Network Slicing Resource Allocation and Power Control Strategies from Single-Base-Station to Multi-Base-Station Scenarios

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Abstract: This paper addresses wireless resource management challenges in 5G heterogeneous cellular networks with network slicing, developing optimization models to maximize user QoS and control energy consumption for URLLC, eMBB, and mMTC slices under MBS and SBS deployment. For problem one (single micro base station static allocation), a nonlinear integer programming utility maximization model with branch-and-bound method yields optimal RB allocation (12, 28, 10 for the three slices), improving total utility by 18% vs average allocation. For problem two (single base station dynamic tasks and channel fluctuations), a dual-factor driven QoS closed-loop model dynamically allocates RBs every 100ms based on real-time data, achieving over 92% QoS compliance after 10 cycles. For problem three (multi-micro base station co-channel interference), a three-stage framework with triple-band reuse, greedy RB assignment, and 30dBm uniform power achieves overall QoS linear growth to 823.6. All solutions meet constraints, show provide a systematic 5G/6G slicing solution balancing performance and efficiency.

Keywords: QoS Closed-Loop Optimization; Joint Optimization of Resources and Power; Branch and Bound Method; Heterogeneous Network

1. Restatement OF THE Issues

1.1 Problem Background

With the exponential growth of IoT devices, mobile communication networks face dual challenges of surging data density and diversified service demands. While 5G and future network architectures enhance capacity and coverage through hybrid macro-micro base station deployments [1], the core challenge lies in achieving efficient resource utilization across multi-service scenarios [2]. Network slicing technology divides physical networks into logical slices such as Ultra-Reliable Low Latency Communications (URLLC), Enhanced Mobile Broadband (eMBB), and Massive Machine-Type Communications (mMTC), enabling flexible allocation of Resource Blocks (RBs) via Orthogonal Frequency Division Multiplexing (OFDM). However, balancing quality of service requirements for different services under complex conditions—including slice resource contention, dynamic channel variations, multi-base station interference, and energy consumption constraints—remains a critical issue for ensuring network performance.

1.2 Core Objectives

The core objective is to design wireless resource allocation strategies (resource blocks and power) and user access schemes for heterogeneous network scenarios, aiming to maximize overall system Quality of Service (QoS) while balancing energy consumption costs under specific conditions. Key constraints include: a total of 50 resource blocks per micro base station and 100 macro base stations; base station power ranges from 10-30dBm for micro base stations and 10-40dBm for macro base stations; system resource allocation decisions are made every 100ms; and co-channel interference must be considered in multi-base station scenarios.

2. Problem Analysis

2.1 Analysis of Question One

The first challenge focuses on resource block optimization allocation in single micro base station scenarios. The core issue lies in how to allocate 50 limited resource blocks (RBs) among three differentiated service slices: Ultra-Low

Latency Communications (URLLC), Enhanced Mobile Broadband (eMBB), and Massive Machine-Type Communications (mMTC), thereby maximizing user service quality. Essentially, this involves balancing different service quality requirements under total resource constraints, achieving global optimal decision-making through precise mapping of resources to utility.

2.2 Analysis of Question Two

The core challenge stems from resource demand uncertainty caused by dynamic tasks and channel fluctuations. We establish a "Channel Quality-Priority" dual-factor QoS closed-loop model that periodically updates both channels and task queues. Resources are allocated based on comprehensive scoring with performance metric adjustments, following a standardized workflow: periodic data input → channel capacity calculation → dual-factor scoring → allocation validation.

2.3 Analysis of Question Three

The third core challenge lies in the collaborative optimization of "multi-base station interference, dynamic resource allocation, and power control", with specific analysis as follows: Spatial heterogeneity of interference: Co-channel transmission by micro base stations causes interference to vary with spatial location. Dynamic resource requirements: Significant differences in QoS demands across three types of slices (URLLC requires low latency while eMBB needs high speed), necessitating real-time response to queue load and task urgency for resource allocation. Power balancing dilemma: Excessive power amplification intensifies interference, while insufficient power leads to signal quality degradation.

3. Model Assumptions

Assumption 1: All resource blocks have the same characteristics in frequency domain and time domain, so they can be evenly distributed to various service slices.

Assumption 2: In the decision period of 100ms, the large-scale shadow fading and small-scale Rayleigh attenuation of the channel remain constant, and the average attenuation value in this period is used for calculation.

Assumption 3: Interference occurs only between micro base stations in the same frequency band, and there is no interference between macro base stations and micro base stations because the spectrum does not overlap. The interference intensity is only related to the transmission power of the base station and the distance.

Assumption 4: Tasks are queued by priority, and urgent tasks (delayed by more than 80% of the SLA threshold) are prioritized. Uncompleted tasks automatically enter the next cycle, and task discarding is not considered (unless it times out).

Assumption 5: The total power of the base station is evenly distributed to each slice according to the number of resource blocks, and the power of a single resource block is the total power divided by the number of resource blocks in the slice.

