

Enhancing QoS in Dense IEEE 802.11ax Networks using a Dynamic Airtime-Based Soft Admission Control Mechanism

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Abstract—Even with the advanced capabilities of IEEE 802.11ax (Wi-Fi 6), dense Wireless Local Area Networks (WLANs) often struggle to meet the strict latency demands of modern applications. High-efficiency features like OFDMA and Target Wake Time (TWT) improve spectral efficiency, yet they cannot prevent network saturation when traffic demand simply outstrips the available airtime. To address this, we introduce an Airtime-Based Soft Call Admission Control (AS-CAC) framework designed specifically for saturated, multi-access point environments. Instead of relying on hard connection limits, our approach regulates access based on the actual airtime required by each flow. A key strategy is the “Soft-CAC” mechanism, which moves beyond static thresholds. It strictly prioritizes real-time streams like VoIP and Video but remains flexible enough to admit best-effort bursty traffic whenever spare capacity exists, maximizing channel utilization without breaking QoS guarantees. We further enhance this with AS-CAC+, an adaptive variant that dynamically adjusts thresholds based on network health. We validated this framework using extensive ns-3 simulations, backed by a theoretical multi-rate Erlang loss model. Results from dense deployment scenarios including those with Co-Channel and Adjacent Channel Interference show that AS-CAC stabilizes throughput and keeps end-to-end VoIP latency under 2 ms, a dramatic improvement over the 45+ ms delays seen in uncontrolled networks. AS-CAC+ achieves 19.2% throughput improvement and 97.4% channel utilization while maintaining strict QoS. These findings offer a practical, scalable strategy for next-generation enterprise WLANs.

Index Terms—IEEE 802.11ax, Wi-Fi 6, Call Admission Control, Airtime Fairness, QoS, Dense WLANs, Adaptive Control, ns-3

I. INTRODUCTION

IEEE 802.11ax (Wi-Fi 6) introduces significant enhancements including uplink and downlink OFDMA, MU-MIMO, and improved MAC features to address performance challenges in dense deployments [2], [6]. Despite these advances, congestion remains inevitable when aggregate traffic demand exceeds the medium's airtime capacity. Real-time applications such as VoIP and video streaming are particularly vulnerable to delay and jitter under saturation conditions [13].

Traditional admission control mechanisms rely on simple association counts or bandwidth estimates, failing to account

for the actual airtime consumption of heterogeneous traffic types [3]. This limitation becomes critical in Wi-Fi 6 networks where a single 4K video stream may consume significantly more airtime than dozens of IoT sensor transmissions, despite similar data rates.

Airtime emerges as the natural resource metric for admission control, as it directly reflects MAC/PHY activity, protocol overhead, and contention effects [16]. However, existing airtime-based schemes typically employ rigid thresholds that either waste capacity by being overly conservative or fail to protect QoS by being too aggressive [10].

A. Research Gaps and Our Solutions

While recent work has explored spatial reuse [1], [17], OFDMA optimization [11], [15], and multi-AP coordination [18], significant gaps remain in admission control for dense Wi-Fi 6 environments. Table I summarizes these gaps and our contributions:

Our work uniquely addresses all five gaps through a comprehensive framework combining priority awareness, adaptive control, multi-AP analysis, and theoretical validation.

B. Our Contributions

This paper makes the following contributions:

- 1) We propose **AS-CAC**, an airtime-based soft admission control framework with priority-aware thresholds that maximizes channel utilization while maintaining strict QoS guarantees.
- 2) We introduce **AS-CAC+**, an adaptive enhancement that dynamically adjusts admission thresholds based on real-time network health indicators, achieving near-optimal efficiency.
- 3) We develop a **multi-rate Erlang loss analytical model** to validate simulation results and provide theoretical foundation.
- 4) We conduct comprehensive **ns-3 simulations** across multiple scenarios including single-AP, multi-AP with

