Wireless Resource Management in Indoor Multi-UAV Environments for Avoiding Congestion

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***Abstract*—Indoor autonomous UAVs are increasingly deployed for real-time monitoring, surveillance, inventory tracking, entertainment and underground missions in constrained environments like warehouse, museum and commercial facilities. Indoor multi-UAV networks like Wi-Fi face significant challenges in maintaining reliable communication due to congestion which is caused when the density of operational UAVs is increased. As UAVs contend for shared network capacity, the resulting congestion adversely impacts connectivity, mission reliability, and Quality of Service (QoS). In this research, we propose an application layer resource management framework to address this problem for indoor multi-UAV networks. Our approach leverages an edge-based network controller deployed on an edge server, enabling fine-grained control over dynamic transmission rates and UAV–AP link associations. The edge based network controller monitors system-wide performance metrics (e.g., RSSI, throughput, jitter, delay, QoS) in real-time and manages the UAV-based parameters like data rates, and access point (AP) link association. We implement and evaluate heuristic algorithms using the NS-3 simulator, which demonstrated improved network efficiency and system scalability in dense UAV deployments. The results show an improvement in QoS between UAVs with rate control and link association compared to the default operation.**

***Index Terms*—Indoor Multi-UAVs, Autonomous UAVs, Indoor Networking, Edge Computing, Resource Management**

I. Introduction

The deployment of Unmanned Aerial Vehicles (UAVs) in indoor environments has gained a lot of attention due to their potential to revolutionize various technical industries. Utilization of indoor UAVs in industries has been increasing [1]. In indoor industry environments such as warehouses, factories, entertainment museums, indoor sports halls, or large commercial spaces, multi-UAVs are increasingly deployed for tasks like surveillance, inventory management, and delivery operations [2]. In smart warehouses and logistics centers, UAVs can perform autonomous inventory tracking and object scanning without suffering network disruptions [3]. Industrial inspection and maintenance processes benefit from UAVs equipped with real-time video and sensor streaming, which require the high-throughput, low-latency connectivity that this framework supports [4]. Public infrastructure such as airports, train stations, and indoor arenas can deploy multiple UAVs for surveillance, 3D mapping, and monitoring, where resilient communication is crucial for safety and operational awareness [5]. In emergency and disaster recovery scenarios, UAVs can quickly establish aerial communication links in damaged indoor environments, maintaining performance even when infrastructure is limited [6]. The agility and flexibility of indoor UAVs (e.g., Quadcopters, Bicopter, and multi-rotors) make them suitable for navigating complex indoor spaces [7]. UAV operation in an constrained indoor environment presents significant challenges like the absence of GPS, limited operation spaces, static obstacles, and wireless signal quality. Their operation demands advanced control systems, sensing, navigation, high throughput networking, and reliable communication. These UAVs rely heavily on real-time wireless connectivity to exchange data with Ground Control System (GCS). As the number of UAVs increase while connected with shared wireless APs especially in large or dense indoor environments, the APs experience growing congestion. This congestion leads to degraded QoS metrics, including increased delay, jitter, and reduced throughput. Although a straightforward solution might be to introduce additional APs to distribute the load, this approach has limited effectiveness. All APs operate within a shared and finite spectrum — for example, the 5 GHz band offers up to 160 MHz of total bandwidth. As a result, multiple APs operating in the same environment compete for the same limited spectrum, leading to co-channel interference and reduced spectral efficiency.

In this research, we propose an application-layer solution that enables control over UAV transmission rates and their associations with available APs using an edge based network controller framework. Our architecture is built around a network controller deployed on an edge server, which continuously collects, stores, and analyzes real-time performance metrics for each UAV. The network controller has complete visibility into both sending and receiving data rates. The network controller observes the peak demands and the actual throughput of the entire system by real-time monitoring of all UAV data. This integrated approach enables efficient resource management which can minimize network congestion, and our approach yields a significant improvement in QoS compared to the default behavior. Current indoor UAV systems often lack such coordination between AP link management, adaptive data rate control, and UAV positioning. Our proposed framework addresses this critical gap by providing dynamic, system-wide management that holistically improves the performance and reliability of indoor multi-UAV networks.

