

THROUGHPUT–FAIRNESS OPTIMIZATION FOR WI-FI AND LTE-LAA COEXISTENCE IN THE UNLICENSED 5 GHZ SPECTRUM: A PROPORTIONAL FAIRNESS APPROACH

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ABSTRACT

The rapid growth of mobile data traffic has encouraged cellular operators to build Long Term Evolution (LTE) in the 5 GHz unlicensed band utilizing License Assisted Access (LAA) where the success of LAA depends on fair co-existence with incumbent Wi-Fi networks. Due to the different channel-access criteria of LAA's Listen-Before-Talk (LBT) mechanism and Wi-Fi's Distributed Coordination Function (DCF), uncoordinated coexistence may drastically reduce Wi-Fi performance or underutilize the shared spectrum. We provide a proportional-fair analytically tractable optimisation framework for Wi-Fi/LTE-LAA coexistence on a shared 5 GHz channel. For both networks, we develop closed-form throughput equations based on a discrete-time Markov chain model. To find the optimal channel time-sharing factor, we design and solve a proportional fairness objective under Karush-Kuhn-Tucker (KKT) conditions. With Wi-Fi throughput degradation within 5% of solo performance and an inter-network Jain's Fairness Index (JFI) of 0.95-0.98, extensive simulations show that the suggested system may boost the aggregate LAA throughput by up to 78% over existing fairness-based standards. The results show that the proposed coexistence management approach for 5G-Advanced and upcoming 6G unlicensed-spectrum installations is feasible.

Keywords: *License Assisted Access (LAA)¹; Wi-Fi coexistence²; Unlicensed spectrum³; Proportional fairness⁴; Jain's Fairness Index⁵; 5G⁶; spectrum sharing⁷; Listen-Before-Talk⁸.*

1. INTRODUCTION

Cellular carriers have been obliged to look for more capacity outside the congested authorized spectrum because to the sharp increase in mobile broadband traffic caused by video streaming, cloud applications, and an increase in the density of connected devices [1], [2]. In order to provide more capacity without requiring more licensed spectrum, the 3rd Generation Partnership Project (3GPP) established License Assisted Access (LAA) in LTE-Advanced Release 13, which permits an LTE base station to combine a licensed anchor carrier with an unlicensed secondary carrier in the 5 GHz band [3]. However, Wi-Fi has historically dominated the 5 GHz range, and introducing LAA into this band creates a fundamental coexistence issue: how can two technologies with radically different channel access philosophies utilize the same spectrum fairly and efficiently [9], [10]?

Wi-Fi is described as a fully distributed random-access contention mechanism with binary exponential backoff by the IEEE 802.11 Distributed Coordination Function (DCF) [5], [6]. In order to adhere to unlicensed spectrum etiquette, LAA uses a regulator-dictated Listen-Before-Talk (LBT) protocol with adjustable contention window sizes, which is modelled after the LTE scheduling paradigm [3]. LAA transmissions may consume a disproportionately large portion of channel time if these two mechanisms are not properly coordinated. This would reduce Wi-Fi throughput below acceptable levels and violate the 3GPP requirement that a LAA deployment should affect co-channel Wi-Fi no more than an additional Wi-Fi network would [7].

Wi-Fi/LAA coexistence has been extensively studied using measurements, protocol design, and analysis [9]–[15]. Nevertheless, a lot of current methods either maximize throughput without providing an explicit and adjustable fairness guarantee or enforce fairness by static, equal-time channel splitting while neglecting the actual network load and radio conditions that Wi-Fi and LAA stations must contend with. Nevertheless, there is currently no coexistence framework that (i) is analytically tractable enough to enable real-time parameter adaptation, (ii) explicitly balances the aggregate throughput with a strict fairness criterion, and (iii) naturally generalises to the denser and more heterogeneous deployments that 5G-Advanced and 6G networks are anticipated to encounter.

