POLITECNICO DI TORINO

Management and Content Delivery for Smart Networks

Algorithms and Modeling

LAB REPORT

Group 3

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Contents

Lab 1

Task 1-a

Introduction

This project focuses on simulating a drone-assisted communication system to enhance network capacity during peak traffic periods. We aim to analyze the system performance of a UAV equipped with a single antenna base station (m=1) under various arrival rates. The performance metrics include average waiting time, average system time, and throughput.

Simulation Details

A queuing system is modeled where:

- **Service Rate** (μ) is fixed at one packet per time unit.
- **Simulation Time** is set to 10,000 time units.
- **Arrival Rates** (λ) vary from 0.1 to 2.0 in increments of 0.1.

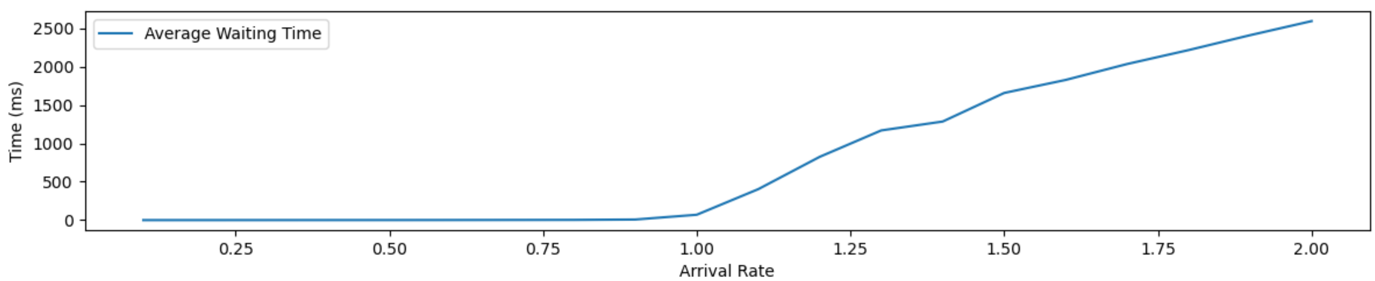
The metrics calculated are:

- **Average Waiting Time**: A packet's average time waiting to be processed.
- **Average System Time**: The total time a packet spends in the system (waiting + service).
- **Throughput**: The number of packets processed per time unit.

