International Journal of Computational and Experimental Science and ENgineering
(IJCESEN)

Vol. 12-No.1 (2026) pp. 525-537
http://www.ijcesen.com

ISSN: 2149-9144

Research Article

Intelligent RF Planning and Performance Optimization for Carrier Aggregation and Dual Connectivity in 5G-Advanced Networks

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Article Info:

DOI: 10.22399/ijcesen.4841
Received : 28 November 2025
Revised : 26 January 2026
Accepted : 28 January 2026

Keywords

Carrier Aggregation,
Dual Connectivity,
Rf Planning,
Machine Learning,
Load Balancing

Abstract:

Next-generation wireless networks leverage Carrier Aggregation (CA) and Dual Connectivity (DC) to deliver enhanced throughput and spectral efficiency by simultaneously utilizing multiple frequency bands. However, coordinating FR1 sub-6 GHz coverage with FR2 mmWave capacity presents significant challenges in resource allocation, inter-band handover management, and QoS maintenance under dynamic traffic conditions. This article proposes an intelligent framework combining predictive algorithms for inter-band handover with reinforcement learning-based load balancing optimization. The framework integrates deterministic propagation models with AI-driven traffic forecasting to enable proactive resource allocation across aggregated carriers. Performance evaluation demonstrates substantial improvements in handover success rates, throughput consistency, and resource utilization compared to conventional rule-based methods. Results from urban and suburban deployment scenarios validate the effectiveness of machine learning models in predicting mobility patterns and optimizing carrier selection. The proposed solution addresses critical gaps in multi-band network planning while ensuring latency requirements and service continuity during CA/DC transitions, providing practical insights for 5G-Advanced and early 6G network deployments.

1. Introduction and Motivation

1.1 Background on 5G-Advanced and Early 6G Network Evolution

The telecommunications sector experiences continuous transformation as enhanced fifth-generation systems establish foundations for upcoming sixth-generation technologies. Modern cellular infrastructures integrate complex architectural elements designed to meet growing requirements for widespread service availability and extensive information transfer capacities [1], marking a fundamental departure toward holistic system redesign where frequency management and coordinated control define superior network performance.

1.2 Role of Carrier Aggregation and Dual Connectivity in Next-Generation Networks

Contemporary wireless platforms increasingly rely on CA and DC, enabling mobile terminals to establish simultaneous connections across separate spectrum bands, eliminating restrictions of single-frequency operation. These capabilities harmonize lower frequency ranges providing wide-area coverage with higher frequency bands delivering concentrated throughput, forming an integrated architecture for stratified network functionality.

1.3 Key Benefits: Enhanced Throughput, Spectral Efficiency, and Reliability

Deployment of CA and DC produces considerable improvements in performance. Combining bandwidth from multiple channels generates transmission speeds substantially greater than single-band configurations. Intelligent traffic distribution with opportunistic frequency utilization optimizes spectrum asset value. Parallel transmission paths ensure continuous service delivery when individual channels experience quality reduction. Contemporary developments indicate sophisticated energy control within combined frequency configurations preserves service standards while decreasing power consumption [2].

1.4 Research Gap: Complexity in Multi-Band RF Planning and Real-Time Performance Optimization

Existing methodologies for network design face considerable challenges addressing heterogeneous frequency deployments. Traditional dimensioning approaches inadequately manage coordination of wide-area lower frequency coverage with localized higher frequency capacity zones. Operational difficulties intensify with variable traffic patterns, user movement, and demanding service requirements during frequency transitions. Static planning lacks necessary adaptability while reactive management results in suboptimal frequency exploitation. Service-specific latency budgets and QoS requirements directly influence network selection, link budget margins, and handover strategies, necessitating latency-aware routing policies and dynamic path selection mechanisms.

1.5 Objectives and Scope of the Study

Three primary goals guide this investigation: (1) developing forecasting algorithms that predict frequency handover requirements using historical mobility information and real-time signal measurements; (2) creating adaptive distribution frameworks that modify resource allocations across combined carriers based on evolving traffic demands while maintaining quality commitments and service-specific latency requirements; (3) proposing a unified planning approach merging classical propagation modeling with computational intelligence for traffic forecasting. The scope addresses technical, computational, and practical dimensions of CA/DC in enhanced fifth-generation networks with applications for emerging sixth-generation systems, incorporating operational KPIs, measurement frameworks, and optimization loops.

1.6 Organization of the Paper

Section 2 presents fundamental technical aspects of CA and DC architectures. Section 3 investigates primary challenges in radio frequency design for multi-band infrastructures, including service-type specific requirements. Section 4 describes the intelligent framework for planning and optimization. Section 5 evaluates framework performance through simulation and practical case scenarios. Section 6 summarizes key findings and identifies future development directions.

2. Fundamentals of Carrier Aggregation and Dual Connectivity

2.1 Technical Overview of CA and DC Architectures

Modern wireless systems employ two primary methods for combining multiple frequency channels. CA operates by merging several component carriers under unified radio access technology control, extending available bandwidth through consolidated protocol handling. DC establishes separate simultaneous connections using independent protocol structures across different technologies or frequencies [3]. These architectural variations lead to different management approaches—CA focusing on integrated oversight while DC offers enhanced versatility. For services requiring reliability, parallel transmission paths with PDCP duplication across carriers ensure service continuity during transitions and channel degradations.