A. Key contribution

Our key contributions are:

1) We propose an advanced resource management architecture using an edge-based network controller to manage data rates and AP associations. The adopted approach ensures scalability, and allows for the integration of new UAVs and adjusts to abrupt changes.
2) We developed heuristic congestion control algorithms for rate control and association of AP, which run on the network controller to dynamically improve QoS under congestion in the indoor network.
3) We implemented and evaluated the algorithms in a detailed simulation environment NS-3 that was modeled using the Wi-Fi 6 network AP. We evaluated the algorithms and demonstrated the improvement gained in QoS for network congested scenarios.

B. Paper Structure

The rest of the research paper is structured as follows. Section II presents related work. Section III discusses the system architecture framework. Section IV presents the system model and control algorithms. Section V presents the simulation results. Finally, section VI presents the conclusion of the work.

II. Related Work

Resource allocation strategies for multi-UAVs have been explored for outdoor environments but research for indoor environments is limited and underexplored. *Khan* addressed efficient deployment and allocation of UAV resources in public safety networks, formulating a joint optimization problem to improve video transmission quality through strategic positioning and resource management of UAVs [8]. *Grover* presented a rate-aware congestion control framework for Wireless Sensor Networks (WSNs) to minimize packet loss and energy usage [9]. *R.Li* proposed a joint optimization framework that integrated UAV trajectory design with wireless resource allocation for UAV communication systems [10]. *Lee* developed an adaptive TCP transmission control methodology tailored for outdoor UAV-based infrastructure. The framework dynamically tunes TCP parameters such as the retransmission timeout and congestion window size based on variations in link quality caused by UAV mobility [11].

III. Multi-UAVs System Architecture and Components

In our system architecture, we consider an indoor warehouse environment, where multi-UAVs operate for specific applications and require a robust architectural framework to ensure seamless communication, coordinated central control, and efficient data processing. The proposed system architecture used strategically placed Wi-Fi 6/7 APs to provide high-speed wireless connectivity throughout the indoor industry. These APs serve as the communication bridge between UAVs and the ground-based edge servers, allowing real-time data exchange, low-latency command dissemination, and reliable mission coordination.

A. Indoor Autonomous UAVs and Operation Scenarios

In our research, the main aerial agents are indoor autonomous UAVs that possess advanced capabilities that enable them to operate efficiently in GPS-denied conditions autonomously. They rely on technologies such as vision-based SLAM, LiDAR, and ultra-wideband (UWB) positioning for precise localization and autonomous navigation. UAVs communicate requirements and status in real time to the edge based network controller using a wireless link (Wi-Fi AP). Multi-UAV systems have control over their resources and implement the commands sent to them by network controller to optimize task allocation and improve QoS. In indoor environments, deploying multiple UAVs can be configured to specific operational needs and requirements. In our research, we model an edge-based continuous streaming scenarios in which multiple indoor UAVs transmit real-time video and telemetry data to nearby edge servers. These edge servers perform low-latency processing and act as the central decision-making units, managing critical control functions such as data rate adjustment and AP association for congestion mitigation. This architecture allows for edge network control, where the edge controller continuously monitors system-wide performance metrics (e.g., RSSI, throughput, QoS) and dynamically adjusts UAV behavior to maintain reliable communication and mission efficiency in dense indoor environments.

B. Edge Server and Display Unit

Edge servers are key computing units in which the implementation of a centralized controller interacts with UAVs and APs to manage resources, handle congestion, and ensure efficient multi-UAV coordination. The network controller runs on an edge server to execute heuristic algorithms, manage network resources, orchestrate UAV tasks, and process incoming data from UAVs. Each UAV periodically reports its data rate peak demand, received signal strength (RSSI), and QoS parameters to the controller. With this real-time feedback, the controller maintains a database in servers that stores both the requested and received data rates of all UAVs in the system. This global visibility allows the controller to make informed decisions using heuristic algorithms that adjust data rates and reassign AP links according to network congestion levels, link quality, and UAV behavior.