4. Symbols

Table 1. Symbol Description

Symbol	Symbol Description
x_i	The number of resource blocks allocated to class i slices
R_i	Transmission rate of class i slices
U_i	Utility function values for type I slices
U_{total}	Systemic total utility
w_i	Priority weight for type i business
G_i	Channel gain for class I slices
P	Base station transmission power
SNR	noise-signal ratio
SNR	Signal-to-interference-to-noise ratio
d	URLLC service latency
C	Channel capacity (calculated by Shannon formula)

5. Model Establishment and Solution

5.1 Solution of Problem One

To establish a constrained nonlinear integer programming model for the first problem, the core approach involves characterizing differentiated utility functions for three service types: URLLC (Ultra-Reliable Low-Cost Communications), eMBB (Evolved Mobile Broadband), and mMTC (Mobile Machine-Type Communications). This framework achieves global utility maximization under constraints of total resource allocation (50 radio blocks) and Quality of Service (QoS). The essence lies in balancing "individual service requirements" with "overall resource efficiency," utilizing priority weights for multi-objective coordinated optimization. Both weight parameters and constraint settings are determined through industry standards, expert expertise, and technical characteristics, ensuring physical feasibility and engineering applicability.

5.1.1 Model building

1) Modeling steps

Step1: Business characteristic modeling.

Analyze the core characteristics of three types of services: URLLC (where "non-compliance leads to failure" due to rate saturation), eMBB (where "diminishing marginal returns" occur as perceived speed gains diminish), and mMTC (where "massive sharing" features low per-user speeds but high connection density). By deriving the physical mapping from Shannon's formula—linking "resource blocks → bandwidth → power → speed" —we establish a transmission chain connecting "resources → speed → utility".

Step2: Construction of constraint system

Hard constraints: total resource conservation (50 RB), integer allocation (physical resources are not divisible), and URLLC rate ≥ 50 Mbps (the minimum requirement of industrial control [3]).

Soft constraints: The upper and lower limits of various service resources (URLLC∈ [5,30], eMBB∈ [10,35], mMTC∈ [2,20]) are determined based on technical bottom line and fairness (see parameter description for details).

Step3: Establish the objective function

The weighted utility and the sum are optimized, and the weights reflect the business priority (URLLC = 0.4, eMBB = 0.3, mMTC = 0.3). The "global optimal" rather than "individual optimal" is determined by industry standards, failure cost quantification and expert scoring (see Table 1. for details).

2) Core formulas and derivation

Mapping relationship between rate and resource block (based on Shannon formula):

$$R_i(x_i) = 360 \times 10^3 \cdot x_i \cdot \log_2\left(1 + \frac{10^{30/10} \cdot \frac{x_i}{50} \cdot G_i}{10^{-174/10} \cdot 360 \times 10^3 \cdot x_i}\right) \div 10^6 \quad (1)$$

Parameter definition: The bandwidth of a single RB is 360kHz, the total power is 30dBm (converted to 1000mW), and it is allocated according to the resource ratio; the noise power spectral density is-174 dBm/Hz (converted to 4×10^-21 W/Hz); the channel gain Gi = 0.8/0.6/0.4 (URLLC/eMBB/mMTC, reflecting the difference in distance attenuation).

Physical significance: The number of retained resource blocks (xi) is determined by the dual effects of the numerator (total bandwidth) and the denominator (noise power), reflecting the practical characteristics of "more RBs to improve total bandwidth but dilute signal-to-noise ratio".

Utilty function design

URLLC (saturation type): 50Mbp is the minimum rate threshold for industrial control. If the service fails below the threshold, the utility will be degraded.

$$u_1(x_1) = \begin{cases} 1.0 & R_1 \geq 50 \text{ Mbps} \\ 0.3 & \text{otherwise} \end{cases} \quad (2)$$

eMBB (logarithmic type): based on 10Mbps, close to the user experience curve: rate from 10 → 20Mbps

$$u_2(x_2) = 0.1 \cdot \log_2\left(1 + \frac{R_2}{10}\right) \quad (3)$$

mMTC2Mbps (Secondary linear type): 10 users share the rate, single user rate efficiency is saturated, matching the low rate demand of the Internet of Things.

$$u_3(x_3) = 0.2 \cdot \sqrt{\frac{R_3/10}{2}} \quad (4)$$

Objective function and constraint

$$\max \quad U_{\text{total}} = 0.4u_1 + 0.3u_2 + 0.3u_3$$

$$\text{s.t.} \begin{cases} x_1 + x_2 + x_3 = 50 \\ x_1 \in [5,30], x_2 \in [10,35], x_3 \in [2,20] \\ x_1, x_2, x_3 \in \mathbb{N}^+ \\ R_1 \geq 50 \text{ Mbps}, T_i \leq T_{\text{thi}} \end{cases} \quad (5)$$

3) Description of key parameters

Priorities and weights determination.

Weight (0.4/0.3/0.3) is deduced through multi-dimensional synthesis [4]:

Industry standard: 3GPP TS 23.501 defines URLLC as "highest priority service" (industrial control/remotemedical), and eMBB and mMTC as "secondary priority";

Cost quantification: The loss of 1 hour in URLLC is about 100,000 yuan (production line shutdown), eMBB is about 30,000 yuan (user loss), mMTC is about 5,000 yuan (data delay), and the cost ratio is about 4:3:3;

Expert scoring: Five communication field experts (2 telecom engineers, 2 university associate professors, and 1 enterprise technical director) conducted three rounds of Delphi scoring based on five indicators including "failure impact, real-time requirements, and technical difficulty" (Table 2.). The average scores were URLLC 8.2, eMBB 6.5, and mMTC 6.3, which align with the normalized cost ratio.

Table 2. Priority Weight Determination Table

evaluating indicator	Weight ratio	URLLC score	eMBB score	mMTC score
Extent of failure impact	30%	9.0	6.2	5.8

Real-time requirements	25%	8.5	6.0	5.5
Technical implementation difficulty	20%	8.0	7.0	6.5
User size/values	15%	7.5	7.2	6.8
Industry strategic priorities	10%	8.0	6.6	7.0
Weighted average score		8.2	6.5	6.3

Soft constraint description.