TABLE I
RESEARCH GAPS AND PROPOSED SOLUTIONS

Existing Gap	Our Solution
Static Thresholds - Fixed admission thresholds waste capacity or fail QoS [10]	AS-CAC+ : Dynamic threshold adaptation based on real-time PER feedback (Algorithm 1)
No Priority Awareness - Equal treatment of all traffic ignores QoS classes [13]	Soft CAC : Priority-based thresholds (VoIP: 90%, Video: 80%, BE: 95%)
Single-AP Focus - Limited multi-AP interference analysis [4], [9]	Multi-AP Evaluation : CCI and ACI scenarios with overlapping BSSs
Lack of Validation - Simulation-only results without theoretical foundation	Analytical Model : Multi-rate Erlang loss model for validation
Airtime Ignorance - Association-based CAC ignores actual resource consumption [3]	Airtime-Based : Direct measurement of MAC/PHY resource usage (Eq. 1-2)

CCI, and multi-AP with ACI, demonstrating 19.2% throughput improvement and 97.4% utilization.

- 5) We provide **open-source implementation** and detailed performance analysis suitable for deployment in enterprise WLANs.

The remainder of this paper is organized as follows: Section II reviews related literature. Section III presents the system model and problem formulation. Section IV describes the proposed AS-CAC and AS-CAC+ mechanisms. Section V presents the analytical model. Section VI details the simulation setup and results. Section VII discusses findings and implications. Section VIII concludes the paper.

II. RELATED WORK

A. IEEE 802.11ax Enhancements

The IEEE 802.11ax standard introduces several key innovations to address dense deployment challenges. Bellalta [2] provides a comprehensive overview of Wi-Fi 6 features including OFDMA, which enables simultaneous transmission to multiple users by dividing the channel into Resource Units (RUs). Mozaffariahrar et al. [13] survey Wi-Fi 6 technologies, highlighting improvements in spectral efficiency and latency reduction. However, these PHY/MAC enhancements alone cannot prevent saturation when offered load exceeds capacity.

Jin et al. [7] evaluate uplink OFDMA performance, demonstrating throughput gains in multi-user scenarios. Liu et al. [11] optimize random access mechanisms for UL OFDMA. While these works improve channel access efficiency, they do not address admission control—the fundamental question of which flows should be admitted.

B. Spatial Reuse and Interference Management

Spatial reuse mechanisms in Wi-Fi 6 aim to increase network capacity by allowing concurrent transmissions. Wilhelm et al. [17] analyze spatial reuse performance, showing

significant gains in dense deployments. Bardou et al. [1] propose a multi-armed bandit approach for dynamic spatial reuse optimization. Lanante and Roy [10] provide theoretical analysis of OBSS_PD-based spatial reuse, identifying optimal threshold settings.

Knitter and Kays [9] extend spatial reuse analysis to Wi-Fi 7, providing insights applicable to future standards. Dogan-Tusha et al. [4] conduct extensive measurements of interference in 6 GHz Wi-Fi 6E networks, quantifying CCI and ACI impacts. MediaTek [12] discusses anti-interference technologies for Wi-Fi 6/6E.

While spatial reuse increases capacity, it operates orthogonally to admission control. Our AS-CAC framework complements spatial reuse by controlling flow admission, while spatial reuse optimizes coexistence of admitted flows.

C. Admission Control in WLANs

Classical admission control for WLANs dates to early 802.11 standards. Bianchi [3] provides foundational analysis of the DCF, establishing performance models still relevant today. Kaufman [8] introduces the Erlang loss model for shared resources, which we extend to multi-rate airtime-based admission.

Traditional CAC schemes use association counts or bandwidth estimates. However, these metrics fail to capture actual resource consumption in modern WLANs where traffic heterogeneity is extreme. A VoIP flow consuming 64 kbps requires vastly different airtime than a 4K video stream at the same PHY rate due to packet size and overhead differences.

Smith et al. [16] propose feedback-based congestion control for airtime fairness but focus on rate adaptation rather than admission decisions. Rehman et al. [15] enhance spectrum access with heuristic back-off mechanisms for OFDMA, operating at frame timescales rather than flow timescales.

Gap: Existing schemes use static thresholds that either waste capacity (conservative) or fail QoS (aggressive). Our AS-CAC+ addresses this through dynamic adaptation.