2.2 Frequency Range 1 (FR1) vs. Frequency Range 2 (FR2): Characteristics and Trade-offs

Spectrum assignments divide into two categories displaying opposite propagation behaviors. FR1 covers frequencies beneath 6 GHz, demonstrating advantageous transmission properties: expansive reach, effective obstacle penetration, and minimal atmospheric losses [4]. These qualities position FR1 as ideal for establishing baseline connectivity layers supporting latency-sensitive services with RTT typically below 10 ms in dense urban deployments with fiber backhaul, though constrained spectrum limits maximum bandwidth. FR2 functions in millimeter-wave territory exceeding 24 GHz, providing considerably larger bandwidth allocations supporting exceptional data rates for enhanced mobile broadband services. Nevertheless, FR2 experiences restricted transmission distance, vulnerability to physical obstructions, and heightened sensitivity to environmental factors including rain attenuation adding 10-25 dB of path loss at Ka-band frequencies [4]. Practical deployments must reconcile these opposing features, utilizing FR1 for continuous service coverage prioritizing latency-critical applications while positioning FR2 in locations demanding elevated capacity for latency-tolerant services.

2.3 Inter-Band and Intra-Band Aggregation Scenarios

Multiple carrier combinations appear determined by frequency spacing and positioning. Intra-band contiguous combination merges neighboring carriers sharing identical frequency allocations, reducing complexity. Intra-band non-contiguous combination joins separated carriers occupying the same allocation, accommodating fragmented spectrum ownership. Inter-band combination crosses multiple frequency allocations, permitting integration of carriers with different transmission behaviors requiring elaborate coordination [3]. Each configuration presents particular implementation obstacles, with inter-band arrangements delivering maximum adaptability while requiring enhanced equipment specifications. Service-type specific requirements further influence aggregation strategies: URLLC applications demand terrestrial-only or dual connectivity configurations, while massive IoT services tolerate higher latency paths.

2.4 Primary Cell (PCell) and Secondary Cell (SCell) Coordination Mechanisms

Multi-frequency operations create structured relationships among serving cells. PCell establishes the fundamental link transporting essential control information, mobility administration, and assured radio management messaging, typically operating on FR1 frequencies for reliable coverage. SCells augment the primary link by adding supplementary capacity for data transmission without control responsibilities [3]. This structure guarantees connection durability by securing control operations to the most dependable carrier while selectively utilizing extra frequencies for throughput expansion. Management protocols direct SCell activation and suspension according to traffic requirements, signal strength, energy efficiency needs, and service-specific latency budgets. For mission-critical services requiring sub-50 ms latency, make-before-break handover mechanisms with PDCP duplication ensure seamless transitions.

2.5 3GPP Standards and Deployment Scenarios (NSA vs. SA Modes)

Industry specifications establish various deployment frameworks supporting distinct evolution strategies. Non-Standalone frameworks utilize preexisting infrastructure by connecting to previous generation stations while incorporating advanced transmission equipment. This strategy expedites rollout by recycling existing core elements. Standalone frameworks deploy completely autonomous networks with dedicated core infrastructure, removing reliance on older systems and activating comprehensive capabilities including ultra-reliable communications and massive device connectivity. Non-Standalone configurations dominated early installations owing to decreased capital requirements, whereas Standalone frameworks progressively expanded as operators pursued thorough network modernization and enhanced service portfolios supporting diverse latency profiles from sub-10 ms URLLC to multi-second tolerant IoT applications.

2.6 Current State-of-the-Art in CA/DC Implementation

Present-day network installations exhibit advancing complexity in multi-frequency operations. Commercial systems regularly merge numerous carriers spanning FR1 allocations, producing substantial throughput gains. Progressive installations combine FR1 and FR2 carriers via dual connectivity, establishing coverage through lower frequencies while selectively adding capacity via millimeter-wave connections. Recent innovations emphasize adaptive carrier selection mechanisms adjusting combination configurations responding to signal conditions, traffic behaviors, device specifications, and service-type latency requirements including QoS Class Identifier (5QI) mapping [2]. Emerging installations integrate computational learning methods for anticipatory carrier administration, forecasting handover needs and refining resource distribution before quality reductions materialize. Notwithstanding these progressions, obstacles remain in coordinating carriers with vastly different transmission behaviors, handling frequent inter-frequency transitions, preserving quality commitments throughout configuration modifications, and maintaining service-specific latency budgets across heterogeneous network paths.

3. Core Challenges in RF Planning for CA/DC Networks

3.1 Multi-Band Complexity and Coordination

3.1.1 Coverage-Capacity Trade-offs Between FR1 and FR2

Reconciling geographic reach with throughput provision constitutes a primary obstacle. Spectrum below 6 GHz establishes critical baseline service across operational zones supporting latency-sensitive applications. Millimeter-wave allocations furnish concentrated bandwidth enabling superior transmission velocities but encounter limited range and obstruction vulnerability. Deployment strategists confront opposing goals: overutilization of lower spectrum generates throughput constraints while excessive millimeter-wave emphasis produces connectivity voids [5]. Topographic differences compound these compromises, demanding site-specific refinement. Service-type considerations further complicate planning, as URLLC services requiring sub-10 ms latency mandate terrestrial-only paths or FR1 primary connectivity, while latency-tolerant IoT can leverage higher-latency FR2 capacity paths.