Results and Interpretation

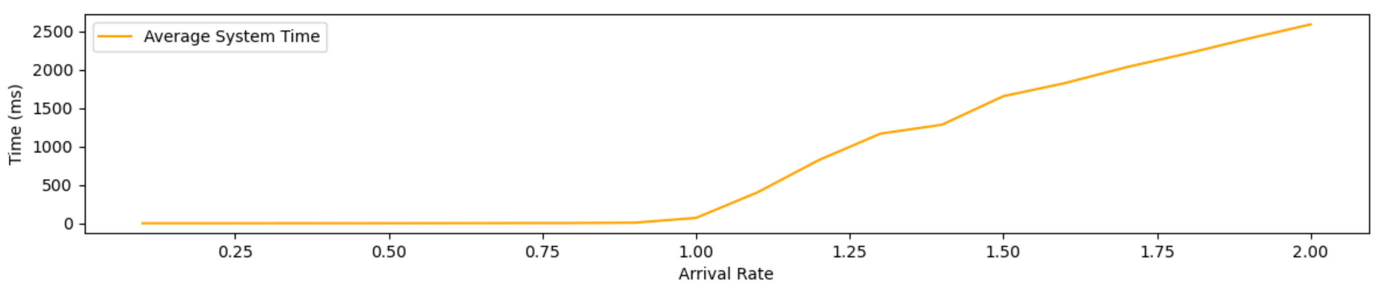
Average Waiting Time vs. Arrival Rate

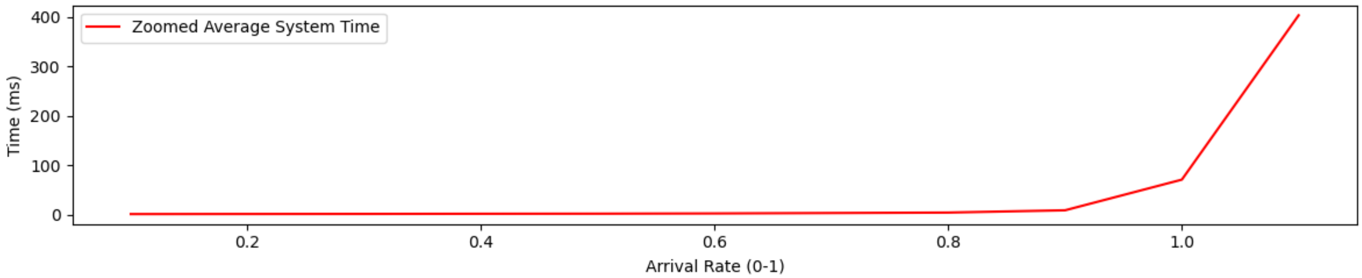
- **Observation**: As the arrival rate (λ) increases, the average waiting time increases sharply.
- **Interpretation**: The system can process packets quickly without significant queuing at lower arrival rates. However, as λ approaches the service rate (μ), waiting times escalate due to increased congestion.



Average System Time vs. Arrival Rate

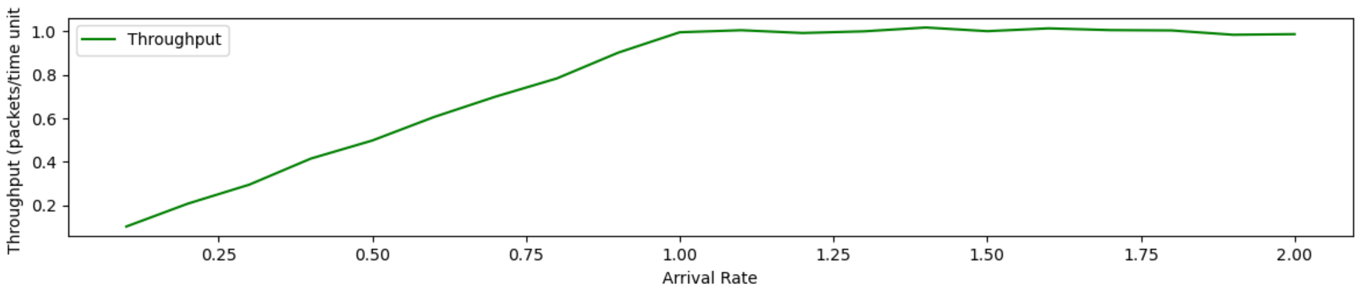
- **Observation**: Similar to waiting time, the average system time increases with the arrival rate. The system time rises gradually in the 0 to 1 arrival rate range.
- **Interpretation**: System time includes both waiting and service times. As the system becomes busier, packets spend more time waiting and being processed. The zoomed view shows the system's behavior before reaching critical congestion, providing insights into performance during lower traffic volumes.





Throughput vs. Arrival Rate

- **Observation**: Throughput increases linearly with the arrival rate up to a certain point and then saturate.
- **Interpretation**: Initially, the system can handle the increased load, but as λ nears μ, the system reaches its maximum capacity, and throughput stabilizes, indicating saturation.