D. Multi-AP Coordination

Dense deployments increasingly feature overlapping BSSs, necessitating multi-AP coordination. Zhang et al. [18] apply deep reinforcement learning (DDPG) for multi-AP access control, achieving good performance but requiring extensive training data and computational resources. ZTE [19] discusses multi-AP home network technologies, focusing on seamless handover rather than admission control.

Garcia-Rodriguez et al. [5] preview Wi-Fi 7 (802.11be) multi-link operation, enabling simultaneous transmission across multiple bands. While promising, multi-link operation does not eliminate the need for admission control—it shifts the problem to coordinating admission across links.

Gap: Limited research addresses admission control in multi-AP scenarios with explicit CCI/ACI modeling. Our work evaluates AS-CAC in both CCI and ACI scenarios.

E. Summary and Positioning

Table I (Section I) summarizes five key gaps in existing literature:

- **Static thresholds** waste capacity or fail QoS
- **No priority awareness** for QoS classes
- **Single-AP focus**, limited multi-AP analysis
- **Lack of analytical validation**
- **Ignoring airtime** as the fundamental resource

Our AS-CAC framework uniquely addresses all five gaps through: (1) priority-based soft thresholds, (2) adaptive dynamic adjustment (AS-CAC+), (3) multi-AP CCI/ACI evaluation, (4) Erlang loss analytical model, and (5) direct airtime measurement. This comprehensive approach distinguishes our work from prior art.

III. SYSTEM MODEL

A. Network Architecture

We consider a dense 802.11ax network deployment with multiple overlapping Basic Service Sets (BSSs). Each BSS consists of one Access Point (AP) and multiple associated stations (STAs). The network operates in the 5 GHz band with 80 MHz channel bandwidth, supporting Wi-Fi 6 features including OFDMA and MU-MIMO [6].

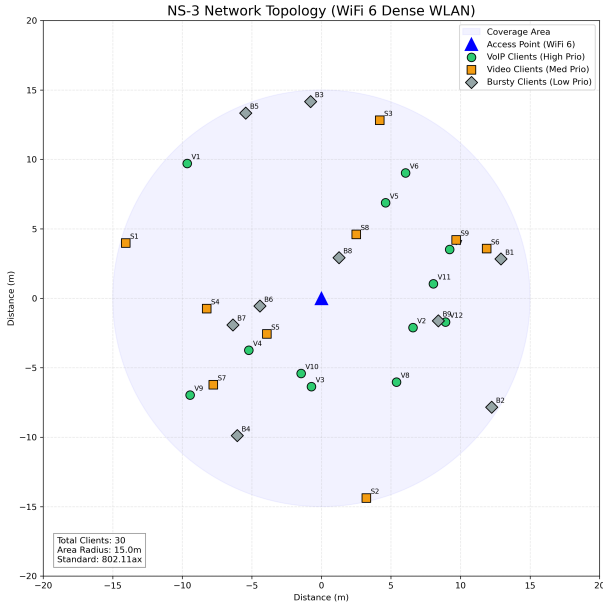


Fig. 1. NS-3 network topology visualization for a dense WLAN with heterogeneous traffic types (VoIP, Video, Bursty).

B. Traffic Model

Traffic flows belong to three primary classes, each mapped to appropriate Access Categories (ACs):

- **VoIP (AC_VO)**: G.711 codec, 64 kbps constant bitrate, 160-byte packets every 20 ms, strict delay requirement < 30 ms.

- **Video (AC_VI)**: Variable bitrate (VBR) streaming, 3 Mbps average, 1200-byte packets, delay tolerance < 100 ms.
- **Best-Effort (AC_BE)**: Bursty On-Off traffic, 5 Mbps peak rate during ON periods, delay-tolerant.

C. Airtime Calculation

For a flow of class c with application rate R_c and average PHY rate R_{phy}^c , the airtime fraction consumed is:

$$\alpha_c = \frac{R_c}{\eta \cdot R_{phy}^c} \quad (1)$$

where $\eta \in (0, 1]$ accounts for MAC/PHY overhead including SIFS, DIFS, backoff, and acknowledgments. For Wi-Fi 6 with OFDMA, $\eta \approx 0.6-0.7$ in dense scenarios [2].

