Inter-Cell Interference Coordination in Cellular Networks

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Abstract: Inter cell interference is a common challenge in cellular networks, particularly affecting users located at the edges of cells whose signal quality is compromised due to overlapping coverage areas of adjacent base stations. Effective ICI coordination is crucial for improving network performance, ensuring high data rates, low latency, and reliable connections. This article studies the performance of three ICI coordination methods in dual base station scenarios under different traffic loads (low, medium, and high) based on multiple indicators: non coordinated scheduling, queue load based selection, and P-persistent scheduling. Intended to provide the most effective scheduling solution for different load conditions and service scenarios, while also offering an effective approach for selecting suitable scheduling solutions.

Index Terms: Inter-Cell Interference Coordination, Cellular Networks, P-persistent Scheduling, Monte Carlo Simulation, Shannon's Theorem

1. Introduction

The exponential growth of mobile data traffic and the increasing demand for high-quality wireless services have significantly intensified the challenges faced by cellular networks. Among these challenges, inter-cell interference (ICI) remains a critical bottleneck that adversely affects the performance and reliability of mobile communication systems, particularly for users located at the cell edges [1]. As cellular networks evolve towards more advanced generations, such as 5G and beyond, effective ICI coordination becomes paramount to ensure seamless connectivity, enhanced data rates, and improved user experiences.

Inter-cell interference primarily arises from the overlapping coverage areas of adjacent base stations (BSs), where simultaneous transmissions on the same frequency bands lead to significant signal degradation [2]. This interference not only diminishes the signal-to-noise ratio (SNR) but also reduces the achievable transmission rates, increases the error rates, and can cause connection interruptions. Consequently, cell-edge users often experience suboptimal service quality, which undermines the overall network performance and user satisfaction [3].

To mitigate the adverse effects of ICI, various interference coordination techniques have been developed and implemented. Among these, Inter-Cell Interference Coordination (ICIC) and Coordinated Multi-Point (CoMP) transmission stand out as prominent strategies [4]. ICIC techniques typically involve dynamic resource allocation and scheduling to minimize interference [5, 6, 7], while CoMP leverages coordinated transmission and reception among multiple BSs to enhance signal quality and coverage [8, 9]. Despite their effectiveness, these methods exhibit varying performance under different traffic loads and network conditions, necessitating a comprehensive evaluation to identify optimal strategies for diverse scenarios.

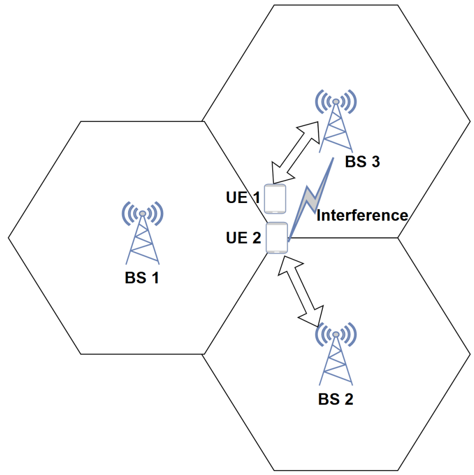


Fig. 1. Illustration of inter-cell interference between adjacent base stations (BSs).

Previous studies have explored numerous aspects of ICI management, including power control, frequency reuse schemes, and advanced scheduling algorithms. For instance, some researchers have proposed p-persistent Carrier Sense Multiple Access (CSMA) schemes based on predefined probabilities to regulate access and reduce collisions [10]. Others have investigated queue-length-based scheduling methods that prioritize transmissions based on the current load at each BS [11]. However, there remains a gap in understanding how these coordination methods perform under varying traffic intensities, particularly in balancing throughput and latency across different load conditions.

This paper aims to address this gap by systematically evaluating and comparing three ICI coordination methods—Uncoordinated Scheduling, Queue Load Based Selection (QLBS), and P-persistent Scheduling—in a dual-base station scenario under low, medium, and high traffic loads. Through simulation-based experiments, we analyze the throughput and delay performance of each method, identifying their strengths and limitations in different operational environments.

This paper has the following contributions:

1) We compared and analyzed three ICI coordination methods under the assumption of no inter base station interference, and evaluated their throughput and latency performance under ideal interference free conditions and different traffic loads.
2) We optimize the p-value in the P-persistent scheduling method through extensive simulations, identifying optimal settings that balance collision avoidance and resource utilization.
3) We specifically evaluated the transmission performance of users in interference sensitive areas under three different scheduling methods, and demonstrated the effectiveness of QLBS strategy in scheduling in interference areas through throughput and delay indicators.
4) We conducted Monte Carlo simulations for all possible users within the coverage area of the base station, simulating real-life scenarios, calculating the comprehensive transmission success rate of three scheduling methods under different loads, and combining the ideal throughput to calculate the actual throughput.
5) Based on Shannon's theorem and combined with Monte Carlo simulation data, we obtained the throughput from the perspective of Shannon's theorem and compared it with the previously calculated throughput to analyze the reasons for the differences.

The remainder of this paper is organized as follows. Section 2 describes the system model and the three ICI coordination methods under study. Section 3 outlines the simulation setup and methodologies employed in our experiments. Section 4 presents and analyzes the simulation results, highlighting the performance trade-offs of each method. Finally, Section 5 concludes the paper and suggests directions for future research.

2. System Model

We will introduce some basic settings and theoretical formulas used in this experiment in this section, providing the background for our simulation.