IV. System Model and Control Algorithms

The system model comprises autonomous UAVs, wireless APs, and a network controller deployed on an edge server. This architecture is designed to manage resource allocation on the UAVs side by running real-time heuristic algorithms and enforce decisions on UAVs. The software stack is shown in Figure 1. This setup enables rapid decision making and responsiveness, which are essential for maintaining the stability and performance of UAV operations. UAVs are assumed to be operating autonomously, which in our context means that they complete their assigned mission and operate without continuous human input. However, network parameters are only partially controllable, introducing uncertainty in communication conditions. In our approach, we incorporate RSSI values reported in simulations to estimate the distance and link quality between UAVs and their associated APs. Autonomous UAVs operate using fast PID control loops, and even minor delays can lead to unstable behavior or sensor-driven errors. To address this, we propose a heuristic approach that simplifies the computational time by pre-defined rules in the algorithms. Instead of evaluating all combinations, the algorithm considers only the top two RSSI-based UAV-AP links and selects the best-fit assignment among them.

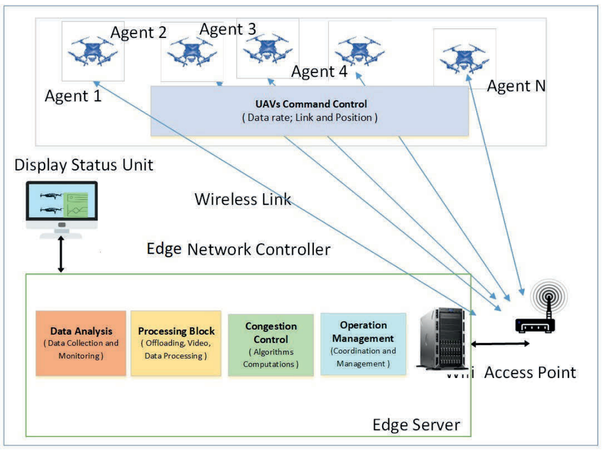


Fig. 1: Edge Network Controller Overview

A. *Multi-UAVs Data Rate Adjustment*

In this technique, the data rate transmitted by each UAV is dynamically adjusted based on heuristic algorithm decisions, which are taken based on the achieved throughput of the UAVs and their RSSI from the associated AP. QoS is calculated by the achieved throughput data rate divided by the demand of the UAVs. The RSSI values are observed by UAVs and communicated to the edge server. UAVs located closer to an AP typically experience stronger signal strength and better channel conditions. As a result, they can maintain reliable communication even at lower data rates. The assignment of lower data rates helps limit unnecessary spectrum usage, as higher data rates require wider bandwidth and more transmission power. This strategy also reduces overall network congestion, leaving more spectrum resources available for UAVs farther from the AP, which may need higher data rates to maintain connectivity under weaker signal conditions. These adjustments are coordinated by a network controller using input such as data rate demands, RSSI, and estimated link quality. The heuristic algorithm, on the basis of which the amount of data is reduced, is shown in Algorithm 1.

Algorithm 1 Throttling-Based UAV Data Rate Assignment

Input: U: Set of UAVs $RSSI[i][j]$: Signal strength between UAV u_i and AP a_j θ: QoS threshold (e.g., 0.9) γ: Throttling factor (e.g., 0.8) $D_{\text{min}}[i]$: Minimum allowable data rate for UAV u_i $D_{\text{peak}}[i]$: Peak data demand for UAV u_i Δt: Monitoring interval

Output: Assigned data rates R_i for each UAV u_i Assignment list: (UAV_ID, Assigned_AP)