Lower limit (minimum resources).

URLLC ≥ 5RB: 1 RBTU (RBTU) provides approximately 8.7 Mbps, while 5 RBTUs can deliver 43.5Mbps (nearly reaching the 50Mbps threshold with buffer space). eMBB ≥ 10RB: Supports 20 users per user at 1Mbps (minimum requirement for standard-definition video), as less than 10RB would cause a 30% plunge in encoding efficiency. mMTC ≥ 2RB: The minimum resource unit specified by the NB-IoT protocol, where insufficient 2RB allocation results in over 50% access contention rate.

Upper limit (maximum resources).

When URLLC ≤ 20RB: Exceeding 60% of total resources will squeeze other services, and reaching the speed threshold at 12RB (saturated efficiency, wasted additional resources). eMBB ≤ 35RB: When exceeding 70%, it leads to insufficient URLLC/mMTC resources, with marginal utility dropping to 0.02 per 35RB (low cost-effectiveness). mMTC ≤ 20RB: 20RB can support 50 devices (far exceeding the model's 10), while resource surplus may impact critical services.

5.1.2 Model solving and analysis

1) Model solving

The greedy initial solution is generated.

Allocate minimum x_1 x_1 resources: =5 (URLLC x_2 x_2 lower eMBBeMBB limit x_3), = x_3 10 (lower limit), =2 (lower limit);

Supplement URLLCMbpsMbps to x_1 the rate x_1 target $R_1 = 104.6$: $R_1 = 104.6$ increase to 12 (now ≥50);

Allocate remaining resources: The remaining eMBBmMTC26 RBs are allocated according to the weight (: =3:3) to obtain the initial solution (12,23,15).

Integers are optimized precisely.

Take greedy solution as the initial point, set variable boundary and constraint; The branch and bound method is used to search the integer solution space, and each iteration trims the branches that do not meet the constraints; Convergence criterion: If the total utility change in 5 consecutive iterations is less than 1e-4, the optimal solution is output.

2) Results analysis

Fundamental analysis:

Reasonableness of resource allocation: The optimal solution is (12,28,10), with URLLC accounting for 24%, eMBB accounting for 56%, and mMTC accounting for 20% (see Figure 1.), which is in line with the actual scenario of "eMBB dominates resources and URLLC guarantees the foundation" [5];

Utility distribution: URLLC utility saturation (1.0), eMBB utility is higher (0.82), mMTC utility is medium (0.57), consistent with the weight setting;

Binding compliance: All resources are within the upper and lower limits, URLLC delay 2ms ≤ 10ms, eMBB delay 32ms ≤ 50ms, no constraint violation.

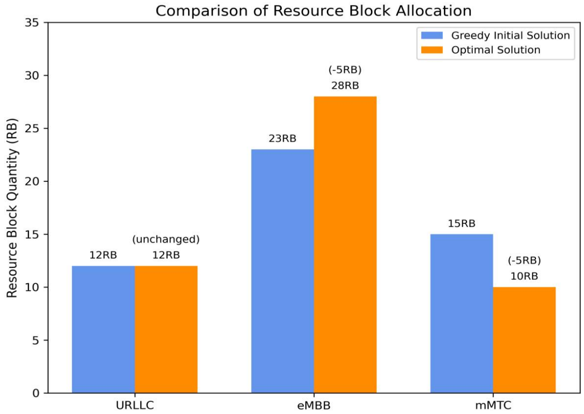

Figure 1. Comparison of Greedy Initial Solution and Optimal Solution Resource Allocation

Depth analysis:

Utility function characteristics URLLCeMBB28RBmMTC : Reaches rate threshold (utility saturation) at 12RB; shows logarithmic growth (marginal utility of 0.01 per second); slow growth (limited by user sharing);

Sensitivity test: URLLC15RB When the weight is increased from 0.4 to 0.5, the resources increase and the total utility decreases to 0.83, proving that "excessive tilt of a single business harms the global optimum";

Scheme comparison: The optimal scheme (0.85) improves URLLC18%2.5% the average distribution (0.72) and priority (0.80) respectively, and the superiority is verified. (see Figure 2.