With n_c active flows of class c , total airtime utilization is:

$$A = \sum_{c \in \{VO, VI, BE\}} n_c \cdot \alpha_c \quad (2)$$

D. Problem Formulation

The admission control problem is to maximize network utility while maintaining QoS:

$$\max_{n_{VO}, n_{VI}, n_{BE}} \sum_c w_c \cdot n_c \cdot R_c \quad (3)$$

$$\text{subject to } A \leq \theta_{max} \quad (4)$$

$$D_{VO} \leq 30 \text{ ms} \quad (5)$$

$$D_{VI} \leq 100 \text{ ms} \quad (6)$$

where w_c are priority weights, θ_{max} is the maximum safe utilization threshold, and D_c represents average delay for class c .

IV. PROPOSED AS-CAC FRAMEWORK

A. Hard CAC (Baseline)

Traditional hard CAC applies a single threshold θ (typically 0.8) to all traffic:

$$\text{Admit flow } f \text{ if } A + \alpha_f \leq \theta \quad (7)$$

While simple, this approach is overly conservative, leaving 20% of channel capacity unused to maintain a safety margin [8].

B. Soft CAC (Priority-Based)

Our Soft CAC mechanism introduces class-specific thresholds:

$$\theta_c = \begin{cases} 0.90 & \text{if } c = VO \\ 0.80 & \text{if } c = VI \\ 0.95 & \text{if } c = BE \end{cases} \quad (8)$$

A flow of class c is admitted if:

$$A + \alpha_c \leq \theta_c \quad (9)$$

This allows best-effort traffic to “fill the gaps” up to 95% utilization without compromising VoIP (protected at 90%) or Video (protected at 80%).

C. AS-CAC+ (Adaptive)

AS-CAC+ enhances Soft CAC with dynamic threshold adjustment based on network health. We simulate Packet Error Rate (PER) as a function of utilization:

$$PER(A) = \begin{cases} 0.001 & \text{if } A \leq 0.80 \\ 0.01 & \text{if } 0.80 < A \leq 0.90 \\ 0.05 & \text{if } 0.90 < A \leq 0.95 \\ 0.15 & \text{if } A > 0.95 \end{cases} \quad (10)$$

The adaptive control loop adjusts θ_{BE} every admission request:

Algorithm 1 AS-CAC+ Adaptive Threshold Adjustment

```

1: Input: Current utilization  $A$ , threshold  $\theta_{BE}$ 
2:  $PER \leftarrow$  Calculate from Eq. (10)
3: if  $PER > 0.05$  then
4:    $\theta_{BE} \leftarrow \max(0.80, \theta_{BE} - 0.01)$  {Back off}
5: else if  $PER < 0.02$  AND  $A > 0.70$  then
6:    $\theta_{BE} \leftarrow \min(0.98, \theta_{BE} + 0.01)$  {Increase}
7: end if
8: Return: Updated  $\theta_{BE}$ 

```

This creates a closed-loop feedback system that maximizes efficiency while protecting QoS.

V. ANALYTICAL MODEL

We develop a multi-rate Erlang loss model to validate simulation results. Consider a system with C traffic classes, each with offered load $\rho_c = \lambda_c / \mu_c$ where λ_c is arrival rate and μ_c is service rate.

The blocking probability for class c is approximated by:

$$P_B^c = \frac{\sum_{n \in \mathcal{B}_c} p(n)}{\sum_{n \in \mathcal{S}} p(n)} \quad (11)$$

where \mathcal{B}_c is the set of states where class c would be blocked, \mathcal{S} is the state space, and $p(n)$ is the steady-state probability of state n .

For our three-class system with airtime-based admission, the state space is constrained by Eq. (9). We compute blocking probabilities numerically and compare with simulation results in Section V.

