigns tasks, decides on routing, keeps track of network state, implements load balancing, and forecasts network conditions [56]. By giving the primary controller the information necessary to make intelligent decisions, the queueing model is essential for assuring the network's effectiveness and efficiency. Moreover, the queueing model's application provides effective coordination of UAVs in the network and efficient resource consumption.

In the SDUAV network, using the M/M/1 queueing model for the primary and the M/M/c model for the secondary controllers can be a feasible approach for network analysis and design. The M/M/1 model, which can be a reasonable approximation for the primary controller, which serves as a scheduler and distributes incoming traffic to the secondary controllers based on their current workload, represents a single-server, first-in, first-out (FIFO) queue with Poisson arrival and exponential service times. For the secondary controllers, which govern traffic inside their designated zones, the M/M/c model, on the other hand, approximates a multi-server, FIFO queue with Poisson arrival and exponential service times. The queueing model of the proposed architecture is illustrated in Fig. 11. In this Fig, $P_u, P_p,$ *and* P_s represent the probability of packets for the UAVs, primary controller, and secondary controller, respectively. Based on the assumption that packets arrive external to the network according to the Poisson distribution and could be defined as the state of a Markov, whereas μ_u, μ_p, *and* μ_s represent the service rate of the UAVs, primary controller, and secondary controller, respectively, and λ_0 denotes packet arrival rate at the UAV nodes at the data plane.

The overall packets (Λ_u) entering into a UAV node can be calculated as [56]

$$\Lambda_u = \lambda_0 + \lambda_0 P_s \tag{17}$$

At the UAV nodes, the average packet processing delay at a UAV node (T_u) is expressed as

$$T_u = \frac{1}{\mu_u - (1 + P_u)\lambda_0} \tag{18}$$

The arrival rate (Λ_p) at the primary controller can be calculated as

$$\Lambda_p = \lambda_0 P_p \tag{19}$$

The primary controller's packet processing time (T_p) is given as

$$T_p = \frac{1}{\mu_p - P_p \lambda_0} \tag{20}$$

At the secondary controller, the total arrival rate (λ_s) can be formulated as

$$\Lambda_s = \lambda_0 P_p + \lambda_0 P_u \tag{21}$$

TABLE 1. Threshold variables for the performance assessments.

Key performance indicators	Threshold value
Packet probability at primary controller, P_p	0.04
Packet probability at secondary controller, P_s	0.7
Total packet probability at UAV, P_u	0.8
Packet arrival rate at the UAV node, λ_0	8000 packets/sec
Primary controller's service rate, μ_p	6600 packets/sec
Secondary controller's service rate, μ_s	7000 packets/sec
UAVs service rate, μ_u	7700 packets/sec
Number of UAVs at the data plane, U	12
Number of servers at the secondary controller, c	4

The secondary controller's overall average packet processing delay (T_s) is stated as

$$T_s = \frac{1}{\mu_p - (P_p + P_u)\lambda_0} \tag{22}$$

VI. RESULTS AND DISCUSSION

This section provides an overview of the experimental setting and comprises simulation tests and performance analyses of the suggested strategy. Table. 1 also display the fundamental parameter settings for the investigation.

A. SIMULATION ENVIRONMET SETTING

The experiment uses a configuration of an Intel Core processor which has a 3.4 HZ CPU with 16 GB RAM to be representative of a HP personal computer. On the other hand, MATLAB is used to investigate the mathematical models that were established using the M/M/1 and M/M/c queueing models. We have installed the OpenDaylight controller [20] as the selection of controllers. By using the basic concepts of queueing theory, it is possible to understand how the network performance of an SDUAV network is affected by the arrival rate of packets, the service rate of the network, the utilization of network resources, and the length and waiting time of the queue. To evaluate the proposed approach, simulation-based experimentation is conducted. Firstly, the network is defined and the M/M/1 and M/M/c queuing models are utilized to evaluate this proposed framework. After running the computation in MATLAB, we analyzed the outcomes and made adjustments. Through several iterations, we were able to improve the efficiency of the proposed framework and determine the optimal cutoff values for performance assessments. To conduct the simulation-based experimentation, the "SimEvents" module in MATLAB is utilized in this work.