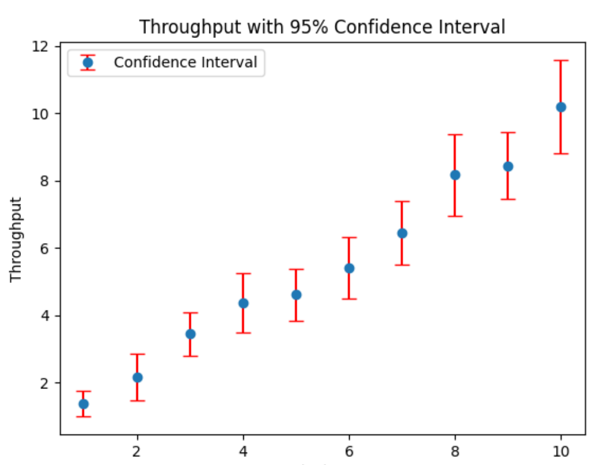


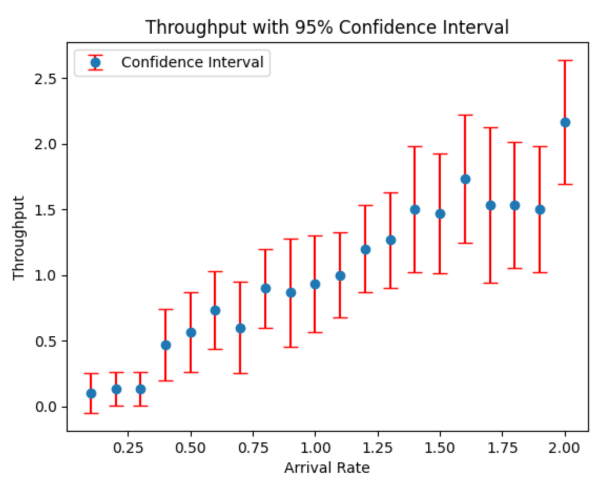
Task 1-b

Confidence Intervals

The purpose of calculating a confidence interval is to evaluate the reliability of the results obtained from a simulation. We derive an estimate of the phenomenon of interest (X), which is the mean of multiple observations taken over an extended period. This estimate has a variance of s^2/N. By applying the central limit theorem and normalizing the distribution for a large number of observations, the confidence interval is centered around the estimator X, plus or minus the product of the normal distribution quantiles Z. The standard deviation is divided by the square root of the number of observations ($I = X \pm Z \cdot \frac{S}{\sqrt{N}}$).

The confidence level is expressed as a percentage and indicates the probability that the estimate lies within the confidence interval. To achieve greater certainty, having a narrow confidence interval and a high confidence level is essential. A narrow confidence interval can be attained by increasing N and reducing sample variability. A high confidence level can be achieved by having smaller quantiles (lower α), which results in a larger confidence interval. The simulation is run multiple times using different random seeds to estimate the confidence interval of the measured loss probability.

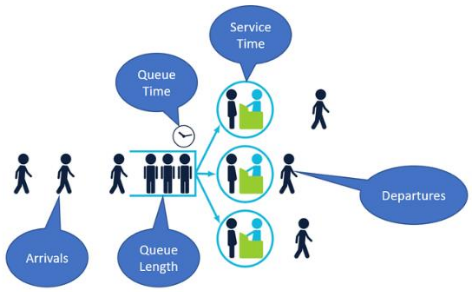




Task 1-c

Theoretical Consistency

The results obtained from the simulations are consistent with the theoretical expectations of an M/M/1 queue:



$$\boxed{E[N] = E[\lambda]E[T]}$$

Ergodicity condition

It is ergodic if λ <μ (arrival rate smaller than service rate)

- **Low Arrival Rates**: Minimal queuing, low waiting, and system times.
- **High Arrival Rates**: Significant queuing, high waiting, and system times, with throughput reaching the service rate limit.

Task 2-a

Introduction

This task focuses on comparing the performance of two different configurations of UAV-based communication systems, assuming an infinite buffer size:

1. A single drone equipped with two antennas. (one queue and two servers: M/M/2)
2. Two drones, each equipped with a single antenna. (2 independent M/M/1)

The key performance metric analyzed is the average delay experienced by packets.

Simulation Details

The simulation considers the following parameters:

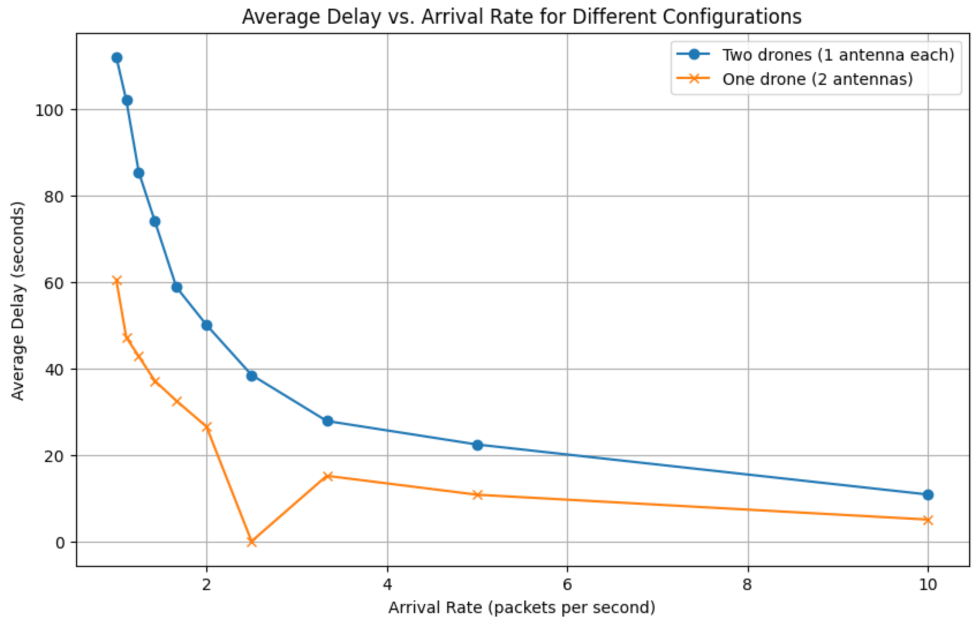
- **Service Rate**: 10 packets per second for each server.
- **Simulation Time**: 1,000 seconds.
- **Arrival Rates**: Varied from 0.1 to 1 packet per second in increments, corresponding to interarrival rates from 10 packets/second to 1 packet/second.