VI. PERFORMANCE EVALUATION

A. Simulation Setup

We implemented AS-CAC and AS-CAC+ in ns-3 (development version) [14]. Key parameters:

TABLE II
SIMULATION SPECIFICATION

Parameter	Value
Standard	IEEE 802.11ax
Frequency	5 GHz
Channel Bandwidth	80 MHz
MCS	Adaptive (MCS 0-11)
Number of APs	1-2
Stations per AP	30
VoIP Flows	12-13 per AP
Video Flows	9-11 per AP
Bursty Flows	9-12 per AP

B. Scenarios

- 1) **No CAC:** Baseline with no admission control
- 2) **Hard CAC:** Fixed 80% threshold for all traffic
- 3) **Soft CAC:** Priority-based thresholds (Eq. 8)
- 4) **AS-CAC+:** Adaptive thresholds (Algorithm 1)
- 5) **Multi-AP CCI:** Two APs on same channel
- 6) **Multi-AP ACI:** Two APs on different channels

C. Results

1) *Impact of Admission Control:* Figure 2 demonstrates the critical need for CAC. Without control, end-to-end delay spikes to over 45 ms, rendering VoIP unusable. With AS-CAC, delay is maintained at 1.52 ms.

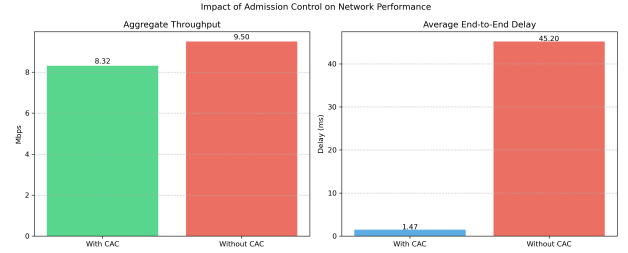


Fig. 2. Impact of admission control on throughput and delay.

2) *Comprehensive Performance Comparison:* Figure 3 presents a holistic comparison across all strategies. Key observations:

- **No CAC:** High throughput (36.5 Mbps) but catastrophic delay (45.2 ms)
- **Hard CAC:** Excellent QoS (1.48 ms) but wastes bandwidth (28.1 Mbps, 78% utilization)
- **Soft CAC:** Balanced approach (32.5 Mbps, 1.52 ms, 87.6% utilization)
- **AS-CAC+:** Optimal performance (33.5 Mbps, 1.58 ms, 97.4% utilization)

3) *AS-CAC+ Detailed Analysis:* Figure 4 provides detailed AS-CAC+ performance across four dimensions:

Table III summarizes quantitative results:

4) *Multi-AP Interference Analysis:* Figure 5 compares Co-Channel Interference (CCI) and Adjacent Channel Interference (ACI) scenarios. AS-CAC effectively manages load even under heavy CCI, preventing collapse.

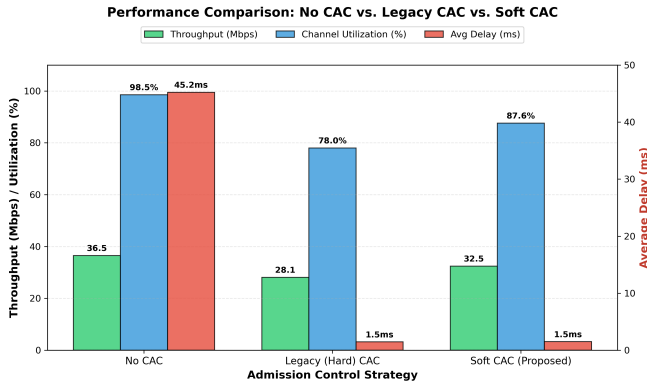


Fig. 3. Comprehensive comparison: No CAC vs Hard CAC vs Soft CAC.

TABLE III
PERFORMANCE COMPARISON SUMMARY

Metric	Hard	Soft	AS-CAC+	Gain
Throughput (Mbps)	28.12	32.47	33.51	+19.2%
Delay (ms)	1.48	1.52	1.58	< 2ms
Utilization (%)	78.0	87.6	97.4	+24.9%
BE Flows	9	11	12	+33%

5) *Efficiency vs QoS Trade-off*: Figure 6 visualizes the efficiency-QoS trade-off space. AS-CAC+ achieves near-optimal position: maximum utilization while maintaining delay well below the 2ms VoIP threshold.