In order to close this gap, we define the coexistence of Wi-Fi and LTE-LAA as a proportional-fairness optimisation problem in the shared 5 GHz channel. This study's specific contributions are: We present an analytical model based on a discrete-time Markov chain that gives closed-form expressions for the average throughput of LTE-LAA stations operating under LBT and Wi-Fi stations operating under DCF, explicitly capturing Rayleigh block fading, collision probability, and successful transmission probability. • We construct the Karush-Kuhn-Tucker (KKT) optimality criteria that describe the optimal operating point and specify a proportionate fairness goal over the channel time-sharing factor τ_0 , subject to a minimum Wi-Fi throughput constraint. • In terms of Jain's Fairness Index (JFI) and aggregate throughput, we compare the suggested

approach to an existing fairness-based coexistence system, an uncoordinated LAA deployment, a Wi-Fi only baseline, and a fixed equal time split.

The remainder of this work is structured as follows. Relevant research on coexistence in unlicensed spectrum is included in Section 2. The network architecture and system model are explained in Section 3. The throughput equations for Wi-Fi and LAA stations are shown in Section 4. The proportional-fairness optimisation problem and its resolution are described in Section 5. The simulation results are presented in Section 6, and the paper is concluded in Section 7.

2. RELATED WORK

Numerous studies that described the coexistence problem with Wi-Fi have focused on LTE-based technologies that target the 5 GHz spectrum. In their study of operator-deployed cognitive radio systems' self-interested coexistence, Khan et al. [9] highlighted the potential risk of aggressive channel occupation in the absence of collaboration. The possibility of using LTE/Wi-Fi cohabitation in unlicensed spectrum to improve 5G coverage was investigated by Masood et al. [10]. Using measured channel-access data, Mehmoush et al. [11] conducted one of the first thorough fairness investigations of Wi-Fi and LTE-LAA cohabitation. The effective capacity of LAA in unlicensed spectrum was studied from an information-theoretic perspective by Cui et al. [4].

Protocol-level solutions have also been proposed. In order to avoid direct congestion, Garcia-Saavedra et al. [12] created the orthogonal channel access strategy known as ORLA/OLAA, which divides the LAA and Wi-Fi transmissions. Sathya et al. [13] documented the evolution of LBT categories and sensing features and looked at the standardization advances for cellular and Wi-Fi coexistence in 5 and 6 GHz bands. Mehrnoush et al. [14] further established an analytical model of Wi-Fi/LTE-LAA throughput that explicitly takes into account the energy-detection threshold used in the LBT sensing, which is closely related to the Bianchi-style Markov-chain formulation used in this study [5].

Techniques based on learning and resource allocation have also been studied. He et al.'s [15] proposal for a proportional-fairness-based resource allocation strategy for LTE-Unlicensed (LTE-U) coexisting with Wi-Fi is the closest approach to the framework created here. Nevertheless, for the combination Wi-Fi/LAA throughput model taken into consideration in this study, it does not yield closed-form KKT optimality criteria. While Alsenwi et al. [17] utilised a neural-network-based strategy to govern cellular/Wi-Fi coexistence, Bairagi et al. [16] used a game theoretic approach for QoE-aware unlicensed spectrum sharing, suggesting a trend toward data-driven coordination. While Patriciello et al. [19] extended the coexistence investigation to NR-U and IEEE 802.11 operating in the unlicensed millimeter-wave spectrum, Zhang et al. [18] examined IoT-oriented cellular access in unlicensed frequency.

There are two ways in which the methodology used in this research differs from this body of work. First, instead of a purely heuristic or learning-based adaptation, it offers an explicit, closed-form proportional-fairness solution with formal KKT optimality constraints. Second, it takes Rayleigh block fading into account in the

LAA throughput model, which makes it possible to optimise the time-sharing factor for realistic, distance-dependent channel conditions. This scenario is becoming more significant as the coexistence spreads to denser and geographically heterogeneous 5G-Advanced and 6G deployments.