1. Initialization:
foreach *UAV* $u_i \in U$ **do**
  Find AP a_j with highest $RSSI[i][j]$ Add tuple (u_i, a_j) to $AssignmentList$ Assign u_i to AP a_j cluster $R_i \leftarrow D_{\text{peak}}[i]$; $PrevRate[i] \leftarrow D_{\text{peak}}[i]$; $QoS_{\text{main}}[i] \leftarrow 1.0$;
end
Sort all UAVs in descending order of $RSSI$ to their assigned APs $QoS_{\text{stable}} \leftarrow false$; $index \leftarrow 1$; $Throttled \leftarrow \emptyset$; $FirstIteration \leftarrow true$;
2. Throttling Loop:
repeat
  Wait for Δt
  foreach *UAV* $u_i \in U$ **do**
    Update throughput T_i $QoS_i \leftarrow \frac{T_i}{D_{\text{peak}}[i]}$; $QoS_{\text{prev}}[i] \leftarrow QoS_{\text{main}}[i]$; $QoS_{\text{main}}[i] \leftarrow QoS_i$;
  end
  if $FirstIteration = false$ **then**
    foreach $u_k \in Throttled$ **do**
      if $QoS_k < \theta$ ***or*** $QoS_k < 0.8 \times QoS_{prev}[k]$ **then**
        $R_k \leftarrow PrevRate[k]$; `// Revert throttling`
      end
    end
    Clear $Throttled$;
  end
  if *All* $QoS_i \geq \theta$ **then**
    $QoS_{\text{stable}} \leftarrow true$; **break**
  end
  foreach *UAV* u_i *where* $QoS_i < \theta$ **do**
    $R_i \leftarrow D_{\text{min}}[i]$;
  end
  while $index \leq |U|$ **do**
    Let u_k be the UAV at position $index$ in sorted list **if** $QoS_k < \theta$ **then**
      $index \leftarrow index + 1$; **continue**
    end
    $PrevRate[k] \leftarrow R_k$; $R_k \leftarrow \max(D_{\text{min}}[k], \gamma \times R_k)$; Add u_k to $Throttled$; $index \leftarrow index + 1$;
  end
  $index \leftarrow 1$; $FirstIteration \leftarrow false$;
until $QoS_{stable} = true$
3. Continuous Monitoring:
while *true* **do**
  Wait for Δt **foreach** *UAV* $u_i \in U$ **do**
    Update throughput T_i $QoS_i \leftarrow \frac{T_i}{D_{\text{peak}}[i]}$; $QoS_{\text{prev}}[i] \leftarrow QoS_{\text{main}}[i]$; $QoS_{\text{main}}[i] \leftarrow QoS_i$;
  end
  if *any* $QoS_i < \theta$ **then**
    $QoS_{\text{stable}} \leftarrow false$; $index \leftarrow 1$; $FirstIteration \leftarrow true$; **go to Throttling Loop**
  end
end

Algorithm 2 Access Point Link Change Algorithm (Edge-Based Controller)

Input: M: Number of UAVs N: Number of Access Points $D_{\max}[M]$, $D_{\min}[M]$: Demand bounds for UAV i $RSSI[M][N]$: RSSI of UAV i from AP j $RSSI_{\text{THRESHOLD}} = -90$ dBm $TimeInterval = 2$ seconds

Output: Assigned APs List Ap_j for each UAV u_i Assignment list: (UAV_ID, Assigned_AP)

Initialization (First Assignment Only):
foreach *UAV* i **do**
  Find AP j with highest $RSSI[i][j]$ and $\geq RSSI_{\text{THRESHOLD}}$; $connection\_table[i] \leftarrow j$;
end
foreach *UAV* i **do**
  Calculate $qos[i]$ based on AP j load and UAV i demand; $prev\_qos[i] \leftarrow qos[i]$; $prev\_connection\_table[i] \leftarrow connection\_table[i]$;
end
foreach *AP* j **do**
  $cluster[j] \leftarrow$ list of UAVs assigned to j;
end
$stable \leftarrow 0$;
Repeat Loop (Every 2 Seconds):
while $stable == 0$ **do**
  Wait for 2 seconds; **1. QoS Evaluation Phase:**
  foreach *UAV* i **do**
    Calculate $qos[i]$ based on $connection\_table[i]$;
  end
  $stable \leftarrow 1$; $congested\_uav\_list \leftarrow \emptyset$; $congested\_ap\_list \leftarrow \emptyset$; **foreach** *UAV* i **do**
    $ap_j \leftarrow connection\_table[i]$; **if** $qos[i] < D_{min}[i]$ ***or*** $RSSI[i][ap_j] < RSSI_{THRESHOLD}$ **then**
      Add (i, ap_j) to $congested\_uav\_list$; Add ap_j to $congested\_ap\_list$ if not already in list; $stable \leftarrow 0$;
    end
  end
  if $stable == 1$ **then**
    Continue to Monitor Phase
  end
  2. Reassignment Phase:
  foreach (uav_i, ap_j) *in* $congested\_uav\_list$ **do**
    Find AP $k \neq ap_j$ such that: $k \notin congested\_ap\_list$ and $RSSI[uav_i][k]$ is highest and $\geq RSSI_{\text{THRESHOLD}}$;
    if *such AP* k *is found* **then**
      $connection\_table[uav_i] \leftarrow k$;
    end
    else
      $connection\_table[uav_i] \leftarrow ap_j$ `// retain current`
    end
  end
  3. Update Phase:
  Recompute $cluster$ from updated $connection\_table$;
  foreach *UAV* i **do**
    $prev\_qos[i] \leftarrow qos[i]$; $prev\_connection\_table[i] \leftarrow connection\_table[i]$;
  end
end
Monitor Phase (When $stable == 1$**):**