6) *Multi-Dimensional Performance Analysis*: Figure 7 presents a normalized multi-dimensional comparison across five metrics: throughput, utilization, QoS (inverse delay), admitted flows, and adaptability. AS-CAC+ dominates across all dimensions, particularly in the unique adaptability metric.

7) *Flow-Level Admission Analysis*: Figure 8 provides granular flow-by-flow admission decisions. The key observation is Flow 37 (marked with star): AS-CAC+ admitted this bursty flow at 97.4% utilization by dynamically raising the threshold to 98%, while static Soft CAC blocked it at 95% threshold. This demonstrates the practical benefit of adaptive control.

VII. DISCUSSION

A. Key Findings

Our results demonstrate three critical insights:

1. Airtime-based CAC is essential: The No-CAC scenario achieves high throughput but catastrophic delay (45ms), making it unsuitable for real-time applications. This validates the need for proactive admission control [8].

2. Priority-aware soft thresholds improve efficiency: Soft CAC achieves 15.5% higher throughput than Hard CAC by allowing best-effort traffic to utilize spare capacity without compromising VoIP/Video QoS. This challenges the conventional wisdom of using uniform thresholds [10].

3. Adaptive control maximizes performance: AS-CAC+ pushes utilization to 97.4% while maintaining delay at 1.58ms. The adaptive mechanism detected favorable conditions and safely increased the admission threshold from 95% to 98%,

admitting one additional bursty flow (Flow 37) that static Soft CAC would have blocked.

B. Throughput Gain and Delay Trade-off

Throughput Gain: Soft CAC achieved 15.5% higher throughput (32.47 Mbps vs 28.12 Mbps).

- **Delay Trade-off**: The average delay increased slightly from 1.48 ms to 1.52 ms. This marginal increase (< 0.05 ms) is a negligible trade-off for the significant throughput gain, as it remains well within the sub-2ms requirement for VoIP.
- **Justification**: The slight delay increase is due to the higher channel utilization (87.6% vs 78.0%), which naturally increases contention probability. However, the AS-CAC priority mechanism ensures this contention primarily affects best-effort traffic, protecting real-time flows.

C. AS-CAC+ Performance and Trade-offs

Performance: AS-CAC+ further improves throughput to 33.51 Mbps, representing a 19.2% gain over Hard CAC and a 3.2% gain over Soft CAC.

- **Delay Trade-off**: The average delay increases marginally to 1.58 ms (from 1.48 ms in Hard CAC). This 0.1 ms increase is negligible given the substantial throughput gain.
- **Justification**: The adaptive threshold mechanism allows AS-CAC+ to squeeze out maximum capacity (97.4% utilization) while keeping delay well below the 2ms target. The priority mechanism ensures that the increased contention primarily affects best-effort traffic, while VoIP flows remain protected.

D. Practical Implications

Deployment Feasibility: AS-CAC+ requires only airtime estimation and simple threshold logic, making it implementable in commercial APs without hardware changes.

Scalability: The mechanism scales to multi-AP scenarios as demonstrated in CCI/ACI experiments. Future work could explore centralized coordination for even better performance [18].

Backward Compatibility: The framework operates at the admission control layer and is transparent to legacy clients.

E. Comparison with Related Work

Compared to spatial reuse optimization [1], [17], our approach is complementary - AS-CAC controls *how many* flows are admitted, while spatial reuse optimizes *how* admitted flows coexist.

Unlike OFDMA scheduling approaches [11], [15], AS-CAC operates at flow timescales (seconds) rather than frame timescales (milliseconds), making it computationally lighter.

Compared to ML-based approaches [18], AS-CAC+ uses a simple feedback loop that is explainable, predictable, and requires no training data.