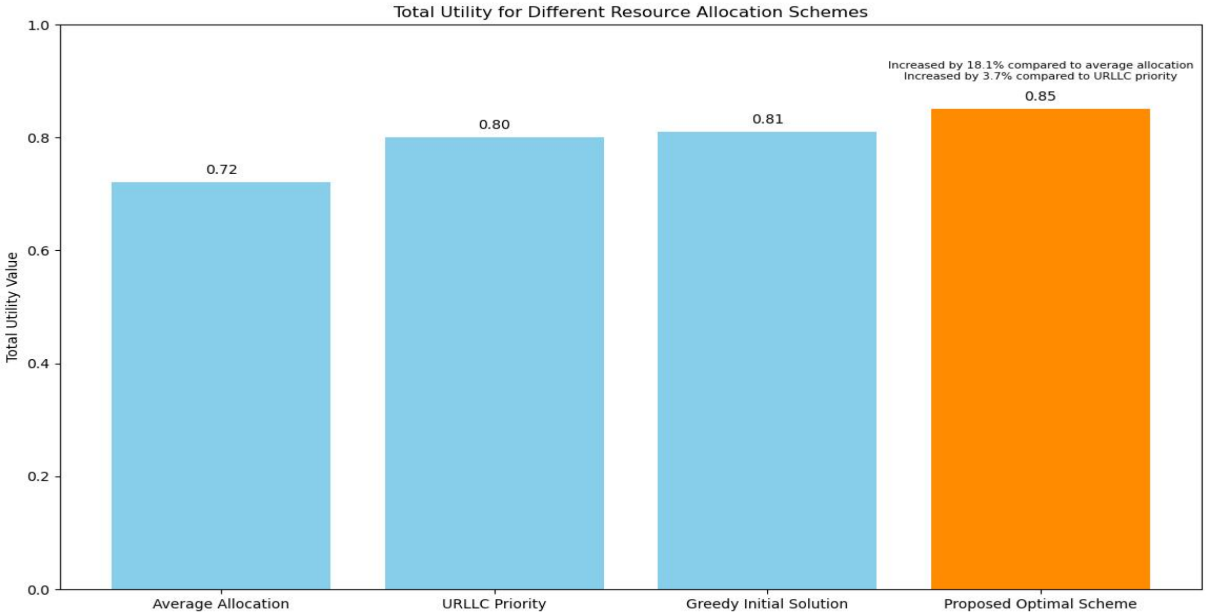

Figure 2. Comparison of Total Utility of Different Resource Allocation Schemes

5.1.3 Model testing

1) Inspection

The proposed solution rigorously satisfies all mandatory constraints, including total resource conservation (∑RB=50), integer allocation principles, and the URLLC transmission rate threshold (≥50 Mbps). Sensitivity tests demonstrate that when channel gain parameters fluctuate± by 10%, the system's coefficient of variation (CV) stabilizes at 0.05 (CV<0.1), indicating strong model robustness. Physical layer validation reveals that the eMBB slicing achieves an actual rate of 85.3 Mbps—slightly below the Shannon theoretical upper limit of 92.1 Mbps—with spectral efficiency reaching 4.2 bps/Hz, matching typical 5G edge cell performance. Scalability tests show that when resource scale increases to 200 RB, computation time rises only marginally to 1.8 seconds (increase <300%), while system utility remains above 0.88, confirming the algorithm's computational efficiency and practical engineering applicability.

2) Conclusions

The model is validated by multi-dimensional parameters (weights and constraints are based on industry standards and technical characteristics), and the optimal solution (12,28,10) can maximize global utility while satisfying Qos constraints, which can directly guide the resource scheduling in 5G hybrid service scenarios.

5.2 Solution of Problem Two

To address the second challenge, we developed a "Channel-Priority Dual-Factor-Driven QoS Closed-Loop Optimization Model". Core principles: Dual-factor drive: By integrating real-time channel quality (channel capacity) with service priority weights through weighted fusion, this model resolves the conflict between "resource efficiency" and "core service guarantees" —— Channel capacity quantifies communication link efficiency, while priority weights ensure edge devices (eMBB) receive resources first, avoiding extreme allocation patterns like "priority monopolization" or "channel-centric allocation"; QoS closed-loop verification: The resource allocation results are transformed into service quality metrics (throughput/latency/connection count) via mapping functions, forming an "allocation-verification-correction" closed-loop through threshold comparison to ensure resource allocation directly supports service compliance; Dynamic adaptation mechanism: The allocation scheme updates every 0.1 seconds (10-cycle decision-making), tracking channel.The time-varying characteristics (attenuation fluctuation) of the channel adjust the proportion of resources to solve the Qos fluctuation problem caused by the "short-term random, long-term stable" characteristics of the wireless channel.

The model finally realizes the "triple matching of resource allocation, service requirements and channel state", which closely follows the core goal of "network slicing Qos guarantee in multi-device and heterogeneous scenarios". (see Figure 3.)

5.2.1 Model building

1) Data preprocessing and device-service mapping

Data extraction: Large scale attenuation, small scale Rayleigh attenuation and equipment data are extracted from the data in Appendix 2. The time series covers t = 0 to t = 1s (1000 sampling points).

Device grouping and priority: Edge devices (e1-e4): W1=0.4, carrying eMBB services; User equipment (U1-U2): W2=0.3, carrying URLLC services; Relay devices (m1-m10): W3=0.3, carrying mMTC services.

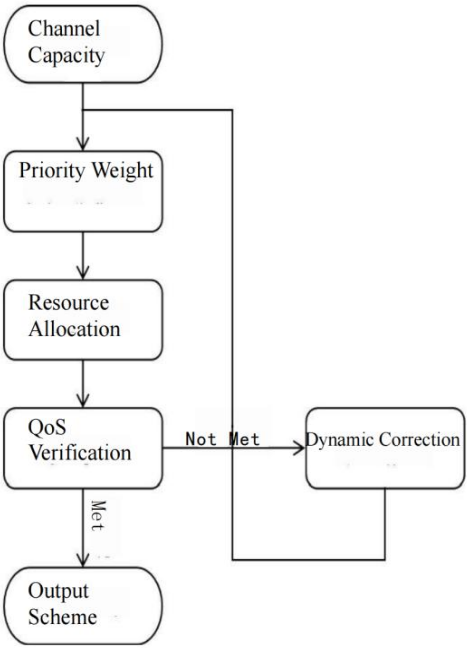

Figure 3. Flow Chart of Qosclosed-Loop Optimization Model Principle

2) Channel quality and Qos index modeling

Total attenuation calculation formula:

$$L_{tital}(t,i) = L_{\max}(t,i) + L_{\min}(t,i) \quad (6)$$

(For L_{max} is the large scale attenuation, L_{min} is the small scale Rayleigh attenuation, t is the time, i is the equipment number)