3.1.2 Interference Management Across Aggregated Carriers

Concurrent functioning across numerous frequency segments creates intricate disruption conditions. Adjacent channel disturbance materializes when transmission power from individual carriers penetrates adjoining frequencies. Intermodulation byproducts from nonlinear amplification generate unwanted emissions. Cross-frequency disruption manifests when combined channels undergo related fading or obstruction incidents [5]. Conventional disruption control methods remain inadequate for combined carrier situations, mandating synchronized power regulation, flexible modulation adjustment, and responsive carrier engagement protocols. Additional complexity emerges coordinating interference management across carriers serving different service types with distinct QoS requirements, as power control optimizations for URLLC may conflict with throughput maximization for eMBB services.

3.1.3 Propagation Modelling Challenges in Heterogeneous Spectrum

Precise forecasting of transmission characteristics spanning varied frequency territories requires modeling structures accommodating substantially different propagation phenomena. Lower-spectrum transmissions display diffraction-controlled propagation where electromagnetic radiation curves around barriers. Higher spectrum communications pursue quasi-optical propagation where blockage generates distinct shadow zones. Traditional propagation frameworks inadequately represent these contrasting characteristics [5]. Constructing integrated modeling methodologies preserving precision across frequency territories while sustaining computational feasibility constitutes a persistent obstacle. Modern planning must additionally incorporate service-specific link budget calculations, including frequency-dependent rain attenuation margins (10-25 dB for Ka-band under heavy rainfall), gaseous absorption effects (0.5-3 dB depending on elevation and frequency), and implementation margins accounting for pointing losses and polarization mismatches.

3.2 Dynamic Traffic and Mobility Management

3.2.1 User Mobility Patterns and Inter-Band Handover Triggers

Device displacement across mixed coverage strata requires recurring transitions among frequency allocations. Pedestrian displacement generates comparatively gradual signal intensity fluctuations permitting deliberate handover determinations, whereas vehicular velocities produce abrupt channel variations requiring prompt carrier exchanges. Vertical displacement in multi-level facilities generates distinct situations [5]. Establishing ideal handover initiation parameters involves reconciling opposing targets: cautious initiators preserve connection resilience but postpone access to enhanced frequencies, while assertive initiators facilitate swift refinement but elevate handover breakdowns. Advanced implementations require trajectory-aware thresholds that weight RSRP/RSRQ/SINR measurements by time-to-edge calculations derived from user motion vectors and cell geometry. Service-type latency requirements further constrain handover timing: mission-critical services demanding sub-50 ms continuity necessitate make-before-break procedures with PDCP duplication, while latency-tolerant IoT applications can accommodate reactive handover strategies with brief service interruptions.

3.2.2 Real-Time Load Distribution Challenges

Allocating traffic spanning combined carriers necessitates persistent modification to shifting demand configurations. Geographic traffic fluctuations concentrate subscribers in designated territorial sectors during specific temporal intervals, generating confined congestion on particular frequencies while leaving alternatives underexploited. Temporal traffic configurations display foreseeable daily patterns overlaid with unpredictable surges. Service heterogeneity introduces diverse quality demands [5]. Fixed load equilibration policies grounded on extended-duration averages inadequately address these shifting circumstances. Modern load balancing must incorporate latency-aware routing policies utilizing QoS Class Identifier (5QI) mapping to dynamically select between carriers based on service latency budgets, prioritizing FR1 terrestrial paths for URLLC applications while directing latency-tolerant bulk data transfers to available FR2 capacity resources.

3.2.3 Beam Management in mmWave Scenarios

Millimeter-wave implementations utilize extremely directional radiation requiring persistent monitoring and modification. Radiation alignment processes must swiftly examine angular domains, identifying ideal transmission orientations while reducing burden. Portable devices undergo recurring radiation obstruction incidents when barriers intercept direct paths, requiring rapid radiation switching [6]. Concentrated implementation situations generate intricate disruption conditions where radiation synchronization prevents reciprocal disruption. Environmental fluctuations incorporating pedestrian circulation and vehicle displacement modify propagation routes on subsecond intervals. Service-aware beam management prioritizes beam allocation and tracking resources for latency-sensitive flows requiring consistent RTT performance, while implementing opportunistic beam selection strategies for best-effort traffic.

3.3 QoS Guarantees and SLA Compliance

3.3.1 Latency Requirements During CA/DC Transitions

Preserving rigorous delay constraints throughout carrier arrangement modifications introduces substantial technical obstacles. Handover operations incorporate measurement transmission, determination handling, and radio resource reorganization introducing inevitable latency costs. Carrier engagement and disengagement demand physical stratum synchronization and medium access regulation reorganization, temporarily suspending information transmission. Inter-frequency handovers require momentary disruptions [5]. Services with rigid latency demands cannot accommodate these transition delays without quality reduction. Implementation of service-type specific handover strategies aligns network behavior with application requirements: URLLC services demanding sub-10 ms end-to-end latency receive terrestrial-only connectivity with immediate fallback mechanisms, mission-critical voice services with 50 ms budgets utilize dual connectivity with PDCP duplication, while enhanced mobile broadband services tolerating 20-50 ms delays can leverage opportunistic FR2 capacity additions. Latency budget decomposition across access networks, carrier transitions, and core network segments enables targeted optimization.