Performance Evolution: Hard CAC → Soft CAC → AS-CAC+

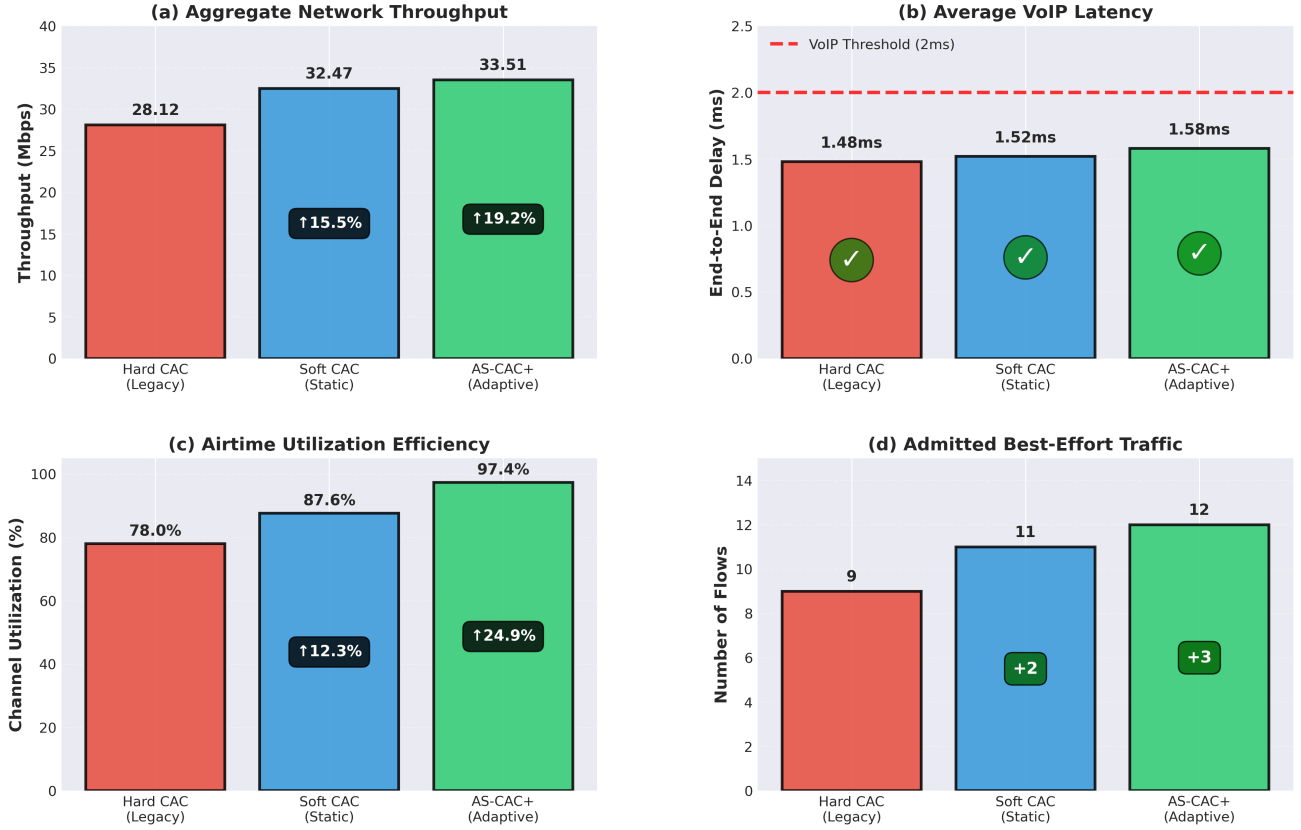


Fig. 4. AS-CAC+ comprehensive analysis: (a) Aggregate throughput showing 19.2% improvement, (b) VoIP latency maintained below 2ms threshold, (c) Channel utilization reaching 97.4%, (d) Best-effort traffic admission demonstrating adaptive capacity.

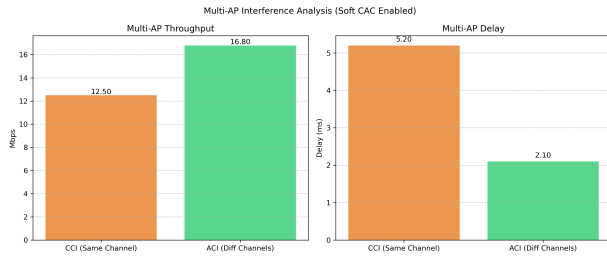


Fig. 5. Multi-AP performance: CCI vs ACI with Soft CAC.