2.1. Path Loss Model

The pass loss model used in the experiments is the log-distance path loss model. It is a commonly used wireless propagation model that describes how the signal attenuates with increasing distance [12]. Its mathematical expression is typically given by:

$$PL(d) = PL_0 + 10\alpha \log_{10}\left(\frac{d_0}{d}\right) \tag{1}$$

where:

- $PL(d)$ is the path loss at distance d (in dB).
- PL_0 is the path loss at the reference distance d_0 (in dB).
- α is the path loss exponent, which reflects the impact of the environment on signal attenuation.
- d is the distance between the transmitter and receiver (in meters).
- d_0 is the reference distance, typically set to 1 meter to simplify calculations.

This model incorporates the path loss exponent α (which is set to 3 in the experiments) to account for the reduction in signal power as the distance increases, capturing environmental effects such as buildings, terrain, and other obstacles. The reference distance d_0 is usually chosen as 1 meter to normalize the path loss, making the model scalable and easier to apply in different scenarios.

2.2. Noise Model

The noise in the system is modeled as Additive White Gaussian Noise (AWGN) with a power spectral density of $N_0 = 10^{-21}$ W/Hz [13]. The total noise power P_n over a bandwidth B is given by:

$$P_n = N_0 \cdot B \cdot \xi, \tag{2}$$

where:

- B is the system bandwidth, set to 10 MHz.
- ξ is a random variable uniformly distributed in the interval $[0, 1]$, introducing variability in the noise power across different time slots to simulate channel fluctuations.

2.3. Signal-to-Interference-plus-Noise Ratio (SINR)

The performance of the network is evaluated using the Signal-to-Interference-plus-Noise Ratio (SINR) at the user equipments. The SINR for a user connected to BS1 is defined as [14]:

$$\text{SINR} = \frac{P_s}{P_i + P_n}, \tag{3}$$

where:

- P_s is the received signal power from the serving base station (BS1), calculated using the path loss model in Equation (1).
- P_i is the interference power from the non-serving base station (BS2). If BS2 is active, P_i is computed using the same path loss model; otherwise, $P_i = 0$.
- P_n is the noise power as defined in Equation (2).

2.4. Traffic Model

The arrival of data packets at each base station follows a Poisson process with arrival rates $\lambda = [0.75, 1.5, 2.5]$ packets per time slot, representing low, medium, and high traffic loads, respectively.

$$P(X = k) = \frac{\lambda^k e^{-\lambda}}{k!}, \quad k = 0, 1, 2, \dots \tag{4}$$

The queue length at each base station is updated at each time slot according to the number of packets arriving and the number of packets successfully transmitted.

2.5. Throughput

Throughput is measured as the total number of successfully transmitted packets during the simulation. For each transmission method and network load, the throughput $\mathcal{T}$ is calculated as:

$$\mathcal{T} = \frac{\sum_{t=1}^{T} S_{BS1}(t)}{T \cdot \Delta t}, \tag{5}$$

where:

- $S_{BS1}(t)$ and $S_{BS2}(t)$ are the number of packets successfully transmitted by BS1 and BS2 at time slot t, respectively.
- T is the total number of time slots (1000 in this study).
- Δt is the duration of each time slot (1 seconds).

2.6. Delay

The average delay is computed as the accumulated queue length over all time slots, normalized by the total throughput. For each method and load condition, the average delay D is given by:

$$D = \frac{\sum_{t=1}^{T} Q(t)}{\mathcal{T} \cdot T}, \tag{6}$$

where $Q(t)$ represents the queue length at the user's base station at time slot t. This metric provides an indication of the latency experienced by the users due to queuing and transmission delays.

2.7. Three ICI methods studied

We conduct the Simulation-based evaluation of three ICI coordination methods.

1. **Uncoordinated :** The two base stations do not wait and coordinate when a message appears in their respective queues to be sent and send the message immediately.
2. **Queue Load Based Selection (QLBS):** The base station coordinates with another base station when a message appears in the queue to be sent, selects the side of the two base stations with the longer waiting queue to send the message, and when the queues are the same, randomly selects a base station to send the message.
3. **P-persistent :** The two base stations do not coordinate when a message appears in their respective queues to be sent. However, it will send a message at this time slot with probability p. The p-value is chosen dynamically based on the high and low loads to achieve the best performance. In the medium-high load case $p = 0.55$ and in the low load case $p = 0.9$, the basis for such a choice will be explained later in the experimental section.

2.8. Experimental parameter description

All the parameters used in the experiment are listed in Table 1. We have referred to a large number of literature and industry sources to ensure that the data we selected is in line with real-world reality, and all the calculated data have display significance.

TABLE I
PARAMETER TABLE OF THE EXPERIMENT

Parameter	Description
P_s	30W, the standard reference is 4G LTE base station(Macro Base Station)[15].
B	10MHz, refers to the 4G LTE bandwidth configuration(Urban areas).[15]
N_0	$10^{-21}\,W/Hz$, a common noise power density value in 4G system.[15]
d_0	1m, the reference distance is a standard distance that describes the distance from the transmission source to the receiving point.[15][16]
α	3, the path loss index depending on the propagation environment.[15]
R	700m, this coverage is suitable for 4G macro base stations in urban areas.[16]
BS_dist	1200m, this distance is consistent with the actual scene situation.[15]
$numSlot$	1000, this number of time slots is sufficient and adequate for out research.[16]
$numUsersPerSlot$	500, The number of subscribers at a 4G base station in the real world is affected by the coverage area and the terrain, and the model considers the number of subscribers in the case of low density of subscribers in suburban areas.