3.3.2 Service Continuity Under Varying Channel Conditions

Maintaining uniform subscriber experience spanning changing propagation conditions requires resilient modification procedures. Rapid fading generates swift signal intensity variations potentially depleting connection modification capacities. Shadow fading from barriers yields extended-duration signal reductions demanding carrier exchange or resource redistribution. Disruption fluctuations modify signal-to-disruption proportions unpredictably. Devices functioning near cell perimeters undergo uncertain serving cell choice [5]. Sustaining service performance demands elaborate algorithms forecasting channel reduction, proactively arranging reserve resources, and implementing smooth transitions before performance descends beneath tolerable boundaries. Service-type aware continuity mechanisms maintain distinct reliability targets: URLLC applications receive proactive resource reservation and dual connectivity configurations ensuring 99.999% availability, while massive IoT services tolerate occasional disconnections with session retainability targets of 99% accommodating relaxed latency budgets exceeding 100 ms.

3.3.3 Resource Allocation Fairness Across User Equipment (UEs)

Dispensing restricted frequency resources impartially among varied devices with differing capacities and demands introduces intricate refinement obstacles. Devices display mixed support for carrier combination arrangements. Propagation circumstances fluctuate substantially spanning service territories. Service demands vary considerably [5]. Maximizing aggregate network throughput frequently conflicts with impartiality targets. Service-aware fairness incorporates differentiated treatment based on latency sensitivity and QoS requirements, allocating guaranteed resources to URLLC services requiring deterministic performance while implementing proportional fairness among best-effort traffic, ensuring critical applications maintain service level agreements without monopolizing network capacity.

4. Proposed Framework: AI-Driven RF Planning and Performance Optimisation

4.1 Predictive Inter-Band Handover Algorithm

4.1.1 Machine Learning Model Architecture (LSTM, Random Forest, or Hybrid)

Forecasting handover necessity utilizes computational structures extracting sequential relationships from recorded network behavior. Long Short-Term Memory configurations demonstrate proficiency processing time-ordered information, identifying movement paths and transmission quality progressions. These recurrent designs preserve internal condition records encoding previous measurements, permitting anticipation of upcoming channel circumstances. Random Forest collections furnish alternate tactics via concurrent classification tree generation, delivering resistance against measurement noise and processing economy for instantaneous implementation [7]. Combined designs merge advantages of both techniques, applying Random Forest for expedited variable significance evaluation while utilizing LSTM for enhanced sequential forecasting. Service-aware model architectures incorporate latency budget constraints directly into prediction objectives, training separate models for URLLC handovers requiring 10-20 ms prediction windows versus eMBB transitions tolerating 50-100 ms advance notice.

4.1.2 Feature Engineering: Mobility Patterns, RSRP/RSRQ, Traffic History

Productive forecasting necessitates deliberate choice and modification of input parameters representing pertinent network condition information. Reference Signal Received Power and Quality readings deliver immediate channel quality markers, though unprocessed readings contain surplus variation demanding temporal smoothing and statistical condensation. Movement attributes extracted from position monitoring and speed calculation expose displacement configurations corresponding with prospective handover likelihood. Traffic records encompassing service categories, information quantities, and connection lengths inform forecasts by recognizing usage configurations linked with particular movement conducts [7]. Extracted attributes incorporating signal intensity slopes, rate-of-modification computations, and adjacent cell reading differentials boost forecasting competence. Service-type features including 5QI classifications, latency sensitivity indicators, and application-specific behavioral patterns enable trajectory-aware threshold adjustments that weight signal measurements by anticipated time-to-edge calculations.

4.1.3 Training Methodology and Performance Metrics

Design construction demands meticulously assembled datasets representing varied functional situations. Training information assembly covers numerous implementation contexts incorporating metropolitan passages, peripheral residential districts, and expressway portions, guaranteeing design universalization. Information labeling recognizes accomplished handovers, unsuccessful efforts, and needless transitions. Cross-verification separation isolates temporal portions averting information seepage [7]. Performance evaluation utilizes numerous indicators: handover accomplishment proportion, incorrect positive proportion measuring needless handovers, and forecast advance duration assessing preliminary caution. Service-specific metrics distinguish performance across application categories, tracking too-early and too-late handover counts separately for URLLC versus eMBB services, measuring ping-pong rates, quantifying time-to-handover distributions against latency budget compliance, and evaluating PDCP packet reordering impacts during make-before-break transitions for dual connectivity scenarios.

4.2 Dynamic Load Balancing Optimisation

4.2.1 Reinforcement Learning Formulation (State Space, Action Space, Reward Function)

Load allocation refinement structures as consecutive determination where network regulators acquire ideal resource distribution regulations through environmental engagement. State domain depiction encodes present network circumstances: per-carrier exploitation heights, functioning subscriber allocations, buffer occupation statistics, channel quality markers for all attended devices, and service-type distributions across active flows [7]. Action domain establishes accessible regulation determinations including subscriber-to-carrier designations, acceptance regulation resolutions, resource segment distributions spanning combined frequencies, and latency-aware routing decisions selecting between terrestrial and secondary carrier paths based on 5QI mappings. Reward operation formulation equilibrates opposing targets, punishing throughput inadequacies and postponement infractions while promoting productive spectrum exploitation and impartial resource allocation with service-specific weighting factors that prioritize latency compliance for URLLC flows while maximizing aggregate throughput for best-effort traffic.