B. SIMULATION ANALYSIS

To explore the load balancing strategy for an SDN system with multiple controllers, a control-domain adjustment algorithm (CDAA) based on breadth-first search (BFS) was proposed in [35]. When the traffic changes dynamically, the CDAA model analyzes the effects of numerous elements, such as the number of secondary controllers and the packet arrival rate, on the packet processing time and offers a strategy for optimizing these factors. A mathematical model based on queueing theory is constructed and contrasted with CDAA to validate the effectiveness of the approach.

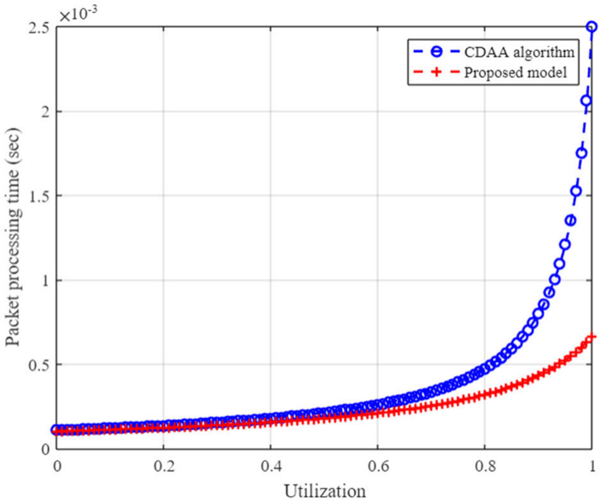


FIGURE 12. Impact of the system's utilization on the packet processing time.

The effects of system utilization, arrival rate, service rate, the number of UAVs at the data plane, and packet processing time on the proposed model are examined as well as the effects of various secondary controller numbers at the control plane. Additionally, how the primary and secondary controllers respond in terms of the duration of the packet processing mechanism is also demonstrated.

C. PERFORMANCE EVALUATION AND ANALYSIS

A network's performance can be significantly impacted by how its resources are used, as high utilization can cause congestion, delays, decreased throughput, and packet loss. On the other side, low utilization may also be a sign of inefficient use of resources and increased expenses. Utilization must be monitored and controlled with an effective resource management strategy to address these problems. Compared to the CDAA method, the proposed model is steady and uses fewer resources as shown in Fig. 12. To obtain the best network performance, queueing models that can forecast network traffic and adapt resources must be used.

Fig. 13 compares the packet processing latency based on the packet arrival rate in an SDUAV network with a primary-secondary SDN controller architecture. For optimal network performance, scalability, and energy efficiency, the packet arrival rate must be monitored and managed. High packet arrival rates can limit the network's capacity to scale by increasing delays, packet loss, and throughput. As a result of network device power consumption is lower, the suggested model is more energy efficient than the CDAA algorithm. The model makes use of effective dynamic resource management strategies, adaptive load balancing, and congestion control to guarantee optimal network resource usage and boost energy efficiency as shown in Fig. 13.

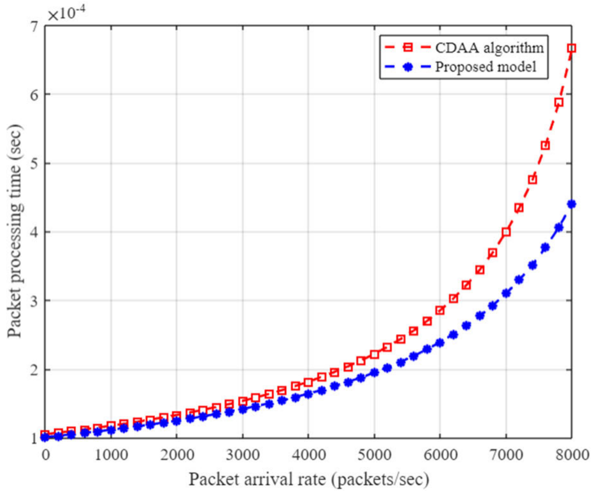


FIGURE 13. Effect of the packet arrival rate on the packet processing time.

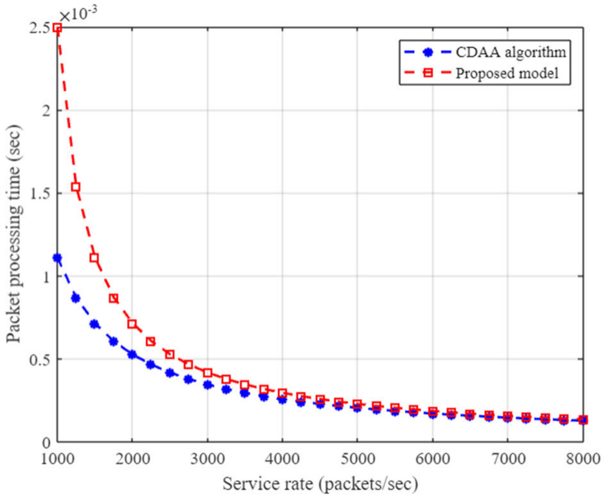


FIGURE 14. Impact of the service rate on the packet processing time.