B. Multi-UAVs Link Association Algorithm

The method above re-balances the data rates to try to improve throughput. In Algorithm 2, we also allow a associated AP for a UAV to change, to rebalance the congestion across the APs. The UAVs sense the RSSI values from each available AP and report to the network controllers. The central system stores the database of all UAVs and RSSI values. Based on the current networking conditions and QoS of UAVs, the heuristic algorithm takes action to associate the UAV with another AP that offers better networking conditions.

V. Simulations and Results

In this study, we utilized the popular open-source ns-3 network simulator to implement and evaluate the proposed framework under indoor multi-UAV scenarios. The simulations were designed to analyze the impact of three key control strategies: adaptive data rate adjustment, dynamic UAV–AP association. The MCS was selected adaptively by `MinstrelHtWifiManager` to emulate realistic UAV mobility and indoor channel variability. During experiments, UAVs operating at strong RSSI typically converged to 64-QAM and 256-QAM, while moderate congestion shifted operation toward 16-QAM, and QPSK fallback occurred only in severe QoS degradation scenarios.

TABLE I: Configuration of Simulations

Parameter	Value
WiFi Standard	WiFi 6 (IEEE 802.11ax)
Path Loss Model	YansWiFiChannel
MAC Rate Control	MinstrelHtWifiManager
Channel Settings	Bandwidth 160 MHz, Band 5GHz
Modulation & Coding Scheme	Adaptive
Traffic Type	UDP
Peak Data Rate	50 Mbps
Min Data Rate	10 Mbps
Simulation Time	30 seconds

A. Configuration of Simulations

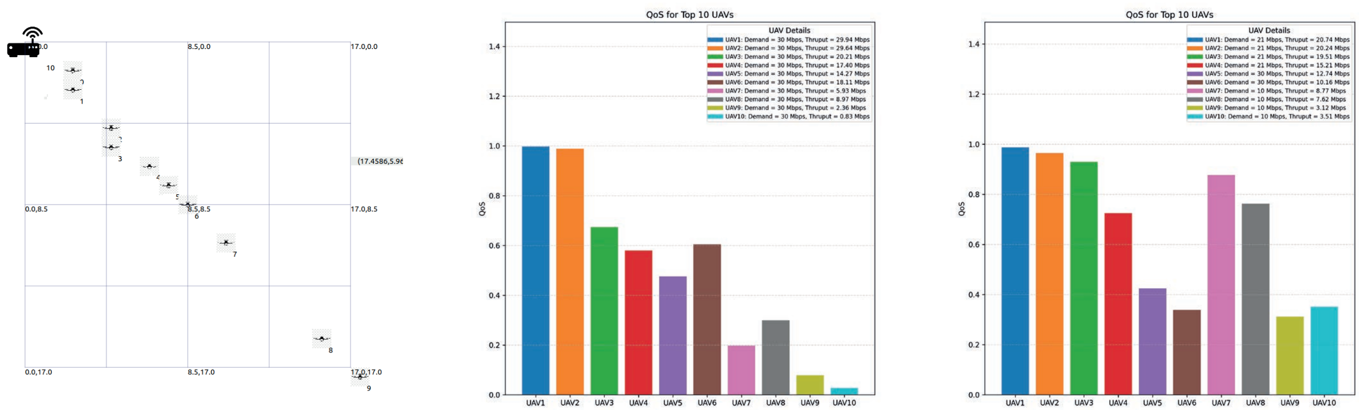
The configuration of simulated parameters is shown in Table I. By modeling an indoor environment with multiple APs and UAVs operating under the random locations, we were able to assess how each approach influenced QoS metrics systematically. The UAVs periodically updated their link status, and snapshots of their performance, such as throughput and RSSI, were captured at fixed intervals. These snapshots allowed the edge controller to perform real-time AP reassignment and data rate regulation decisions. We compare the proposed algorithms to the default case which captures the normal behavior of WiFi as implemented in ns-3. While we currently experimented with maximum channel width, we plan to conduct future experiments with varying channel width.