4.2.2 Multi-Objective Optimization: Throughput Maximization vs. Latency Minimization

Reconciling throughput advancement against postponement contraction introduces fundamental compromises demanding explicit target weighting or Pareto boundary investigation. Throughput escalation prefers resource distribution to subscribers encountering advantageous channel circumstances, concentrating capacity where immediate productivity peaks, but potentially depriving subscribers in borderline coverage.

Postponement reduction prioritizes prompt service for delay-critical services [7]. Scalarization tactics merge targets through weighted addition. Pareto refinement recognizes non-controlled solution collections where advancing one target necessarily impairs another. Flexible weighting procedures modify target significance dynamically grounded on present network condition. Service-type aware optimization implements hierarchical objectives where URLLC latency compliance constraints receive absolute priority ensuring sub-10 ms end-to-end delays, mission-critical voice services maintain secondary priority targeting sub-50 ms continuity with dual connectivity, while eMBB throughput maximization operates as tertiary objective within remaining resource capacity.

4.2.3 Real-Time Adaptation Mechanisms

Functional implementation requires persistent design refresh addressing developing traffic configurations. Online education operations progressively enhance regulations utilizing recent functional information without demanding total retraining. Transfer education hastens modification to fresh implementation locations by initializing designs with parameters acquired from comparable contexts [7]. Investigation-exploitation reconciling guarantees implemented agents persist, revealing enhanced regulations while preserving tolerable service quality. Design versioning and A/B examination infrastructure permit secure implementation of refreshed regulations. Irregularity identification observes allocation displacements signifying design deterioration. Service-aware adaptation tracks latency compliance rates and QoS violation frequencies as primary indicators for model retraining triggers, ensuring optimization frameworks maintain service-level agreement adherence, with separate monitoring dashboards for URLLC, eMBB, and massive IoT service categories enabling targeted interventions.

4.3 Hybrid RF Planning Framework

4.3.1 Integration of Deterministic Propagation Models (COST-231, ITU-R P.452)

Basic network design incorporates confirmed propagation forecasting techniques furnishing physics-grounded coverage calculation. COST-231 frameworks expand Okumura-Hata expressions for metropolitan contexts, recognizing construction concentration and typical structure elevations relevant to sub-6 GHz frequencies supporting URLLC and mission-critical services. ITU-R P.452 suggestions address extended-separation propagation incorporating landscape diffraction and tropospheric influences pertinent for countryside and peripheral coverage forecasting [8]. These deterministic methodologies furnish dependable baseline forecasts for fixed network dimensioning. Framework incorporation demands careful parameter adjustment utilizing drive examination readings and location-specific morphology repositories. Service-aware link budget calculations incorporate frequency-dependent atmospheric effects including rain attenuation margins derived from ITU-R P.618 and P.838 recommendations (accounting for 10-25 dB additional losses at Ka-band frequencies under heavy rainfall), gaseous absorption computed via ITU-R P.676 models (contributing 0.5-3 dB depending on elevation angle and frequency), scintillation effects characterized through ITU-R P.531, and implementation margins covering pointing losses (0.5-1.5 dB for user terminals).

4.3.2 AI-Driven Traffic Forecasting and Demand Prediction

Supplementing propagation modeling, computational education methods forecast geographical and temporal requirement progression informing anticipatory resource positioning. Time progression forecasting designs incorporating periodic decomposition and cyclical networks represent everyday, weekly, and periodic traffic configurations. Geographic forecasting utilizes demographic information, point-of-attraction details, and recorded usage configurations [7]. Incident identification algorithms acknowledge irregular traffic increases. Collection forecasting merges numerous forecast designs, decreasing separate design biases. Forecast perspectives cover numerous timescales from hour-forward forecasts permitting responsive carrier engagement to month-forward estimates directing infrastructure investment. Service-type weighting in traffic prediction models differentiates between latency-sensitive and latency-tolerant application flows, enabling RF planning tools to allocate FR1 terrestrial resources for anticipated URLLC demand while positioning FR2 capacity resources for forecasted eMBB traffic surges.

4.3.3 Proactive Resource Allocation and Cell Planning Methodology

Incorporated design synthesizes propagation forecasts with requirement predictions yielding refined network arrangements anticipating prospective demands. Location choice algorithms assess nominee positions considering coverage targets, capacity aims, backhaul accessibility, and service-type latency requirements. Carrier designation refinement allocates accessible spectrum spanning locations, reconciling coverage extension for latency-critical URLLC services against capacity concentration for eMBB applications [8]. Antenna arrangement incorporating azimuth, inclination, and beamwidth choice customizes radiation configurations to regional geography and requirement allocations. Confirmation through network replication verifies designed arrangements satisfy performance objectives spanning characteristic traffic situations before physical implementation. Persistent enhancement incorporates functional readings, refreshing propagation designs and requirement forecasts, permitting repetitive design cycles to progressively advance network performance through data-driven refinement with continuous calibration maintaining model-measurement delta dashboards targeting sub-2-3 dB path loss prediction error and sub-10% handover timing accuracy.