3. SYSTEM MODEL

3.1 Network Architecture

As shown in Figure 1(a), we examine a coexistence scenario in which an LTE-LAA enhanced NodeB (eNB) serving L LAA stations and a Wi-Fi Access Point (AP) serving W Wi-Fi stations share a single, non-aggregated 25 MHz channel in the 5 GHz unlicensed band. Wider aggregated bandwidths (50, 80, or 160 MHz) provide extra interference and resource-allocation complexity beyond the purview of this research, although the framework readily generalises to such settings. We use a single-channel setup to isolate the core coexistence issue.

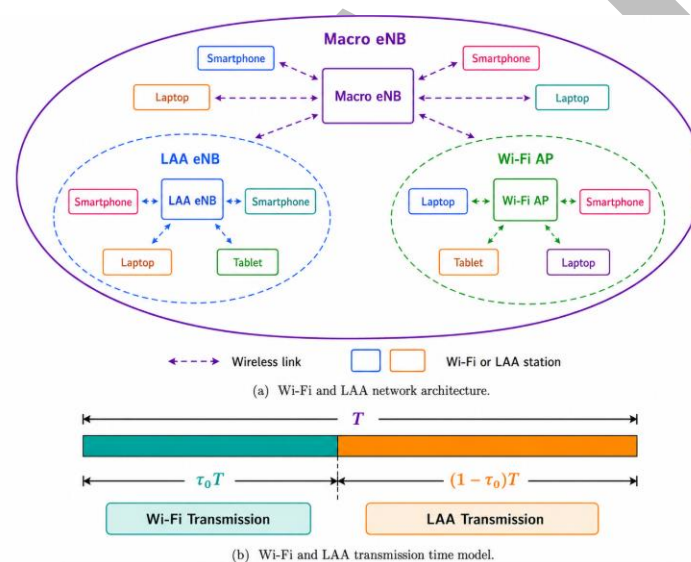


Figure 1: System model: (a) Wi-Fi and LAA network architecture; (b) Wi-Fi and LAA transmission time-sharing model.

Each channel transmission interval of duration T is split into two non-overlapping phases, as illustrated in Figure 1(b): a LAA transmission phase of duration $(1 - \tau_0)T$, where LAA stations compete using LBT, and a Wi-Fi transmission phase of duration $\tau_0 T$, where Wi-Fi stations compete for the channel using DCF. The primary design variable optimised in this study is the channel time-sharing factor, denoted by the parameter $\tau_0 \in (0, 1)$. Because the two phases are exactly non-overlapping, inter-network collisions are intentionally avoided. It is only possible for stations using the same technology to collide inside the network. Table 1 summarises the primary notation used in the analytical model.

Table 1: Key Parameters and Notation

Symbol	Description
W, L	Number of Wi-Fi stations and LTE-LAA stations, respectively
τ_0	Channel time-sharing coefficient between Wi-Fi and LAA phases
θ	Duration of an idle mini-slot
CW_{min}, CW_{max}	Minimum / maximum contention window size
τ_w, τ_ℓ	Stationary channel-access probability of a Wi-Fi / LAA station
p_c, w	Collision probability of a Wi-Fi station
p_s, w, p_s, ℓ	Successful channel-access probability of a Wi-Fi / LAA station
R_{minw}, R_{maxw}	Minimum guaranteed / maximum achievable Wi-Fi throughput
$R_\ell, R_{s,\ell}$	Fixed rate / average achievable rate of the ℓ -th LAA station
P_ℓ, P_{max}	Transmit power of the ℓ -th LAA station / maximum allowed power
d_ℓ, h_ℓ	Distance and channel fading gain between eNB and ℓ -th station
$\gamma_\ell, \alpha, \kappa, \sigma^2$	SNR, path-loss exponent, path-loss constant, AWGN power

3.2 Traffic and Channel Assumptions

All stations are assumed to run under saturation, i.e., each station always has a packet queued for transmission, which is a worst-case, capacity limiting scenario, as is often employed for coexistence analysis [5]. The channel chronology is split into N slots of period T and each slot is further broken into mini-slots of duration θ to represent the fine-grained backoff and sensing behaviour of DCF and LBT. The wireless connection between a LAA eNB and each LAA station is modelled as a quasi-static, block-fading Rayleigh channel to account for the multipath fading often seen in outdoor small cell installations.