This section provides an overview of the basic setup of the wireless networks studied in our experiments, including path loss and noise models, SINR calculations, traffic modeling, transmission methods, and performance metrics. These will serve as the base settings for the simulation experiments that follow.

3. Simulation

To gain a comprehensive understanding of the performance of all three scheduling methods, we conducted a series of experiments.

3.1. Exploring the performance of a single base station under three different scheduling methods (in the absence of base station interference)

3.1.1. Goal

As the first experiment of this project, this experiment builds a relatively simple experimental environment as the basis for subsequent experiments. The experiment analyses the throughput and average delay performance of the three scheduling methods under different load conditions (without considering the inter-base station interference and path signal fading) by simulating a single user in the selected plane, which can be located at any position on the selected plane because the power factor is not considered.

3.1.2. Simulation setup

The network topology consists of two base stations (BS1 and BS2) and two users (UE1 and UE2), which are located near the overlapping area covered by the two base stations. The coordinates of BS1 and BS2 are (0, 0) and (1200, 0) respectively, and the service radius of base station is 700 meters. UE1 and UE2 are located at (450, 0) and (750, 0). As shown in Figure 2,

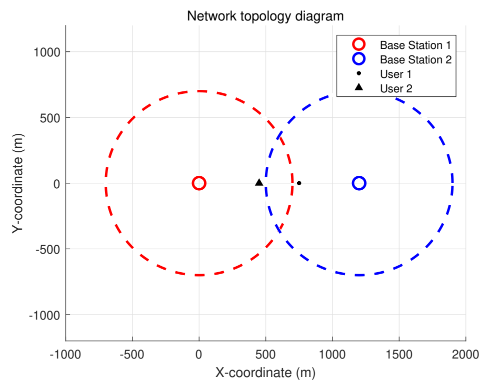


Fig. 2. Exp1 Simulation topology diagram

3.1.3. Simulation method

In this study, we adopt a simulation environment with the assumption of an infinite system bandwidth. This implies that regardless of how many users there are in the service environment, we can guarantee that the maximum transmission rate serving users is a constant value. In the system, the load received by each base station (the amount of services arriving) follows a Poisson distribution, which simulates the queuing process and the service process at the base station by accumulation.

The performance metric of the system is throughput (i.e. the amount of data successfully transmitted per unit of time). The average delay (i.e. the amount of time the data waits in the queue, is directly related to the queue length).

3.2. P optimization under p-persistent access policy

3.2.1. Goal

This experiment aims to investigate the effect of different p-values on the system performance in the case of dual users at multiple base stations. We study the values of p from 0 to 1 with an interval of 0.02. By comparing different p values, we study the system throughput and delay performance under different loads, hoping to obtain the optimal p values under each load, which will provide a reference and a basis for the p values of the p-persistent method for the subsequent experiments.

3.2.2. Simulation Setup

The location and load settings of the base station users are the same as in experiment 1, the SINR threshold is set to 5 dB, and the transmission fails if the SINR of the received signals is lower than this value. Experiments were conducted to analyze the effect on throughput and delay by adjusting the p-values (from 0 to 1 with an interval of 0.02).

3.2.3. Simulation Method

In the experiment, Poisson-distributed message queues were generated for the base stations based on the load conditions. In each time slot, the base station determines whether to attempt transmission based on a probability p. If the transmission was initiated, the base station sent no more than the available data in the queue or the maximum transmission rate per time slot (2 data units). Upon receiving the signal, the user calculated the SINR value. If the SINR was less than 5 dB, the transmission was considered a failure, and the queue data remained unchanged. We have a total of 51 values of p. We obtain the throughput and delay for each value by loop iteration and plot the throughput and delay line graphs for different values of p under three loads. AS shown in figure 4.

3.3. Cooperative dual base station transmission in interference-sensitive areas

3.3.1. Goal

This experiment aims to investigate the impact of different access strategies on the overall system performance (considering both base stations) when users are located in interference-sensitive areas influenced by two base stations. Specific objectives include comparing the throughput and delay performance of three methods: Uncoordinated, QLBS, and P-persistent, under low, medium, and high load conditions. Analyze which method can maintain high throughput while effectively reducing delay when users are in interference-sensitive areas.

3.3.2. Simulation Setup

This experiment focuses on users located in the overlapping coverage area of two base stations and analyzes the performance of different access strategies under interference scenarios. The base station settings and load settings are the same as in experiment 1, UE1 and UE2 are located at (550, 0) and (750, 0), respectively, placing them in the interference-sensitive area, As shown in Figure 2.

The maximum transmission power of the base stations is 30 W, the noise power density is 1×10^{-21} W/Hz, the bandwidth is 10 MHz, and the path loss exponent is 3. To be more realistic, we set up a failure retransmission mechanism, if the SINR is lower than 5 dB, the transmission is considered to have failed.

3.3.3. Simulation Method

Three access strategies were compared: Uncoordinated, Queue-Length-Based Scheduling (QLBS), and P-persistent random access. For the choice of p-value for the p-persistence method, we refer to the results in Experiment 2, where $p = 0.9$ at low loads and $p = 0.55$ at medium and high loads. The experiment utilized Poisson-distributed queues, recording the throughput and delay for each time slot. To achieve the retransmission mechanism, if the SINR is lower than 5 dB, the transmission is considered to have failed, and the number in the queue will not be subtracted in this loop, so that it will continue to try to send in the next time slot to realize retransmission.The simulation was repeated multiple times to obtain stable results.