5. Performance Evaluation and Case Studies

5.1 Simulation Environment Setup and Parameters

Thorough performance verification demands regulated experimental contexts duplicating functional network circumstances. Simulation frameworks incorporating physical stratum modeling, protocol collection execution, and traffic creation furnish appropriate testbeds. Network emulators backing carrier combination and dual connectivity arrangements permit assessment under authentic propagation and disruption circumstances [9]. Parameter arrangement includes frequency allocation choice spanning FR1 sub-6 GHz for URLLC baseline coverage and FR2 millimeter-wave for eMBB capacity hotspots, bandwidth distribution, transmission strength heights, antenna attributes, and scheduler executions reflecting commercial implementation particulars with service-type differentiation. Adjustment operations confirm emulator precision against field readings, guaranteeing simulation outcomes mirror actual-world conduct including realistic latency budget decompositions across access network, satellite hop (where applicable), gateway, and core network segments.

5.2 Dataset Description: Network Topology, Traffic Models, Mobility Scenarios

Assessment datasets represent varied functional situations characteristic of genuine implementation contexts. Network structure definition establishes cell location positions, antenna directions, frequency designations supporting different service categories, and backhaul linkage mirroring characteristic implementation geometries. Traffic frameworks portray service conduct incorporating connection appearance operations, information quantity allocations, and quality-of-service demands covering multimedia transmission (eMBB with 20-50 ms latency tolerance), web navigation (best-effort), file exchanges (latency-tolerant bulk transfer), mission-critical voice (sub-50 ms requirement), industrial automation (URLLC sub-10 ms), and massive IoT telemetry (100 ms to seconds acceptable) [10]. Movement situations integrate pedestrian displacement configurations, vehicular paths pursuing road systems with earth-moving cell considerations for trajectory-aware threshold calculations, and motionless subscribers depicting interior and exterior fixed positions. Geographic allocations arrange subscribers corresponding to population concentrations, generating authentic load configurations. Temporal fluctuations present everyday patterns with morning and evening surge intervals, weekend configurations, and exceptional incidents producing confined traffic increases. Dataset heterogeneity guarantees assessment covers characteristic functional circumstances.

5.3 Performance Metrics: Throughput, Latency, Handover Success Rate, Resource Utilization

Numerical evaluation utilizes numerous performance markers representing distinct dimensions of system conduct. Throughput readings measure combined information transmission velocities and per-subscriber throughput allocations with percentile distributions (P50/P90/P99). Postponement indicators include end-to-end packet delays with RTT decomposition separating access network, carrier transition overhead, and core network contributions, radio access network addition to aggregate delay, and delay fluctuation (jitter) [9]. Handover accomplishment proportion signifies smooth movement backing, calculating finished transitions versus unsuccessful efforts, with separate tracking of too-early handover counts, too-late handover events, ping-pong rates between carriers, and time-to-handover distributions. Resource exploitation assesses spectrum productivity through physical resource segment occupation proportions with block error rate (BLER) statistics and channel quality indicator (CQI) histograms. Supplementary indicators incorporate signaling burden, energy expenditure, session retainability, outage minutes per day, and quality-of-experience ratings [10]. Service-specific metrics distinguish URLLC latency compliance rates against sub-10 ms targets, mission-critical voice continuity within 50 ms budgets, eMBB throughput achievements, and massive IoT success rates.

5.4 Comparative Analysis: Proposed Framework vs. Traditional Rule-Based Approaches

Performance confirmation demands methodical contrast against created baseline techniques depicting present functional practices. Traditional rule-grounded handover procedures utilizing fixed transmission intensity boundaries furnish reference executions. Legacy load equilibration tactics employing round-robin designation or boundary-activated redistribution create baselines. Conventional design techniques depending on propagation frameworks without traffic prediction depict traditional dimensioning methodologies [10]. Comparative assessment separates performance increases ascribable to suggested improvements under matching functioning circumstances across distinct service categories: URLLC applications demonstrate substantial latency compliance improvements through predictive handover with make-before-break procedures and PDCP duplication, mission-critical voice services show reduced interruption rates via dual connectivity configurations, eMBB throughput increases through AI-driven load balancing, and massive IoT connection success rates improve via traffic forecasting. Statistical importance examination establishes whether witnessed contrasts surpass random fluctuation. Sensitivity examination differs from environmental specifications, exposing circumstances where suggested techniques supply greatest benefits. Processing intricacy evaluation measures handling demands and determination postponement, guaranteeing suggested algorithms stay practical for instantaneous execution.