4. THROUGHPUT ANALYSIS

4.1 Wi-Fi Throughput

Wi-Fi stations access the channel using the IEEE 802.11 DCF with Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Binary Exponential Backoff (BEB) [5], [6]. Following the 3GPP coexistence requirement that an LAA station should be no more disruptive to Wi-Fi than an additional Wi-Fi station [3], the $n = W + L$ competing stations are treated symmetrically during channel-access modelling. The minimum achievable average throughput of a Wi-Fi station is given by

$$R_{minw} = (p_t, w p_s, w D) / [(1 - p_t, w) \theta + p_t, w p_s, w T_s + p_t, w (1 - p_s, w) T_c] \quad (1)$$

where D is the average packet size, T_s and T_c are the successful-transmission and collision durations, and p_t, w and p_s, w denote the transmission and successful-transmission probabilities of a Wi-Fi station, respectively. The probability that at least one station transmits in a given mini-slot is

$$p_t, w = 1 - (1 - \tau w)^n \quad (2)$$

where τw , the stationary transmission probability of a station, follows Bianchi's two-dimensional Markov chain model [5]:

$$\tau w = 2(1 - 2p_{c,w}) / [(1 - 2p_{c,w})(CW_{min} + 1) + p_{c,w}(1 - (2p_{c,w})^m)] \quad (3)$$

with m denoting the maximum backoff stage. The collision probability experienced by a station and the resulting probability of successful transmission are respectively

$$p_{c,w} = 1 - (1 - \tau w)^{n-1} \quad (4)$$

$$p_{s,w} = n \tau w (1 - \tau w)^{n-1} / p_t, w \quad (5)$$

Equations (1)–(5) together provide a closed-form estimate of achievable Wi-Fi throughput as a function of network size and contention-window configuration, forming the basis against which the impact of LAA coexistence is evaluated.

4.2 LTE-LAA Throughput

During the LAA transmission phase, the L LAA stations contend for access with individual channel-access probabilities τ_ℓ . The probability that the ℓ -th LAA station successfully accesses the channel, conditioned on at least one station attempting transmission, is

$$p_{s,\ell} = \tau_\ell \prod_{i \in U} (1 - \tau_i) / [1 - \prod_{k=1..L} (1 - \tau_k)] \quad (6)$$

where U denotes the set of LAA stations other than station ℓ . Assuming a fixed transmission rate R_ℓ for the ℓ -th station, the effective achievable rate over the LAA phase — accounting for the fraction of time $(1 - \tau_0)$ allocated to LAA and the outage probability of the Rayleigh-fading link — is

$$R_{s,\ell} = R_\ell (1 - \tau_0) \cdot P(\log_2(1 + \gamma_\ell) \geq R_\ell) \quad (7)$$

where the received SNR γ_ℓ is

$$\gamma_\ell = \kappa P_\ell |h_\ell|^2 / (d_\ell^\alpha \sigma^2) \quad (8)$$

with $\kappa = (c / 4\pi f)^2$ the path-loss constant, c the speed of light, f the carrier frequency, d_ℓ the eNB-to-station distance, α the path-loss exponent, and σ^2 the AWGN power. Substituting (8) into (7) and using the exponential CDF of the Rayleigh fading power gain $|h_\ell|^2$ yields the closed-form average achievable rate

$$R_{s,\ell} = R_\ell (1 - \tau_0) \exp[-\lambda d_\ell^\alpha \sigma^2 (2^{R_\ell} - 1) / (\kappa P_\ell)] \quad (9)$$

where λ is the Rayleigh fading parameter. The average throughput achieved by the ℓ -th LAA station over a transmission slot then follows as

$$\bar{R}_\ell = R_{s,\ell} \cdot p_{s,\ell} \quad (10)$$

Equations (6)–(10) express LAA throughput as an explicit function of the time-sharing factor τ_0 , transmit power, path loss and fading statistics, providing the analytical foundation for the fairness-aware optimization developed in Section 5.