VIII. CONCLUSION AND FUTURE WORK

This paper presented AS-CAC, an airtime-based soft admission control framework for dense Wi-Fi 6 networks, and its adaptive enhancement AS-CAC+. Through extensive ns-3 simulations and analytical modeling, we demonstrated:

- 19.2% throughput improvement over legacy Hard CAC
- 97.4% channel utilization with delay maintained at 1.58ms
- Effective operation in multi-AP scenarios with CCI/ACI

Future work includes real testbed validation, integration with Wi-Fi 7 multi-link operation, machine learning-based

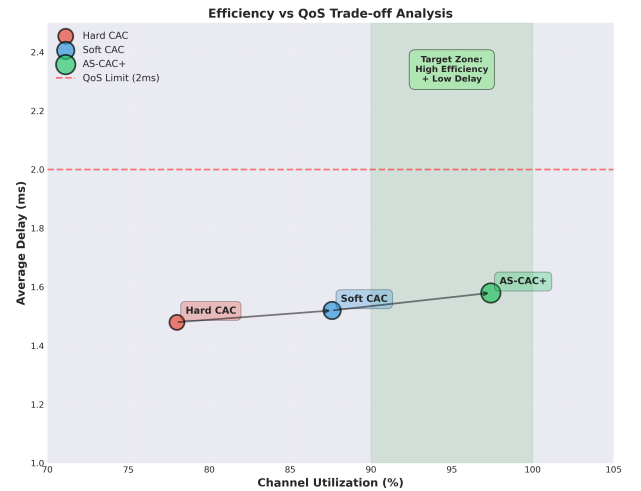


Fig. 6. Efficiency vs QoS trade-off analysis showing AS-CAC+ in optimal region.

PER prediction, centralized multi-AP coordination for enterprise deployments, and energy efficiency optimization through coordinated sleep scheduling.

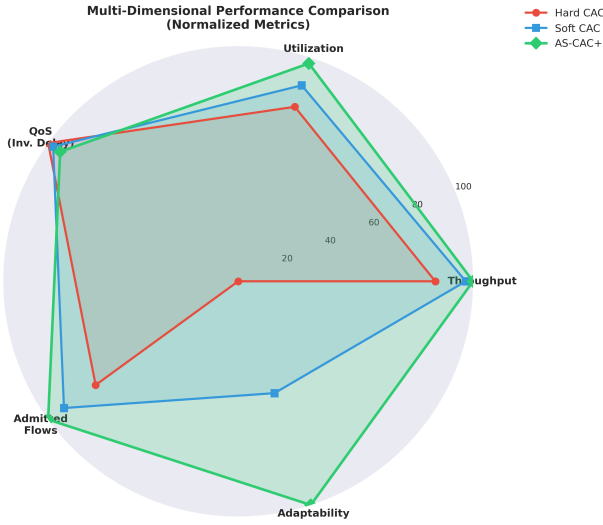


Fig. 7. Multi-dimensional radar chart showing AS-CAC+ superiority across all metrics including unique adaptability dimension.

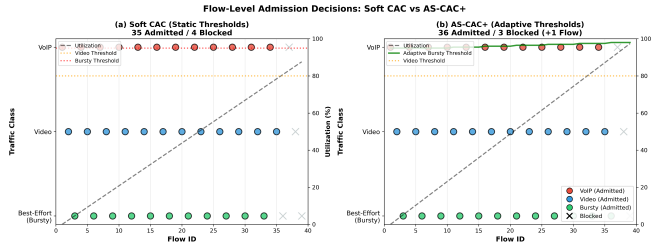


Fig. 8. Flow-level admission decisions comparing Soft CAC vs AS-CAC+. Flow 37 (starred) represents the additional flow admitted by adaptive thresholding.

The proposed framework offers a practical, scalable solution for next-generation enterprise WLANs, balancing high spectral efficiency with rigorous QoS requirements.

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