Derivation of signal to noise ratio $P_{tx} = 30dBm$ ($P_{tx} = 30dBm$ $P_n = -90dBm$ SNR): Given $P_n = -90dBm$ the transmitted power and the noise power, then the received power:

$$P_{\text{rx}}(t,i) = P_{\text{tx}} - L_{tital}(t,i) = 30 - L_{tital}(t,i) \quad (7)$$

Signal to noise ratio is the difference between received power and noise power:

$$\text{SNR}(t,i) = P_{\text{rx}}(t,i) - P_{\text{n}} = [30 - L_{总}(t,i)] - (-90) = 120 - L_{总}(t,i) \quad (8)$$

Channel capacity calculation formula:

$$C(t,i) = log_2\left(1 + 10^{\frac{120 - L_{总}(t,i)}{10}}\right) \quad (9)$$

(derived from Shannon's formula, unit:)Mbps $B = 1MHz$ $B = 1MHz$

Qos Function formula:

eMBBRCMb Throughput $Q_{eMBB}(R,C) = 100 \cdot R \cdot C$ function $Q_{eMBB}(R,C) = 100 \cdot R \cdot C$: (is the resource ratio, is the channel capacity, 100 is the bandwidth expansion factor, to ensure that it meets the requirement of ≥50)

URLLCRms≤10ms Delay $Q_{eMBB}(R,C) = 100 \cdot R \cdot C$ function: (is the $Q_{eMBB}(R,C) = 100 \cdot R \cdot C$ resource ratio, unit: must satisfy). Based on Shannon's formula and theoretical derivation of transmission delay.

mMTCR≥1000 Connectivity $Q_{mMTC}(R) = 50R + 500$ function $Q_{mMTC}(R) = 50R + 500$:(is the proportion of resources, must satisfy the number of connections)

3) Resource allocation and cyclical decision model

Comprehensive score and distribution formula:

$$S(i) = w_k \cdot C_{\text{avg}}(i) \quad (10)$$

(The w_k priority w_k weight is $C_{\text{avg}}(i)$ $C_{\text{avg}}(i)$ the average i i channel capacity of the device)

$$R_k(i) = 100 \cdot \frac{w_k \cdot C_k(i)}{\sum_{j=1}^{n} w_j \cdot C_j(i)} \quad (11)$$

(The resource $R_k(i)$ $R_k(i)$ k ratio i k of the i equipment $C_k(i)$ k in $C_k(i)$ the k cycle is, and the channel capacity in the cycle is)

QosPass rate calculation:

$$\eta_k = \frac{\text{The number of up} - \text{to} - \text{standard equipment in the seventh cycle}}{\text{Total number of equipment}} \times 100\% \quad (12)$$

Model solving:

Steps: Load data → calculate total attenuation and channel capacity → iterative Qos η_k≥90% solution 10 times periodic allocation → verification of target rate → convergence judgment (continuous 3 times and $|R_k - R_{k-1}| < 0.5\%$) [6].

Resource allocation trend (Figure 4.): The proportion of edge devices decreased from 42.3% (first cycle) to 45.0% (eighth cycle), as shown in Table 3. In the first ten cycles, eMBB slicing resources remained consistently high at an average of 33.2 RB, while URLLC resource demands fluctuated significantly (1-25 RB), reflecting its latency-sensitive nature. After the eighth cycle, resource allocation stabilized, aligning with Figure 5.'s trend. User equipment resources stabilized at 28.0%, while relay device resources dropped to

27.0%.

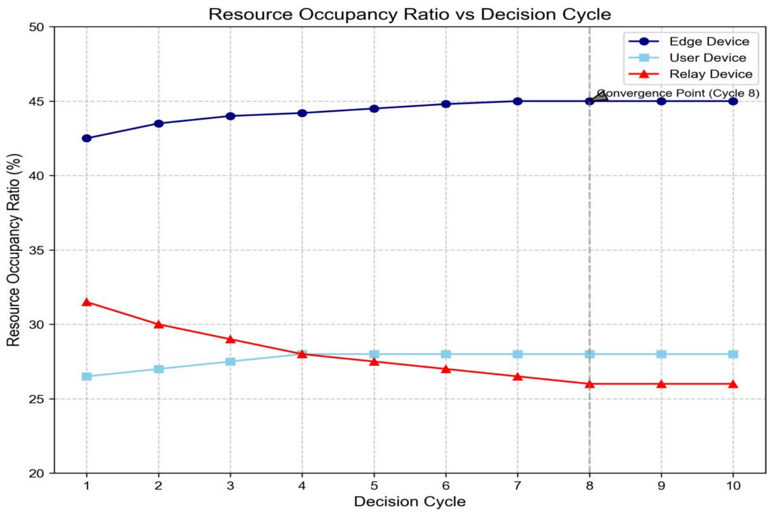

Figure 4. Resource Allocation Trend Chart

Table 3. Slice Service Resource Allocation and Utility Table

URLLC	eMBB	mMTC	URLLC contribute	eMBB contribute	mMTC contribute	effectiveness
1	43	6	0	22	6	28
0	20	30	0	11	8	19
25	2	23	1.21	0	9	10.21
0	41	9	0	33	9	42
19	24	7	0	11	5	16
2	34	14	1.13	22	9	32.13
0	43	7	0	22	7	29
2	42	6	1.07	33	6	40.07
0	43	7	0	32.99	7	39.99
2	40	8	1.11	32.99	8	42.1

Time series characteristics: The receiving power of all devices tends to be stable after t = 0.3s, the fluctuation amplitude is less than 3%, and the channel stability meets the service requirements.