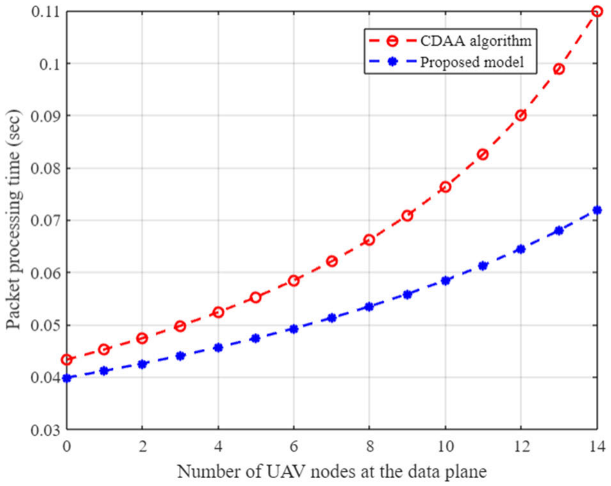


FIGURE 15. Impact of the number of UAV nodes on the packet processing time.

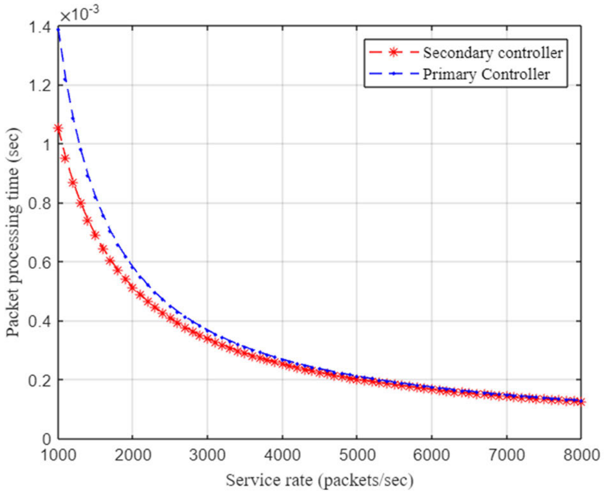
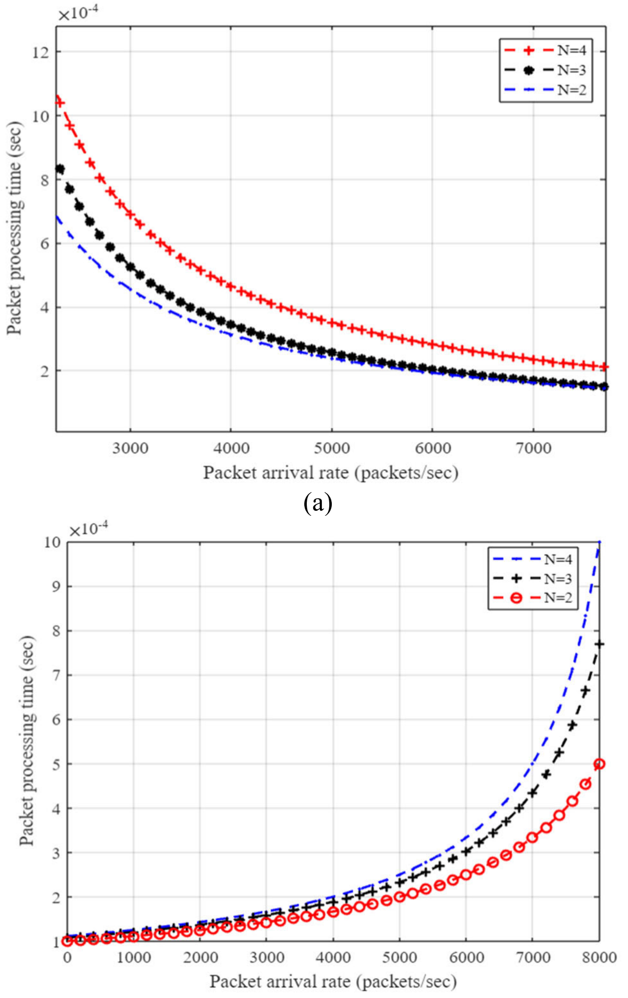


FIGURE 16. Comparison of the service rate between the primary and secondary controllers.