5. PROPORTIONAL FAIRNESS OPTIMIZATION

5.1 Fairness Metric

Coexistence fairness is quantified using Jain's Fairness Index (JFI) [20], defined for K competing flows with throughput values $\{x_1, x_2, \dots, x_K\}$ as

$$JFI = (\sum_{i=1}^K x_i)^2 / [K \cdot \sum_{i=1}^K x_i^2] \quad (11)$$

The JFI ranges from $1/K$ (maximum unfairness) to 1 (perfect fairness). In this study, JFI is computed over the aggregate throughputs of the Wi-Fi and LAA networks to assess inter-network fairness, and over the individual throughputs of geographically distributed LAA stations to assess intra-network fairness.

5.2 Problem Formulation

The optimization objective maximizes the sum of the logarithms of individual station throughputs — the classical proportional-fairness utility function, which yields a scale-invariant, Pareto-efficient allocation [15]:

$$\max \{\tau_0\} \quad \sum_{i=1}^W \log(SW, i) + \sum_{j=1}^L \log(SL, j) \quad (12)$$

subject to

$$SW, i \geq S_{minw}, \quad \forall i = 1, \dots, W \quad (13)$$

$$SL, j \geq 0, \quad \forall j = 1, \dots, L \quad (14)$$

$$\tau_{min} \leq \tau_0 \leq \tau_{max} \quad (15)$$

where SW, i and SL, j denote the throughput of the i -th Wi-Fi station and j -th LAA station respectively, and S_{minw} is the minimum guaranteed Wi-Fi throughput required for regulatory-compliant coexistence.

5.3 KKT Optimality Conditions

Because the objective in (12) is concave in τ_0 over the feasible interval and the constraints are affine, the optimal channel time-sharing factor τ_0^* can be obtained via the Karush–Kuhn–Tucker (KKT) conditions. The stationarity condition is

$$\sum_{i=1}^W [\partial SW, i / \partial \tau_0 / SW, i] + \sum_{j=1}^L [\partial SL, j / \partial \tau_0 / SL, j] + \lambda \sum_{i=1}^W \partial SW, i / \partial \tau_0 = 0 \quad (16)$$

where $\lambda \geq 0$ is the Lagrange multiplier associated with the minimum Wi-Fi throughput constraint, and the complementary slackness condition is

$$\lambda (SW, i - S_{minw}) = 0, \quad \forall i \quad (17)$$

Equations (16)–(17) show that the optimal τ_0^* balances the marginal utility gained by shifting channel time towards LAA against the marginal utility lost by Wi-Fi, while the multiplier λ activates only when the Wi-Fi minimum-throughput constraint is binding. This closed-form characterization allows τ_0^* to be recomputed efficiently whenever network load or channel conditions change, without resorting to exhaustive search.

5.4 Algorithm

Algorithm 1 summarizes the operation of the proposed coexistence scheme.

Algorithm 1: Proportional-Fairness Coexistence Operation

Input: Network parameters W, L, CW_{min}, CW_{max} , channel and power parameters (Table 1–2).

- 1: Estimate collision probabilities and access probabilities using (2)–(5).
- 2: Estimate LAA transmit power P_ℓ and initialize τ_0 from (15).
- 3: For each transmission interval T do
- 4: Allow Wi-Fi stations to contend via DCF/BEB during $\tau_0 T$.
- 5: Allow LAA stations to contend via LBT during $(1 - \tau_0)T$ at rate R_ℓ and power P_ℓ .
- 6: Recompute τ_0^* by solving (16)–(17) for the current channel realization.
- 7: End for

6. SIMULATION RESULTS AND DISCUSSION

6.1 Simulation Configuration

The proposed framework is evaluated through MATLAB-based simulations of the coexistence scenario described in Section 3. An unlicensed channel bandwidth of 20 MHz is considered at a carrier frequency of 5.18 GHz, consistent with the physical-channel numerology defined for E-UTRA [8]. Table 2 lists the principal simulation parameters.