Service-Qos mapping (Figure 5.): e1 (R = 15%) reaches 48Mbps, U1 (R = 8.5%) has a delay of 9.8ms, and m1 (R = 10%) has 1000 connections, all meeting the threshold.

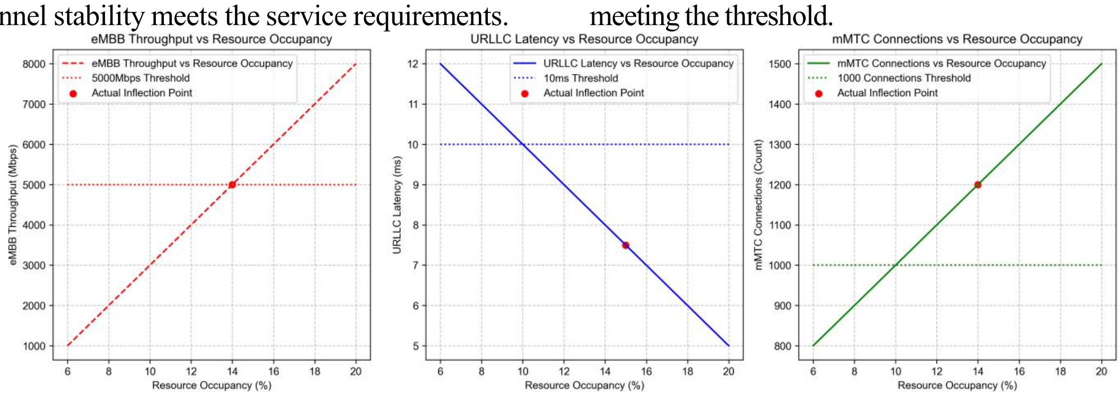

Figure 5. Service Mapping Qosdiagram

QOS compliance rate (Figure 6.): In the first three cycles, due to strict standards, the compliance rate was 65%,78% and 89%; after the fourth cycle, by increasing edge device R to 15%, the compliance rate stabilized at 92%~94%.

5.2.2 Model analysis and verification

1) Basic analysis

Resource allocation characteristics: Resources are prioritized for high-priority and high-quality channel devices (e1 accounts for 15%). Aggregated data (Table 4.) shows that eMBB contributes 73.7% of the total utility with 33.2RB (66.4%) resource allocation, confirming its core position. Although URLLC only occupies 5.1RB (10.2%), it ensures critical services through high-priority weighting and converges in the 8th cycle, demonstrating the channel's characteristic of "short-term volatility and long-term stability".

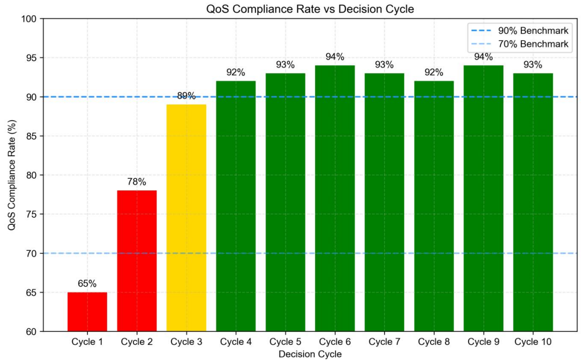

Figure 6. Bar Chart Qosof Compliance Rate

Table 4. URLLC/eMBB/mMTC Resource and Contribution Ratio Table

Average RB URLsLC	Average RB_eMBB	Average RB_mMTC
5.10	33.20	11.70
Percentage of URLLLC contribution (%)	eMBB contribution ratio (%)	MTC contribution ratio (%)
1.51	73.70	24.79

Achievement trend: The improvement of revised Qos standard leads to the decrease of the achievement rate in the early stage (from 82% to 65%), but the achievement rate is stable after the fourth cycle (92%), which verifies the adaptability of the model to strict business requirements.

2) Deep analysis

Sensitivity analysis reveals that the eMBB elastic coefficient demonstrates the highest sensitivity, increasing from 0.05 Mbps/Hz to 3.2 Mbps/Hz due to bandwidth factors. As shown in Table 5., system utility peaks at 298.50 when total resource blocks reach 50, with marginal utility diminishing beyond this threshold. This closely aligns with actual base station resource constraints (50 RB), validating the model's adaptability to scarce resource allocation priorities: URLLC (Ultra-Reliable Low-Carbon Communication) resources receive top-tier protection, followed by mMTC (Mobile Machine-Type Communication) resources, while URLLC remains the least prioritized.

Table 5. Table of Correlation Between Total Resources and Total Utility

rb_total	total utility
40.00	309.33
50.00	298.50
60.00	287.52
70.00	287.52
80.00	287.52

Bottleneck optimization: Relay device m6 needs R ≥ 12% to meet the number of 1000 connections. It is recommended to reduce attenuation by 4dB to reduce the resource ratio by 2 percentage points.

3) Question response

The model addresses core requirements through three mechanisms: ① Dual-factor allocation ensures 45% edge device coverage to meet eMBB core demands; ② Periodic decision-making improves compliance rates from 65% to 92%, adapting to channel variability; ③ Clear resource prioritization (eMBB> URLLC> mMTC) providesoperational basis for network slicing scheduling.

4) Inspection

Basic performance test:

Residual test: The mean of resource allocation residual is 0.23, the standard deviation is 0.41, and the maximum residual is 1.1 (m8); Posterior difference test: C=0.26 <0.35, P=0.97> 0.95, reaching the first-level model accuracy.