B. Performance Comparison of Algorithms

We conducted experiments with varying numbers of UAVs and APs. In the first configuration, we deployed 5 UAVs with a single AP. The second configuration involved 10 UAVs with one AP, while the third setup included 20 UAVs with four APs.

TABLE II: Benchmarking of Indoor Multi-UAV Approaches

Algorithm Approach	**No. of UAVs**	**No of AP**	**Area (m)**	**Peak/Min Data Rate (Mbps)**	**Sum of Avg./Std. QoS Without Algorithm**	**Sum of Avg./Std. QoS With Algorithm**	**% Increase**	**Avg Jain Fairness Index with Algo**
Data Rate	5	1	50x50	30/10	2.49/0.72	4.39/0.47	76.28%	0.92
	10	1	50x50	30/10	4.47/0.45	6.10/0.62	36.5%	0.86
	20	4	100x100	30/10	12.83/0.26	14.53/0.55	13.53%	0.84
Link Association	5	1	50x50	30/10	2.63/0.17	3.69/0.41	40.3%	0.91
	10	1	50x50	30/10	5.83/0.19	7.38/0.43	26.5%	0.85
	20	4	100x100	30/10	13.36/0.33	15.78/0.60	18.11%	0.89



(a) 10 UAVs 1 AP Animation in NS-3

(b) QoS without Data Rate Algorithm

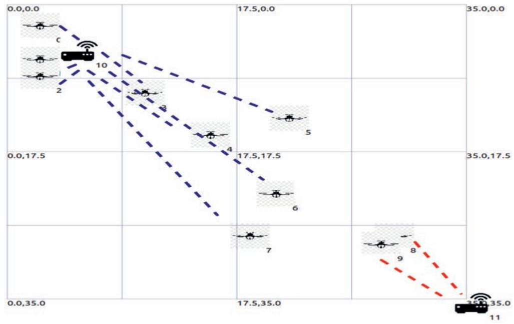
(c) Improved QoS with Heuristic Algorithm