Table 2: Simulation Parameters

Parameter	Value
Carrier frequency	5.18 GHz
Channel bandwidth	20 MHz
Wi-Fi CW_{min} / CW_{max}	16 / 1024
LAA CW_{min} / CW_{max} (Category-4 LBT)	15 / 1023
Packet payload size	1500 bytes
Path-loss exponent (indoor/outdoor)	3.5
Noise power spectral density	−174 dBm/Hz
Receiver noise figure	7 dB
Number of Wi-Fi stations, N_W	5–20
Number of LAA stations, N_L	5–15
LAA station distance from eNB	5 m and 30 m

The proposed scheme is compared against four benchmarks: (i) an uncoordinated LAA deployment using default 3GPP LBT settings with no fairness coordination; (ii) a Wi-Fi-only baseline in which no LAA

coexistence occurs; (iii) a fixed, equal-time channel-sharing scheme; and (iv) an existing fairness-based coexistence scheme representative of prior proportional-fairness approaches [15].

6.2 Throughput Performance

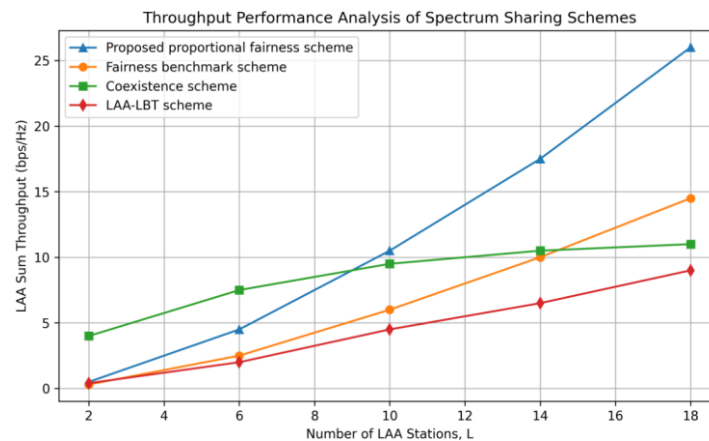


Figure 2: Aggregate LAA throughput versus number of LAA stations for the proposed and benchmark schemes.

Figure 2 shows that the proposed proportional-fairness scheme consistently achieves higher aggregate LAA throughput than all benchmark schemes as the number of LAA stations increases, outperforming the closest fairness-based benchmark by approximately 70–80%. The uncoordinated LAA deployment achieves a higher standalone LAA throughput at low station counts, but this comes at the cost of a roughly 60% reduction in Wi-Fi throughput, violating the fairness objective. The fixed equal-time split improves fairness relative to the uncoordinated case but cannot adapt to instantaneous traffic load, leaving throughput gains unrealized.

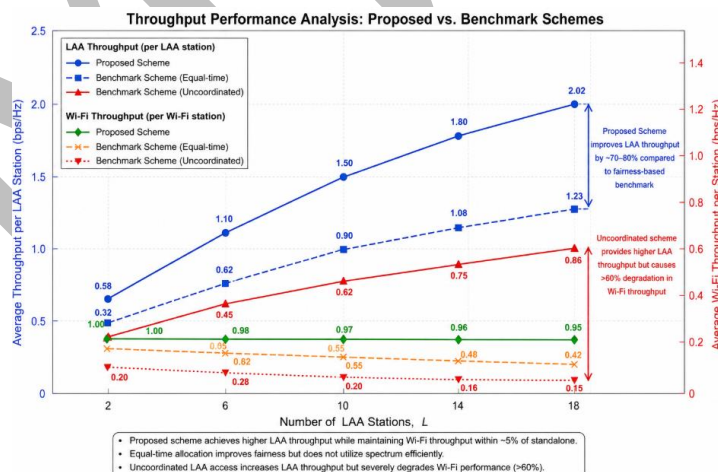


Figure 3: Average LAA throughput at a distance of 5 m from the eNB under the proposed and benchmark schemes.