3.4. Monte Carlo Model for Calculating Unilateral Multi-User Success Rates

3.4.1. Goal

This study is based on the performance analysis of the three scheduling methods in the no-interference scenario and further explores their performance in a multi-user environment. To ensure the simplicity and clarity of the research process, a simplified Monte Carlo[17] model based on a specific transmission policy is used. Consistent with previous studies, all parameters are set according to the 4G LTE base station standard. Under different scheduling methods and load conditions, the user success rate is calculated by counting the number of successful users in all valid time slots8. Then, the user success rate is multiplied by the no-interference throughput of the three methods to obtain the packet throughput under different loads of different scheduling methods in the multiuser case12. Since our experimental assumption divides the timeline into time slots, we get the unit of packets/time slot. In reality, the unit of throughput is bps, and the formula of the throughput of the packet to the actual throughput is:

$$\text{Throughput (bps)} = \text{Throughput (packets/slot)} \times \frac{\text{Packet Size (bits/packets)}}{\text{Slot Duration (seconds/slot)}} \tag{7}$$

After unifying the units, by comparing the differences in multiuser throughput of the three scheduling methods and using the theoretical capacity derived from Shannon's formula as a benchmark, this study provides an in-depth evaluation of the actual performance of these scheduling methods and their deviation from the ideal situation by simplifying the actual situation in a multiuser environment.

3.4.2. Simulation setup

Based on the research model, three additional parameters were additionally introduced: the user locations in each time interval, the SINR threshold and Package size. The number of users is defined as those within the coverage area of Base Station 1, specifically set at 500 users, with a uniform distribution assumed, the packet size is uniformly assumed to be 12000bit/packet. Since the success of users is closely related to the SINR threshold, the study examines the variations in user success rates and the resulting throughput under two SINR thresholds: 5 dB and 15 dB. In exploring the impact of SINR on performance, the range of SINR is taken to be -20dB-60dB.

3.4.3. Simulation method

This study employs a simplified Monte Carlo model[17] to simulate and analyze the dynamic performance of communication networks. The randomness of this method is primarily manifested in three aspects: first, the random generation of 500 stationary users' positions during experiment initialization; second, the independent generation of base stations' message queues across 1000 time intervals; and finally, the independent generation of random noise power for each user during channel state evaluation. This layered random sampling approach maintains the stability of user positions while simulating system dynamic characteristics through the randomness of queue arrival processes and channel noise.

The system parameters for the simulation are set as follows: both base stations have a transmission power of 30 W, and are 1200 meters apart, with a coverage radius of 700 meters. The propagation model uses a path loss exponent of 3 with a reference distance of 1 meter. 500 users are uniformly distributed and remain stationary within the base station coverage radius. The experiment runs for 1000 time intervals, with a background noise power density of 10^{-21}, system bandwidth of 10 MHz, message arrival process following a Poisson distribution, and a maximum transmission rate limit of 2 data packets per time slot.

The experiment evaluates the performance of the three methods. For the persistent method of P, the transmission probability is set to 0.9 under low load conditions, and 0.55 under conditions of medium load and high load according to the result of experiment 3.2 to adapt to different network load situations.

The experiment implementation consists of four key steps: First, the message queues for each base station are generated according to a Poisson distribution; second, the transmission states of the base stations are determined based on different scheduling strategies; third, the user SINR is calculated through path loss model and interference analysis, by using formular 3.

When SINR exceeds the SINR threshold, the transmission is considered successful. Finally, system performance metrics are evaluated. The transmission success rate is calculated as the ratio of successfully transmitted users to the total number of active users:

$$P_{\text{success}} = \frac{\text{Total number of successful transmissions}}{\text{Number of active slots} \times \text{Total number of users}} \tag{8}$$

Meanwhile, this study employs Shannon's formula[18] to calculate the theoretical channel capacity as a reference standard for performance evaluation:

$$C = B \log_2(1 + 10^{\text{SINR}/10}) \tag{9}$$

where C represents the channel capacity (bps), B is the channel bandwidth of 10 MHz, and SINR is the Signal-to-Interference-plus-Noise Ratio (dB). The average Shannon capacity across all time slots is calculated based on users' SINR as a theoretical upper bound reference. According to Jensen's inequality, the upper limit of the theoretical performance of the system for a convex function $f(x)$ can be expressed as:

$$f\left(\frac{\sum_{i=1}^{N} x_i}{N}\right) \leq \frac{\sum_{i=1}^{N} f(x_i)}{N} \tag{10}$$

Based on this, the total system throughput is calculated as:

$$T_{total} = \sum_{i=1}^{N} C_i = \sum_{i=1}^{N} B \cdot \log_2(1 + SINR_i) \tag{11}$$

To obtain the actual system throughput, this study first calculates the transmission states of each base station under different scheduling methods to determine the actual number of data packets transmitted per time slot. This is then multiplied by the user transmission success rate to obtain the actual packet throughput for different scheduling methods under various load conditions in multi-user scenarios.

$$T_{multi-users} = P_{success} \cdot T_{no-interference} \tag{12}$$

By converting the units of actual packet throughput according to equation 1 and comparing it with the theoretical throughput calculated using Shannon's formula, we can effectively evaluate the performance of different scheduling strategies in multi-user environments and assess the deviation between the simplified model and ideal conditions.