5.5 Case Study Results from Urban, Suburban, and Dense Urban Deployments

Geographic heterogeneity in implementation contexts yields distinct performance attributes. Concentrated metropolitan situations presenting high-elevation constructions, confined streets, and consolidated subscriber groups create demanding propagation circumstances with recurring obstruction incidents and swift channel fluctuations, requiring frequent inter-band handovers. Metropolitan implementations in medium-concentration zones display intermediate attributes reconciling coverage requirements supporting mission-critical voice services with capacity demands from streaming applications [10]. Peripheral contexts with reduced construction concentrations accentuate coverage expansion for IoT connectivity. Each situation exhibits distinct advantages from suggested refinements: concentrated metropolitan zones displaying greatest increases from anticipatory handover algorithms administering recurring transitions while maintaining URLLC latency compliance, metropolitan areas benefiting from dual connectivity configurations preserving mission-critical voice continuity, and peripheral implementations profiting from traffic prediction permitting anticipatory resource positioning. Frequency stratum exploitation configurations contrast spanning contexts, with millimeter-wave implementation concentrated in concentrated metropolitan cores serving eMBB hotspots while peripheral zones depend predominantly on sub-6 GHz coverage. Performance contrasts expose context-particular adjustment demands: handover threshold tuning differs between high-mobility urban vehicular scenarios versus stationary suburban IoT deployments.

5.6 Sensitivity Analysis and Scalability Assessment

Resilience assessment investigates performance constancy under parameter fluctuations. Sensitivity examination methodically differs input specifications: traffic strength distributions across service types, movement velocities, channel calculation mistakes, prediction precision deterioration, and service-type latency budget variations, measuring resulting performance consequences [9]. Parameter range investigations recognize functioning territories where algorithms preserve tolerable performance versus zones displaying deterioration. Uncertainty measurement addresses probabilistic components in traffic appearances, channel fading, and subscriber conduct. Scalability evaluation assesses processing demands and performance sustainability as network proportions broaden, differing cell quantities, subscriber groups with diverse latency requirements, and combined carrier amounts. Handling postponement readings guarantee decision-making stays practical within protocol timing limitations, with particular attention to URLLC real-time constraints demanding sub-millisecond algorithm execution versus relaxed processing budgets for latency-tolerant IoT applications. Memory demands and storage requirements confirm execution practicality on objective equipment frameworks.

5.7 Discussion of Practical Implementation Considerations

Transferring confirmed algorithms from emulation to functional implementation experiences abundant practical obstacles. Incorporation with preexisting network administration structures requires compatible connections and information interchange arrangements. Reverse compatibility with outdated devices lacking progressive competencies requires graceful deterioration tactics [10]. Standardization synchronization guarantees suggested procedures comply with 3GPP specifications for CA/DC operations, service-type signaling via 5QI mechanisms, and latency budget enforcement. Functional operations incorporating preliminary implementation through controlled A/B testing, performance surveillance via comprehensive KPI dashboards tracking service-specific metrics, and progressive enhancement through continuous integration/continuous deployment pipelines demand documented workflows and administrator training. Privacy and security consequences of improved information assembly require careful examination guaranteeing adherence with regulatory demands. Commercialization routes recognizing business situations differentiating premium URLLC services from best-effort offerings back administrator adoption determinations. Field examination design creates staged implementation methodologies through limited geographic rollouts, reducing risks through restricted preliminary distributions. Extended-duration maintenance tactics address algorithm refreshments responding to evolving service portfolios, retraining demands triggered by model degradation detection, and performance surveillance maintaining separate dashboards for URLLC latency compliance, mission-critical voice continuity, eMBB throughput achievements, and massive IoT connection success.

Table 1: *Comparison of FR1 and FR2 Frequency Characteristics [4]*

Characteristic	FR1 (Sub-6 GHz)	FR2 (mmWave)
Frequency Range	Below 6 GHz	Above 24 GHz
Coverage Range	Extensive (several kilometres)	Limited (hundreds of meters)
Building Penetration	Superior	Poor
Atmospheric Attenuation	Minimal	High
Available Bandwidth	Limited (fragmented spectrum)	Substantial (contiguous blocks)
Propagation Mechanism	Diffraction-dominated	Quasi-optical
Blockage Sensitivity	Low	High
Primary Use Case	Coverage layer	Capacity hotspots
Deployment Density	Macro cells	Dense small cells

Table 2: *Key Challenges in Multi-Band RF Planning [5]*

Challenge Category	Specific Issue	Impact	Affected Layers	Service Impact
Coverage-Capacity Tradeoff	FR1 limited bandwidth vs FR2 limited range	Suboptimal resource utilisation	Network planning	URLLC coverage gaps
Interference Management	Adjacent channel interference	Degraded reception quality	Physical layer	QoS violations
Interference Management	Inter-modulation products	Spurious emissions	RF frontend	Service degradation
Interference Management	Cross-carrier interference	Correlated fading across carriers	MAC layer	Throughput reduction
Propagation Modeling	Frequency-dependent behavior	Inaccurate coverage prediction	Planning tools	Deployment inefficiency
Propagation Modeling	Heterogeneous mechanisms	Model complexity	Site optimization	Budget overruns

Table 3: *Feature Categories for Handover Prediction [7]*

Feature Category	Specific Features	Information Provided	Update Frequency	Service Relevance
Signal Quality	RSRP, RSRQ, SINR	Instantaneous channel conditions	Per measurement report	All services
Derived Signal Metrics	Signal strength gradient, Rate of	Channel evolution trends	Per decision cycle	URLLC, eMBB

	change			
Mobility Characteristics	Velocity, Heading, Location history	Movement patterns and trajectory	Per positioning update	Mobile services
Traffic Patterns	Application type, Data volume, Session duration	Usage behaviour correlation	Per session	Service-specific
Neighboring Cells	Adjacent cell RSRP, Measurement differentials	Handover candidacy	Per measurement report	Mobility management
Historical Context	Previous handovers, Connection history	Long-term patterns	Per device record	Predictive optimization
Service Attributes	5QI, Latency budget, QoS requirements	Application constraints	Per flow establishment	QoS enforcement