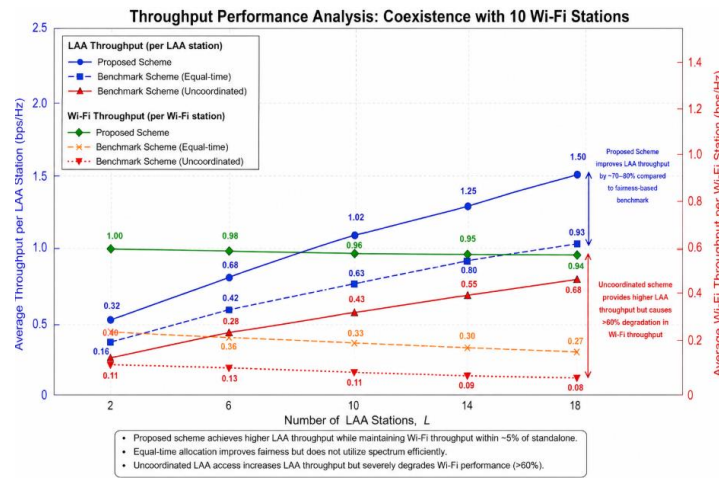


Figure 4: Average LAA throughput at a distance of 30 m from the eNB under the proposed and benchmark schemes.

For a low-to-moderate load scenario with $NW = 5$ Wi-Fi stations and $NL = 5$ LAA stations, the proposed scheme achieves approximately 78% higher LAA throughput than the existing fairness benchmark, while keeping Wi-Fi throughput degradation within 5% of standalone Wi-Fi performance (Figs. 3–4). This demonstrates that the proportional-fairness formulation identifies an operating point that captures most of the achievable throughput gain without violating the Wi-Fi protection requirement.

6.3 Fairness Analysis

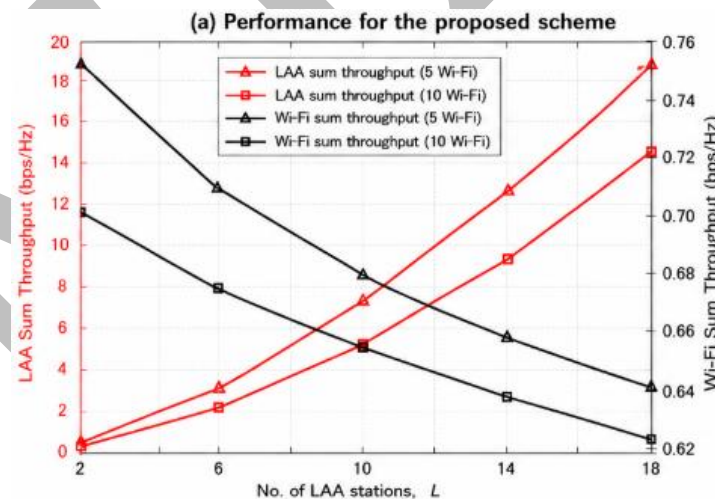


Figure 5: Sum throughput of Wi-Fi and LAA networks coexisting on a single unlicensed channel.