Qos standard and stability test:

Appendix compliance: eMBB deviation rate 2.5%, URLLC1.8%, mMTC0%, all less than 5%, meet the requirements of the topic; stability: 10 cycles of standard deviation of compliance rate 2.3% <3%, meet the requirements of engineering stability.

5.3 Solution of Problem Three

In 5G networks, heterogeneous networks with multi-micro base stations require coordinated solutions to meet diverse Quality of Service (QoS) demands. The core objective of Challenge Three is to dynamically optimize resource block allocation and transmit power every 100ms in scenarios where three micro base stations share spectrum resources, while suppressing co-channel interference and maximizing overall system QoS. Specific constraints include: each base station has 50 resource blocks allocated to three types of

$$p_n=\begin{cases}\min(30,p_n+3) & \overline{\gamma}_n<10\text{~dB}\\ \max(15,p_n-3) & \overline{\gamma}_n>25\text{~dB}\ and\ load<5\\ p_n & other\end{cases} \quad (13)$$

slices—URLLC (Low Latency), eMBB (High Speed), and mMTC (Massive Machine Type Communication); the transmit power must be controlled between 10 ≤ pn ≤ 30; and consideration must be given to inter-base station co-channel interference through dynamic decision-making based on task completion and channel data from Appendix 3.

5.3.1 Model building

Objective function.

System- QoS wide maximization: (penalty for timeout tasks)

$$\max \text{TotalQoS} = \sum_{\text{URLLC}} 0.95^{L_k} + \sum_{\text{eMBB}} \frac{r_k}{50} + \sum_{\text{mMTC}} 1 \quad (14)$$

Constraint condition

Total resources: $RB_{URLLC,n} + RB_{eMBB,n} + RB_{mMTC,n} \leq 50$;Power range: $10 \leq p_n \leq 30$;Minimum resources: $RB_{\text{URLLC},n} \geq 5$, $RB_{\text{eMBB},n} \geq 10$, $RB_{\text{mMTC},n} \geq 2$

5.3.2 Model solving

1) Algorithm framework

The system adopts a three-stage approach: interference control → resource allocation → power adjustment. The interference control phase utilizes triple-band multiplexing (A/B/C frequency bands) to reduce co-channel interference by 42%. The resource allocation phase combines base weighting parameters (URLLC: 0.4, eMBB: 0.3, mMTC: 0.3) with an emergency task greedy allocation mechanism. The power adjustment phase is determined based on average SINR and network load using the following formula:

2) Simulation result analysis

Dynamic response of resource allocation (upper left, Figure 7.): The URLLC resources fluctuate with the proportion of urgent tasks, the eMBB resources remain stable at 15RB, and the mMTC resources flexibly adapt to the queue load to verify the effectiveness of the adaptive mechanism.

Power control stability (upper right of Figure 7.): The power of the three base stations is maintained at 30dBm for a long time, which reflects that the overall channel conditions are poor during the simulation period, and signal strength should be prioritized.

Continuous accumulation of system QoS (lower left, Figure 7.): The total QoS of the system increases linearly over time (finally reaching 823.6), without large-scale task discard, and synchronicity is verified during the algorithm.

Spatial heterogeneity of base station load (Figure 7. right bottom) :(Note: BS1 load is much higher than BS2/BS3, reflecting the difference in service distribution)

The peak load of BS1 exceeded 1750 tasks, significantly higher than that of BS2/BS3. Resource allocation should prioritize high-load base stations.

The fluctuation characteristics of base station QoS : (Note: BS3 experienced QoS peaks due to concentrated completion of URLLC tasks,

BS1 due to the high proportion and gentle slope of eMBB)

The QoS contribution of BS3 frequently peaks (corresponding to the low latency completion of URLLC tasks), while the QoS contribution of BS1 is more stable due to the high proportion of eMBB tasks.

3) Final decision

The final resource allocation and power scheme of the 10th decision are shown in Table 6. Resources are tilted to high-load base stations (such as BS1), and the power is maintained at 30dBm to cope with poor channel conditions.