Fig. 2: Simulation Results for 10 UAVs: Data Rate Analysis

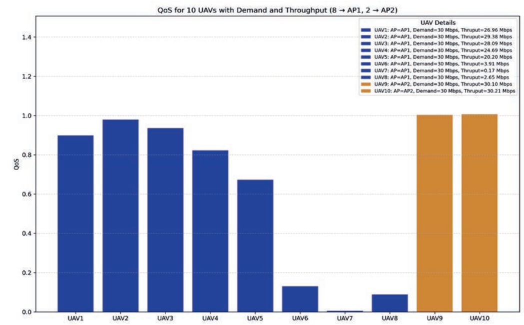
For each configuration, multiple experiments were performed with randomly assigned UAV locations and then averaging the results obtained. The data rate adaptation algorithm, after adjusting the transmission rates, significantly improved overall throughput compared to the initial static rate allocation. As network load requirements changed, several UAVs that initially failed to meet the minimum QoS thresholds were able to achieve acceptable QoS levels with the new rate assignments. This demonstrates that the algorithm effectively adapts to varying network conditions and enhances system performance. For the link association experiments, we evaluated multiple configurations involving different numbers of UAVs and access points (APs). In the first configuration, we deployed 5 UAVs with two access point. The second configuration involved 10 UAVs with two access point, while the third setup included 20 UAVs with four access points. In each scenario, UAVs were placed at random locations. Each configuration ensured full coverage of the operational area by the access points, so that no UAV experienced signal degradation due to lack of coverage. Initially, under static UAV-to-AP assignments, some UAVs failed to achieve the minimum required QoS due to network congestion. However, the proposed link association algorithm dynamically reassigned UAVs to alternative APs—typically the next nearest one—if such reassignment led to improved throughput. This dynamic reassociation significantly enhanced the overall QoS performance across the network. The scenarios specifically focused on evaluating how UAVs respond to network congestion by adapting transmission rates, reassociating with alternative APs. Figures 2 and 3 show the results of one use-case of rate change and access point reassociation with static allocation and with the heuristic algorithm. Table II summarizes the average total QoS achieved in each scenario, comparing results with and without the heuristic algorithm. As shown, the heuristic algorithm consistently improved QoS following rate change and AP reallocation.

VI. Conclusion

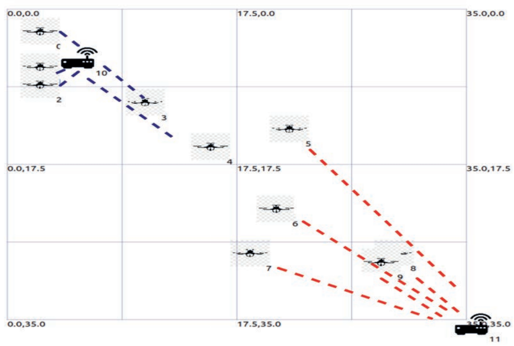
There is growing interest in the use of large numbers of small lightweight UAVs for executing tasks autonomously in indoor settings, leveraging the power of edge computing for analysis of captured video and sensor data. In such settings, wireless network congestion can have a significant effect on the quality of the received data at the edge, and hence the effectiveness of its decision making. Our work addresses this problem, presenting a framework for indoor multi-UAVs for managing network resource allocation at the application layer, aiming to mitigate network congestion and enhance global QoS. We propose a heuristic algorithm running an edge-based network controller, to dynamically adapt the uplink data rate and access point association for the UAVs. By running periodically, the algorithm naturally copes with UAV mobility and changing network conditions. We conducted simulations using the ns-3 network simulator, which demonstrated improved system QoS, better throughput and reduced latency under increasing UAV density. This research lays the groundwork for resilient and intelligent indoor UAV networks. Future work will explore real-time UAV mobility integration with fast mobility, multi-controller coordination for larger envi-



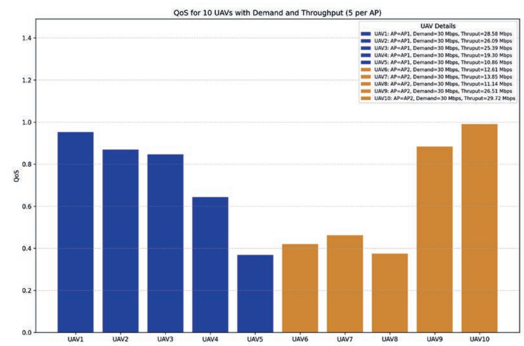
(a) 8 UAVs Connected to AP1 and Two to AP2



(b) QoS of UAVs with AP1 not getting Min QoS



(c) 5 UAVs Connected to AP1 and 5 to AP2



(d) Improved QoS of UAVs with AP1 and AP2

Fig. 3: Simulation Results for 10 UAVs: Link Association Analysis

ronments, and reinforcement learning-based adaptations for dynamic indoor missions. In this extension, the edge controller will dynamically make decisions based on the UAVs' changing locations to improve QoS. While our current approach focuses on centralized control, we also aim to explore decentralized strategies, including hybrid topologies, where certain control aspects are distributed.

VII. Acknowledgment

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