4. Result Analysis

4.1. Exploring the performance of a single base station under three different scheduling methods (in the absence of base station interference)

As shown in Fig. 3, the throughputs of the three methods are close to each other at low load, which is about 0.8. This is because the load is low, the base station resources are sufficient, the conflict probability is small, and all the three scheduling methods are able to adequately transmit the data in the queue. As the load increases the throughput of all the three methods increases and the Uncoordinated method achieves the maximum throughput under high load as it has no additional scheduling constraints. However, its this sending method may lead to conflict or interference between two base stations in more time slots.P-persistent method performs better but is limited by probabilistic constraints and has a throughput around 1.4. QLBS method has the lowest throughput and stays near 1. Its queue priority decision and failure to fully utilise the resources at high loads results in lower throughput.

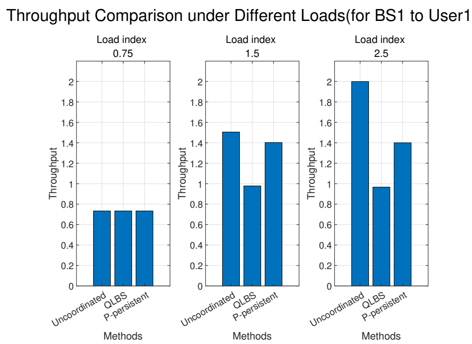


Fig. 3. Throughput of different coordination schemes under different load conditions (without considering path attenuation and inter base station interference)

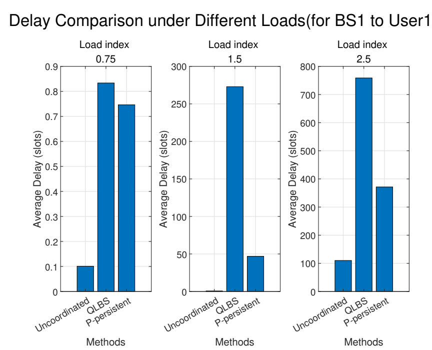
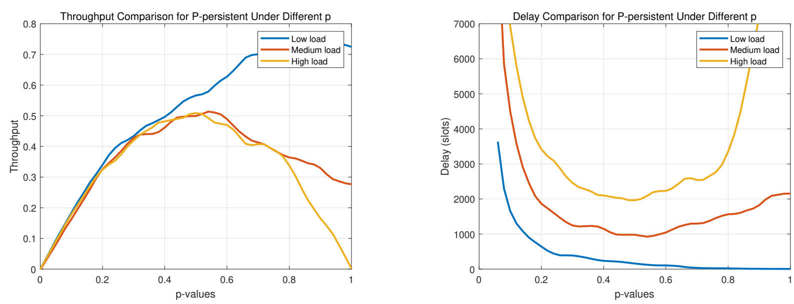


Fig. 4. Delay of different coordination schemes under different load conditions (without considering path attenuation and inter base station interference)

The Uncoordinated method has the smallest latency at low load, about 0.1 time slots. The P-persistent and QLBS methods have higher latency, especially the QLBS method which is close to 1. This is due to the fact that part of the queue is not transmitted in time due to the QLBS scheduling policy. Under high load, the Uncoordinated method has less latency, about 100 time slots, but the throughput is close to the limit. the P-persistent method has a latency of 350 time slots. the QLBS method has the worst latency, more than 800 time slots, and the queue is so backlogged that the system cannot empty the data in time. the uncoordinated method can empty

the queue as soon as possible due to the absence of additional constraints, so the system cannot empty the data in time. The P-persistent method reduces conflicts, but probabilistic scheduling results in some time slots not being utilised, leading to an increase in latency. The scheduling priority of the QLBS method performs poorly under high loads, with increased resource wastage and a serious deterioration in latency. As shown in Figure 4.
Based on the results of this experiment, we find that Uncoordinate has outstanding results in both metrics, but this result is clearly unreliable. The experiment lacks a penalty factor for the collision of two base stations and the occurrence of interference, which leads to the outstanding performance of Uncoordinate. The next step of the experiment will be to simulate wireless interference between base stations to further evaluate the performance of each method under real channel conditions.

4.2. P optimization under p-persistent access policy



(a) (b)

Fig. 5. (a) Throughput of the p-persistent method under different p-values. (b) Delay of the p-persistent method under different p-values. (51 data points using the smoothing function)

Figure 5(a) illustrates the effect of different p-values on the throughput of the p-persistence method for three load cases, and figure 5(b) describes the effect of different p-values on the latency. By analyzing the results of the experiments, it can be concluded that higher p-values (e.g., p=0.9) can achieve better throughput and latency performances under low loads due to the fact that under the low loads scenario, collisions are unlikely to happen, so the transfer strategy can be more aggressive. In medium to high load situation if p value is large it will lead to frequent collision and need to retransmit, resulting in throughput decrease and latency increase, at this time moderate p value (e.g., p=0.55) has better performance, which can balance the avoidance of collision and fast delivery

4.3. Cooperative multi-base station transmission in interference-sensitive areas

The experimental results show that under low load conditions, the throughput of the uncoordinated and QLBS strategies are comparable, while P-persistent is slightly lower. Under medium to high load conditions, the QLBS policy significantly outperforms the other two approaches by maintaining a high level of throughput and a significant reduction in latency due to its avoidance of interference through coordinated scheduling. The uncoordinated policy suffers from frequent disturbances under high loads, resulting in throughput degradation and latency spikes, while the P-persistent policy is also limited under high loads due to insufficient SINR. It is also worth noting that in the high load case of Fig.6 (b), under the uncoordinated method, there is no effective delay data because the throughput rate is zero. As a result, the data is not displayed in the chart.