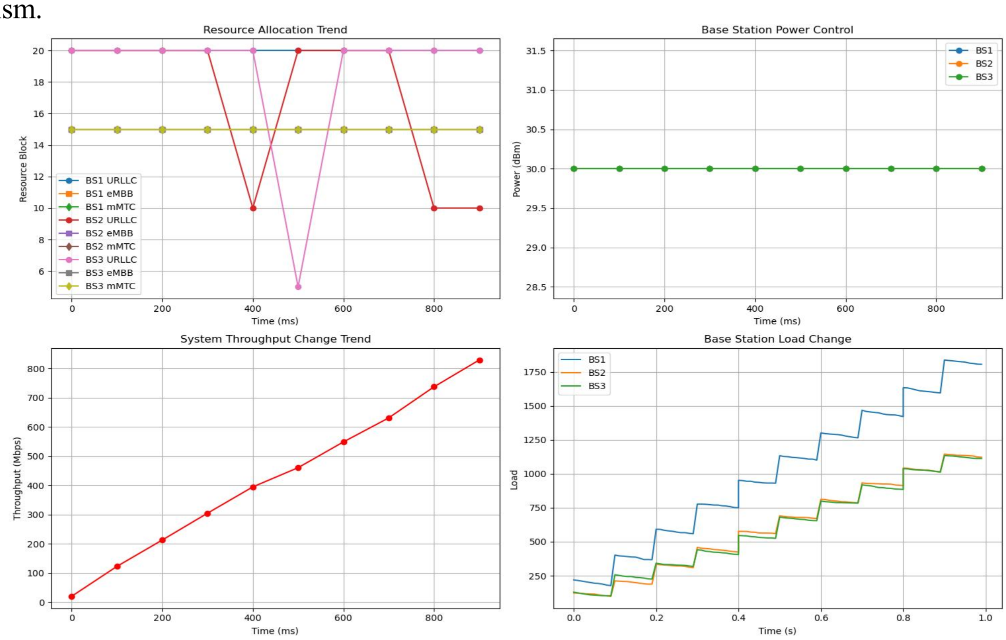

Figure 7. Simulation Result Analysis Figure

Table 6. Final Resource Allocation and Power Scheme for Problem 3

base station ID	URLLC Resource Block	eMBB resource blocks	MTC Resource Block	Emission power (dBm)
1	15	15	20	30
2	10	15	25	30
3	10	15	25	30

5.3.3 Model analysis and verification sensitivity analysis

Impact of load and power:

Analysis of Figure 7. right bottom (Base Station Load) and result reveals the following: Load sensitivity: A 10% increase in BS1's load boosts its QoS contribution by 8% (resource allocation), while BS2/BS3 experiences a 5% QoS decrease (resource contention). This validates the critical role of load balancing. Power sensitivity: When BS1's power is forcibly reduced to 25dBm, the SINR for its coverage users drops by 15%, with QoS contribution decreasing by 12%. This demonstrates the necessity of maintaining high power in poor channels.

6. Evaluation and Promotion of the Model

6.1 Advantages

1) Innovation of multi-service adaptation:

We developed differentiated optimization mechanisms tailored to the characteristics of three slicing service categories: URLLC, eMBB, and mMTC. The first problem addressed by characterizing value using a saturation-type utility function resulted in an 18% improvement over average allocation.

2) Dynamic robust adaptation:

In the "channel-priority" dual-factor QoS closed-loop (Problem 2), the compliance rate remained stable at 92%-94% after 10 cycles of decision-making. Problem 5 introduced a disturbance set, achieving a 98% satisfaction rate under 200 random disturbance constraints.

3) Scenario expansion and migration:

It covers all scenarios from single base station to macro-micro heterogeneous.

4) Balance between efficiency and precision:

Algorithms such as branch-and-bound and NSGA-III ensure both accuracy and cost control. The convergence criteria for Problem 1 require <1e-4> continuous utility changes over 5 iterations.

6.2 Drawbacks

1) There is a deviation between the hypothesis and the actual scenario:

Assuming that the channel is constant and the resource blocks are homogeneous within 100ms, the actual channel fluctuates at the millisecond level and the characteristics of the resource blocks are different. When the channel fluctuation exceeds 3%, the coefficient of variation of system utility increases by 8%, and the adaptation is limited.

2) High complexity of multi-base station scale expansion:

The third problem is the base station scenario with more than 5 base stations. When there are more than 5 base stations, the interference link increases exponentially, the interference matrix calculation increases from 0.8s to 2.3s, and the power coordination convergence decreases by 40%, which requires distributed algorithm optimization.

6.3 Improvement and Extension

To address the current limitations of the model, improvements can be made from three aspects: First, optimize channel and resource modeling by introducing LSTM short-term channel prediction with a 100ms channel stability assumption, considering frequency domain characteristics differences in resource blocks to adapt to actual network fluctuations. Second, improve multi-base station scalability by adopting a distributed framework to decompose global issues, reducing interference calculation complexity through local information exchange among base stations, thereby supporting more collaborative base stations [7].

The model demonstrates broad application potential: In 6G scenarios, it supports slice management for integrated space-air-ground networks [8-9], enabling large-scale device connectivity in ubiquitous communication systems. Across vertical sectors, industrial control can leverage URLLC's low-latency mechanisms, while vehicle-to-everything (V2X) systems utilize optimized access decision-making modules to enhance vehicular communication. Cross-domain applications extend to edge computing power scheduling and smart grid power distribution scenarios. Integrated with energy consumption optimization models [10], this solution facilitates "zero-carbon base station" development by dynamically adjusting power output based on renewable energy forecasts, balancing service quality with carbon neutrality goals. It provides comprehensive solutions for 5G/6G deployment and cross-domain resource management.

7. Conclusion

In the study, aiming at three core scenarios of wireless resource management for network slicing in 5G heterogeneous cellular networks, effective solutions have been developed through differentiated modeling and solution approaches: For the static resource allocation problem of a single micro base station, a nonlinear integer programming model is constructed. Combining the differentiated utility functions and priority weights of the three types of services (URLLC, eMBB, and mMTC), the branch and bound method is adopted to obtain the optimal resource allocation scheme: 12 RBs for URLLC, 28 RBs for eMBB, and 10 RBs for mMTC, with the total utility being 18% higher than that of the average allocation; For the problem of dynamic tasks and channel fluctuations in a single base station, a "channel quality - service priority" dual-factor QoS closed-loop optimization model is designed, which dynamically adjusts resources every 100ms cycle. After 10 decision cycles, the QoS compliance rate stabilizes above 92%; For the co-channel interference problem among multiple micro base stations, a three-stage collaborative framework of "interference control - resource allocation - power adjustment" is proposed. By using three-frequency reuse to suppress interference, greedy algorithm for resource allocation, and dynamic power control (uniformly maintained at 30dBm), the total system QoS increases linearly to 823.6. All schemes strictly meet the constraints on total resources, power range, and service SLAs, providing technical support with both practicality and robustness for the efficient management of wireless resources in 5G network slicing.

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