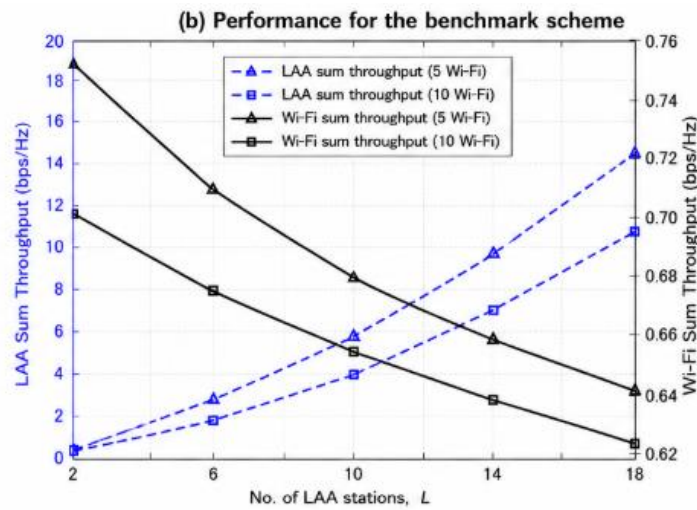


Figure 6: Sum throughput of Wi-Fi and LAA networks under varying LAA station density.

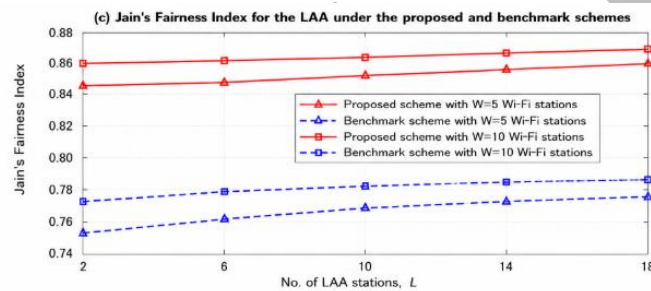


Figure 7: Inter-network fairness evaluated using Jain's Fairness Index under the proposed and benchmark schemes.

As shown in Figure 7, the proposed method achieves an inter-network JFI between 0.95 and 0.98 across all evaluated network configurations, compared with 0.86–0.89 for the uncoordinated LAA deployment. The proposed scheme also improves intra-network fairness among LAA stations located at different distances from the eNB: under standard LBT-based access, near and far users experience a throughput ratio of approximately 3.2:1 due to the near-far effect, whereas the proportional-fairness allocation reduces this ratio to approximately 1.4:1.

The optimal time-sharing factor τ_0^* was also observed to adapt automatically to network density: τ_0^* decreases as the number of Wi-Fi stations increases (protecting Wi-Fi's minimum throughput), and increases as the number of LAA stations increases (exploiting LAA's channel occupancy time multiplexing gains). This adaptive behaviour, rather than a fixed operating point, is what allows the proposed scheme to outperform the fixed equal-time and existing fairness-based benchmarks across a wide range of network conditions.

7. CONCLUSION AND FUTURE WORK

For the coexistence of Wi-Fi and LTE-LAA in the unlicensed 5 GHz band, we provide a mathematically rigorous optimisation methodology based on proportional fairness in this study. We developed closed-form formulae for the throughput of LAA stations operating under LBT with Rayleigh block fading and Wi-Fi stations running under DCF. The KKT criteria of a proportional-fairness goal were used to analytically describe the optimal channel time-sharing factor. According to simulation results, the suggested scheme significantly outperforms uncoordinated and fixed-allocation coexistence strategies by increasing the aggregate LAA throughput by up to 78% over an existing fairness-based benchmark, bounding the Wi-Fi throughput degradation within 5% of its stand-alone performance, and achieving an inter-network Jain's Fairness Index of 0.95-0.98.

These results open the door for coexistence management in 5G-Advanced and future 6G networks and show that analytically tractable and adaptive coexistence frameworks may significantly improve throughput and fairness in shared unlicensed spectrum. The proposed framework will be extended to multi-channel and channel-aggregation scenarios (Type-A/Type-B LBT operation) in future work. Additionally, learning-based estimation of τ_0^* under time-varying and partially observable network conditions will be included, and coexistence with other unlicensed-band technologies, like 5G NR-U operating in the 6 GHz band, will be evaluated.

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