In summary, the QLBS strategy performs best in interference-sensitive areas, effectively reducing latency and increasing throughput.

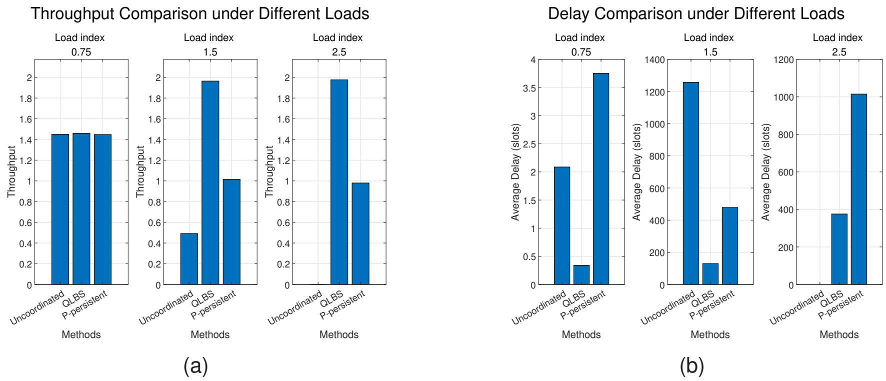


Fig. 6. (a) Throughput comparison of 3 methods under different loads. (b) Delay comparison of 3 methods under different loads.

4.4. Monte Carlo Model for Calculating Unilateral Multi-User Success Rates

In wireless communication systems, the setting of the SINR threshold impacts system performance. Typically set at 5dB, the user success rate under this condition is shown in Table II.

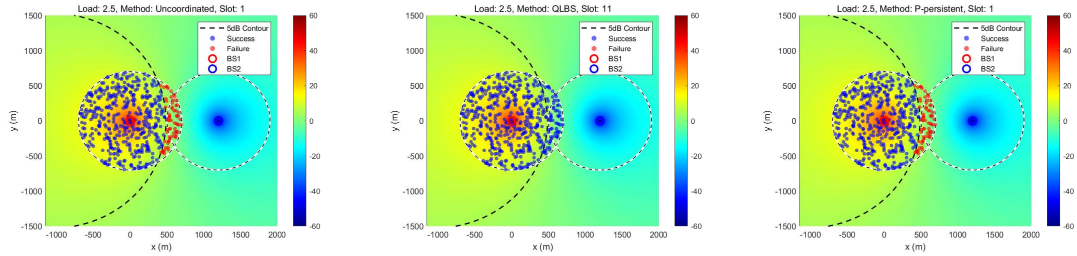
TABLE II
USER SUCCESS RATE UNDER DIFFERENT LOAD CONDITIONS

Method	Low Load ($\lambda = 0.75$)	Medium Load ($\lambda = 1.5$)	High Load ($\lambda = 2.5$)
Uncoordinated	0.9370	0.8970	0.8760
QLBS	1.0000	1.0000	1.0000
P-persistent	0.9388	0.9302	0.9334

In particular, the success rate statistics only consider effective time slots when base station 1 has data packets to transmit. The QLBS method maintains a success rate of 1 due to its exclusive transmission approach, which eliminates inter-base station interference. In contrast, the success rate of the Uncoordinated method decreases as the load increases, primarily because higher loads increase the probability of interference from base station 2, leading to a lower average SINR. The persistent method P maintains relatively stable success rates across different loads through adaptive adjustment of transmission probability p, with performance degradation less severe than the uncoordinated method. As shown in Figure 7, successful users are marked in blue, and unsuccessful users in red below the SINR threshold of 5dB for all three methods. In figure 7(b) The users of the QLBS method are all successful in the high load scenario for a given valid time slot, since it is a tunable method and only base station 1 is communicating. The other two methods failed to communicate for users with SINR below 5 dB in the high load case.

Figure 8(a) demonstrates the normalized actual system throughput calculated based on user success rates. Under medium to high load conditions, the Uncoordinated method shows clear advantages, mainly due to its higher transmission frequency. Under low load conditions, all three methods perform similarly, though QLBS achieves slightly higher throughput due to its effective resource allocation mechanism and interference control capabilities.

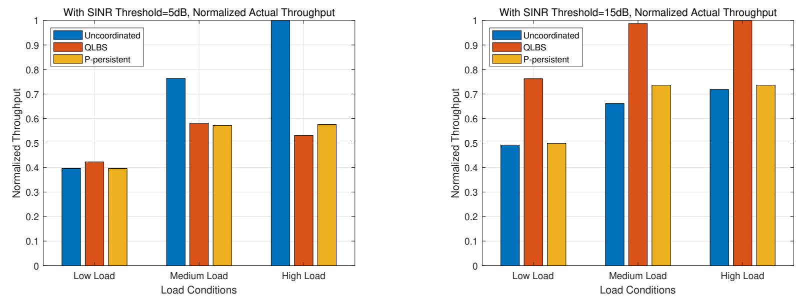
When the SINR threshold increases to 15dB,shown in Figure 8(b), the performance characteristics of the system change significantly. Under these conditions, QLBS method performs optimally in medium to high load scenarios. This is because higher SINR threshold requirements make the system more sensitive to interference, while QLBS effectively reduces interference by prioritizing base stations with longer queues and avoiding concurrent transmissions. To analyze the impact of SINR threshold on performance more deeply, we extended its range to -20dB-60dB, resulting



(a) (b) (c)

Fig. 7. (a)Distribution of successful and failed user communications under the uncoordinate method with a SINR threshold of 5 dB (b)Distribution of successful and failed user communications under the QLBS method with a SINR threshold of 5 dB (c)Distribution of successful and failed user communications under the p-persistent method with a SINR threshold of 5 dB

in the user success rate trends shown in Figure 9.