In an SDUAV network with a primary-secondary SDN controller, Fig. 14 illustrates the effect of the service rate on the packet processing time. To achieve better energy efficiency, performance, and the service rate must be balanced with the available resources. Lower delays and greater throughput are produced by higher service rates, but more resources are needed and costs may rise as a result. Longer delays and lesser throughput can result from a reduced service rate. The SDN controllers' performance can affect the service rate as well, making it a crucial factor to take into account when assessing the service rate.

The effect of adding more UAV nodes to the data plane on the processing time of packets was depicted in Fig. 15. To ensure improved network performance, scalability, and load balancing, it is crucial to strike a balance between the number of nodes and the resources available. Network performance and scalability can be enhanced by adding nodes, but doing so can be costlier, consume more energy, and cause other problems. To ensure the best possible use of network resources, this framework makes use of effective resource management strategies like dynamic provisioning, load balancing, and congestion control. Therefore, Fig. 15 clearly shows that, in comparison to the CDAA model, the proposed model has less impact on packet processing time with the expansion of UAV nodes at the data plane, which helps to increase the overall network efficiency.

Fig. 16 compares the packet processing time between the primary and secondary controllers in the proposed model. In the proposed model, the packet processing time varies between primary and secondary SDN controllers because of the hardware specifications, network load, and controller implementation. In a primary-secondary model, the primary controller is typically responsible for the high-level network management tasks, while the secondary controllers handle the lower-level data plane tasks. Due to these different responsibilities, the primary controller has a slightly higher processing overhead and takes a longer time to process packets compared to the secondary controllers. Additionally, hardware specifications such as CPU, memory, and network bandwidth can also impact the packet processing time.



(a)

(b)

FIGURE 17. Impact of different numbers of secondary controllers on (a) packet arrival rate vs. packet processing time (b) service rate vs. packet processing time.

However, if the primary controller has more resources than the secondary controllers, it may be able to process packets faster. Conversely, if the secondary controllers have more resources, they may be able to process packets faster. than the primary controller. Therefore, by the proper implementation of the SDN controllers, the proposed model has achieved 0.06 sec and 0.09 sec for the packet processing time for secondary and primary controllers, respectively

The performance of a primary-secondary multi-SDN controller-based network can be significantly impacted by the number of secondary controllers. To determine the ideal number of secondary controllers, it is crucial to weigh the trade-offs between load balancing, parallel processing, network congestion, and latency. Increased service rates, decreased latency, and higher reliability can result from more shown in Fig. 17, an increase in the number of secondary controllers results in a rise in the service rate, which in turn affects the packet processing time. However, using more than one secondary controller can increase dependability and load balancing, speeding up processing and preventing network cognitions.

VII. CONCLUSION

In this paper, a primary-secondary multi-SDN controller-based SDUAV network is developed which utilizes an SDN architecture to separate the control plane and data plane in the network. This primary-secondary architecture allows the primary controller to manage and coordinate the network centrally, whereas the secondary controllers can act as backups in case of failure. Besides, based on the queueing parameters, a new adaptive load balancing algorithm is proposed to solve the load inequalities, fault tolerance, and controller failure issues. Additionally, to establish the packet processing mechanism, a robust packet processing algorithm is presented as well in this work. Moreover, the M/M/1 and M/M/c queueing models are also deployed in this framework to design an analytical model to analyze the performance of the proposed network, taking into account key factors such as network traffic, network congestion, and the number of UAVs in the network. Simulation results indicate that the proposed network can effectively manage large-scale UAV networks, providing a reliable and scalable solution for controlling UAVs. Therefore, this work provides a new approach to analyzing the performance of UAV networks and can be useful to improve the scalability and reliability of UAV networks. In future work, we have planned to further evaluate the proposed network under different conditions and scenarios. We are also planning to investigate the integration of other techniques such as machine learning to further optimize the performance of the proposed network. Overall, the proposed primary-secondary architecture provides a promising solution for the management and control of large-scale UAV networks, and the use of the queueing model can be an essential tool for evaluating the network's performance under different conditions.

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