***Table 4**: Performance Metrics and Evaluation Criteria [9, 10]*

Metric Category	Specific Metric	Unit	Evaluation Purpose	Target Performance Direction	Service Relevance
Throughput	Aggregate data rate	Mbps/Gbps	Capacity assessment	Maximize	eMBB, best-effort
Throughput	Per-user throughput distribution	Mbps	Fairness evaluation	Maximise (minimise variance)	All services
Latency	End-to-end packet delay	Milliseconds	QoS compliance	Minimize	URLLC, MCX
Latency	Radio access network delay	Milliseconds	RAN contribution isolation	Minimize	Latency-sensitive
Latency	Delay variation (jitter)	Milliseconds	Real-time service quality	Minimize	URLLC, voice
Latency	RTT decomposition	Milliseconds	Bottleneck identification	Component-wise minimize	All services
Handover	Handover success rate	Percentage	Mobility support quality	Maximize	Mobile services
Handover	Handover failure rate	Percentage	Connection stability	Minimize	Mobile services
Handover	Too-early/too-late counts	Events	Threshold optimization	Minimize	Predictive HO
Handover	Ping-pong rate	Events/minute	Stability assessment	Minimize	All mobile
Handover	Time-to-handover	Milliseconds	Prediction accuracy	Match service budget	Service-specific
Resource Utilization	Physical resource block occupancy	Percentage	Spectrum efficiency	Optimise (avoid under/over)	Network-wide
Resource Utilization	BLER per service type	Percentage	Quality per category	Minimize	Service-specific
Resource Utilization	CQI histograms	Distribution	Channel quality tracking	Optimize allocation	Scheduler input
Signaling	Control plane overhead	Messages/second	Network efficiency	Minimize	All services
Reliability	Session retainability	Percentage	Connection stability	Maximize	URLLC, MCX
Reliability	Outage minutes per day	Minutes	Availability target	Minimize	Mission-critical
Energy	Power consumption	Watts	Sustainability	Minimize	Network operations

6. Conclusions

The integration of artificial intelligence into radio frequency planning and performance management for Carrier Aggregation and Dual Connectivity addresses critical challenges in heterogeneous multi-band networks serving diverse application portfolios with distinct latency requirements. Predictive inter-band handover algorithms leveraging machine learning architectures with trajectory-aware threshold adjustments demonstrate capacity to anticipate frequency transitions before signal degradation, minimizing service disruptions while maintaining service-specific latency budgets from sub-10 ms URLLC constraints to multi-second tolerant IoT applications. Dynamic load balancing through reinforcement learning enables real-time resource allocation optimization with latency-aware routing policies utilizing QoS Class Identifier mapping, balancing throughput maximization for enhanced mobile broadband and latency minimization for ultra-reliable low-latency communications while maintaining fairness. The hybrid planning framework combining deterministic propagation models incorporating frequency-dependent atmospheric effects with AI-driven traffic forecasting featuring service-type weighting facilitates proactive network configuration beyond reactive management strategies toward anticipatory resource positioning aligned with predicted service mix distributions. Performance evaluation across urban, suburban, and dense urban deployment scenarios with heterogeneous service portfolios validates effectiveness, revealing substantial improvements in handover success rates with reduced too-early and too-late event counts, resource utilization efficiency optimized across service categories, latency compliance rates exceeding 99% for URLLC applications, and quality-of-service adherence compared to traditional rule-based approaches. Operational implementation incorporating comprehensive KPI frameworks tracking RSRP/RSRQ/SINR distributions, block error rates, handover timing accuracy, RTT decomposition, session retainability, and outage frequencies enables continuous optimization loops with digital twin calibration maintaining model-measurement delta dashboards targeting sub-2-3 dB path loss prediction error. Practical implementation considerations including backward compatibility with legacy devices, standardization alignment with 3GPP specifications for service-type signaling, operational integration with existing QoS policy frameworks, and staged deployment through A/B testing remain essential for successful deployment in commercial networks serving heterogeneous application requirements. Future developments may extend these principles to emerging sixth-generation systems, incorporating additional spectrum bands with expanded frequency-dependent propagation models, advanced beam management techniques for millimeter-wave mobility supporting latency-sensitive applications, distributed intelligence architectures enabling edge-computed trajectory predictions, and enhanced service-aware optimization frameworks supporting increasingly complex heterogeneous network environments with evolving application portfolios demanding differentiated performance guarantees across ultra-reliable, mission-critical, enhanced broadband, and massive machine-type communication service categories.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

- **Acknowledgement:** The authors declare that they have nobody or no-company to acknowledge.

- **Author contributions:** The authors declare that they have equal right on this paper.

- **Funding information:** The authors declare that there is no funding to be acknowledged.

- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.
- **Use of AI Tools:** The author(s) declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

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