(a) (b)

Fig. 8. (a)Normalized actual throughput results obtained using formula (7) for a SINR threshold of 5 dB (b)Normalized actual throughput results obtained using formula (7) for a SINR threshold of 15 dB

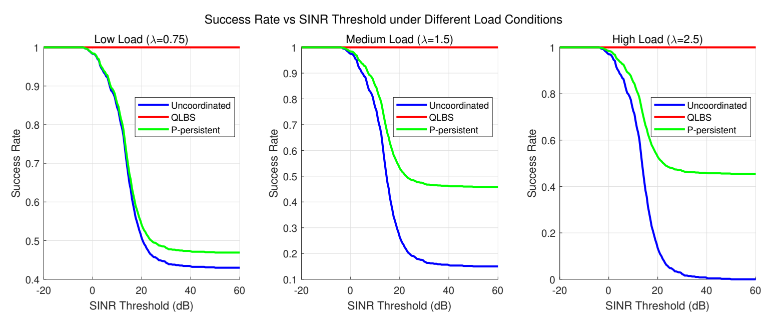


Fig. 9. Changes in user success rates with changes in SINR

It can be seen that regardless of load conditions, as the SINR threshold increases, the user success rates for uncoordinated and p-persistent methods gradually decrease. This is due to the fact that as the SINR threshold increases, users who could have successfully communicated will fail to communicate, as shown in Figure 10, where users within the purple shaded area can communicate normally with a SINR threshold of 5 dB, but will fail to communicate with a SINR threshold of 15 dB.Starting from a threshold of around -4dB, some users are unable to successfully send using the uncoordinated and P-persistent methods. This is because some users with the most severe interference within the service range of the base station are unable to communicate.

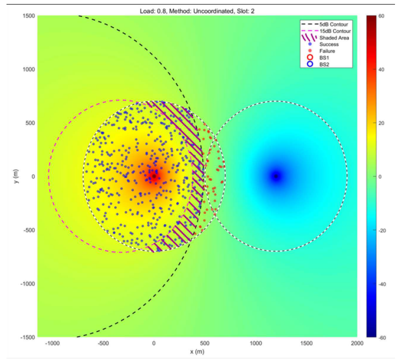


Fig. 10. Impact of SINR threshold changes on user communications (5dB to 10dB as an example)

On the other hand, QLBS maintains a success rate of 1 as it avoids collisions and consistently maintains a high SINR. Using formula 7, we obtained performance curves for different methods under various loads as SINR changes, as shown in Figure 11.

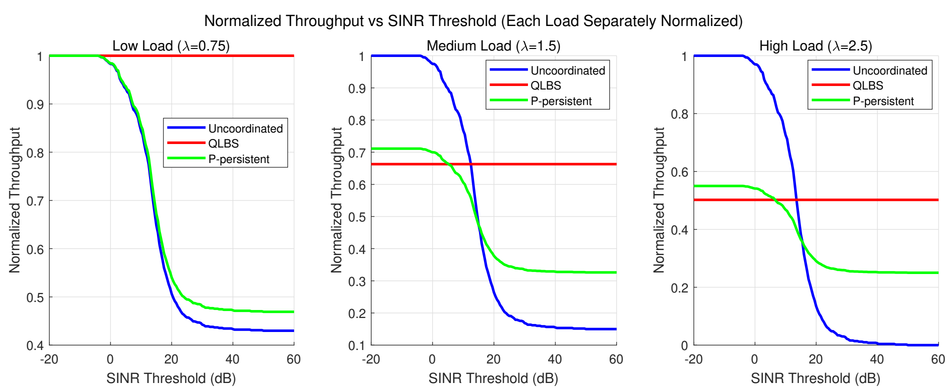


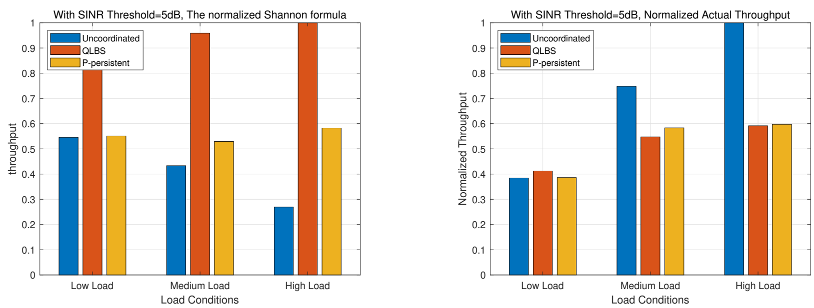
Fig. 11. Changes in actual throughput with changes in SINR

From the normalized throughput curves versus SINR thresholds, we can see that under low load, QLBS maintains the highest and nearly constant throughput, while Uncoordinated and P-persistent show a noticeable decrease as the threshold increases. Under medium and high loads, QLBS still achieves relatively stable and higher throughput, indicating better collision avoidance and resource utilization even when interference grows or thresholds rise. In contrast, Uncoordinated is extremely sensitive to higher SINR thresholds, with throughput dropping sharply. P-persistent lies in between: it degrades more gradually than Uncoordinated but remains slightly lower in both stability and maximum throughput compared to QLBS. Overall, QLBS exhibits superior interference resilience and scheduling performance across different SINR thresholds and load conditions.

These results indicate that SINR threshold selection significantly impacts system performance, and different scheduling methods show varying sensitivity to SINR threshold changes. In practical system design, appropriate SINR thresholds and scheduling strategies must be chosen based on load conditions and performance requirements to balance transmission reliability and system throughput. Particularly under high load conditions, scheduling method selection becomes more critical for system performance.

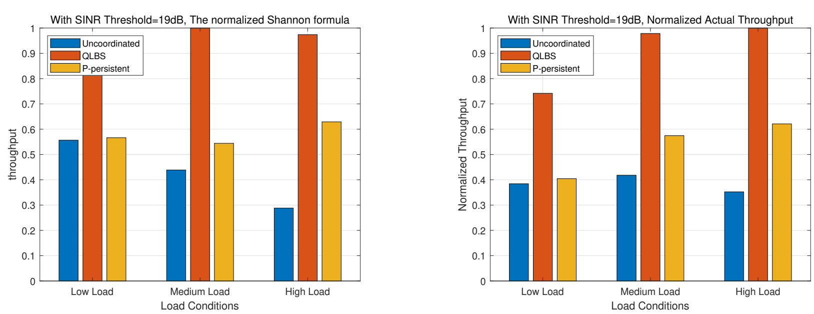
4.5. Comparison of results derived from Shannon's theorem and calculation of actual throughputs

The Shannon formula provides the theoretical upper limit for the maximum error-free transmission rate that a channel can support under given SINR conditions. To evaluate the gap between actual system performance and theoretical limits, we need to calculate the average theoretical throughput that each user can achieve. The theoretical capacity analysis shown in the figure12(a) indicates that QLBS achieves the highest throughput under all three load conditions.



(a) (b)

Fig. 12. (a)Throughput obtained using Shannon's formula for a SINR threshold of 5 dB (b)Normalized actual throughput results obtained using formula 7 for a SINR threshold of 5 dB



(a) (b)

Fig. 13. (a)Throughput obtained using Shannon's formula for a SINR threshold of 19 dB (b)Normalized actual throughput results obtained using formula 7 for a SINR threshold of 19 dB

However, we can see that at the threshold of 5dB, the actual throughput figure7 (b) results are very different from the trend of Shannon formula. Regarding the inconsistency between system throughput calculated by Formula 12 and Shannon formula, the fundamental reason lies in the essential difference between these two calculation methods: Formula 12 uses a binary judgment mechanism based on SINR threshold when calculating system throughput - that is, SINR exceeding the threshold is considered successful (marked as 1), below the threshold is considered failed (marked as 0), which is a discrete evaluation method. The Shannon formula, however, directly calculates the actual throughput of each user without rigid success/failure divisions, resulting in a continuous calculation. This means that the threshold size of SINR is independent of Shannon's result. To achieve consistent trends between these two methods, we need to find an appropriate SINR threshold that matches discrete results with continuous results. Through experimentation, we found that when the SINR threshold is set to around 19dB, It can be seen through figure13, the calculation results of both methods show some similar trends under certain conditions.

5. Conclusions

This study systematically evaluated three ICI coordination methods—Uncoordinated Scheduling, QLBS, and P-persistent Scheduling—in a dual-base station environment under varying traffic loads. The results show that while the Uncoordinated Scheduling method achieves high throughput under low traffic, its performance deteriorates significantly at higher loads due to increased interference. The P-persistent Scheduling method provides a more balanced performance by dynamically adjusting the transmission probability p. Among the methods, QLBS consistently achieves the best results, offering high throughput and low latency across all traffic scenarios by prioritizing transmissions based on queue loads. Monte Carlo simulations confirmed the advantage of QLBS in multi-user environments, showing its ability to closely align with theoretical capacity limits while mitigating interference. These findings highlight its practical potential for improving inter-cell interference management in real-world settings.

5.1. future work

- For bandwidth, the assumption in this experiment is to assign a fixed bandwidth to each user, an assumption that can lead to an infinite bandwidth situation with an infinite number of users. Modulation methods such as OFDM can be used for spectrum resource allocation. The use of modulation coding schemes such as 256-QAM is used to further optimize the use of bandwidth and make the experiment more realistic.
- This experiment only considered the two-base station case, which is not sufficient in today's complex wireless cellular network environment, and future research could extend the study to more complex network topologies to provide deeper insights into the effectiveness of these methods in next-generation wireless networks.

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Appendix

Division of work:

Jianan Liu	Xiang Guo	Yuxin Yang
33%	33%	33%
The work includes overall project experimental design, theoretical derivation, partial code writing, and experimental result analysis	The work includes overall project experimental design, theoretical derivation, partial code writing, and experimental result analysis	The work includes overall project experimental design, theoretical derivation, partial code writing, and experimental result analysis

Our team members were able to complete their assigned tasks well in this project and emphasized mutual cooperation. Everyone participated in the project design and code writing, and also made their own contributions in the material writing section.

Public project Git repository: https://github.com/Jiananliu12138/KTH_IK2560_project.git