The metrics calculated are:

- **Average Delay**: The average time a packet spends in the system from arrival to departure.

Results

- At lower arrival rates, both configurations perform similarly with minimal delays.
- As the arrival rate increases, the configuration with one drone having two antennas consistently outperforms the two-drone configuration in terms of lower average delays.
- The higher service rate provided by two antennas in a single drone helps reduce congestion. It reduces the queuing delay more effectively than having two separate drones with a single antenna each.



Conclusion

The simulation results indicate that a single drone equipped with two antennas(M/M/2) performs better in terms of average delay than two drones with one antenna each(M/M/1), particularly at higher arrival rates. This configuration leverages the increased service capacity to handle traffic more efficiently, resulting in lower delays and improved system performance. This insight is crucial for designing UAV-based communication systems to optimize network capacity and quality of service during peak traffic periods.

Task 2-b

We analyze the system performance by evaluating the loss probability for different buffer sizes.

Simulation Details

The simulation considers the following parameters:

- **Service Rate**: 10 packets per second per antenna.
- **Arrival Rate**: 1 packet per second.
- **Simulation Time**: 100,000 time units.
- **Buffer Sizes**: Ranging from 0 to 10 packets.

The key performance metric analyzed is:

- **Loss Probability**: The fraction of packets that cannot be transmitted because the buffer is full.

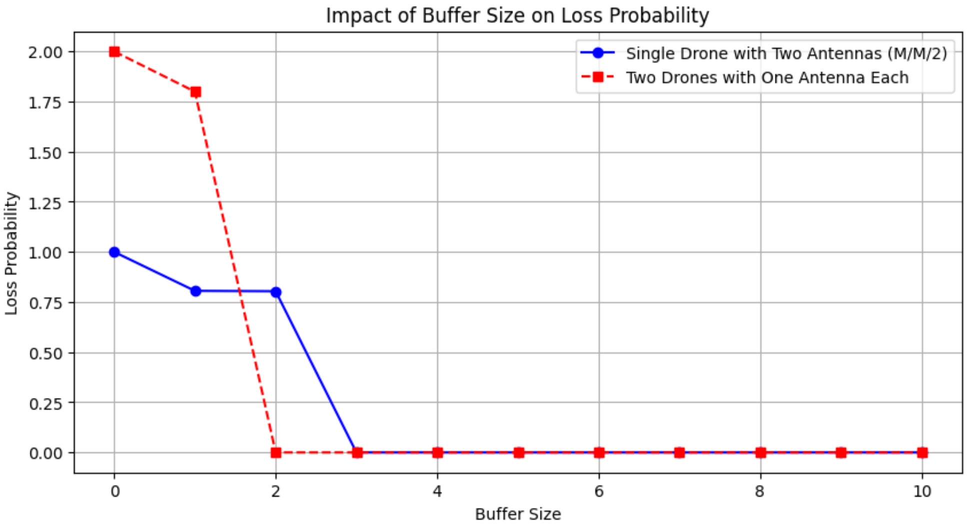
Results

- **At smaller buffer sizes**:

  The single-drone configuration with two antennas (M/M/2) shows a significantly lower loss probability than the two-drone configuration with one antenna each. This suggests that having two antennas on a single drone performs better in handling packet arrivals, even with limited buffer capacity.

- **At larger buffer sizes**:

  Both configurations show reduced loss probabilities, but the single-drone configuration still outperforms the two-drone setup. The advantage of having a shared buffer for a multi-server system (M/M/2) becomes evident as the buffer size increases, allowing more packets to be temporarily stored and reducing losses.



Task 3

Introduction

In Task 3, we investigate the load distribution among servers in a multi-server scenario where a single drone (N = 1) is equipped with multiple antennas (m > 1). The focus is comparing different algorithms for assigning transmission requests to servers and analyzing their impact on system performance. The assignment algorithms tested include:

1. Random assignment
2. Round-robin assignment
3. Assignment to the fastest servers (with different service rates)

Average Queueing Delay: A packet's average time waiting in the queue before being processed.

Simulation Details

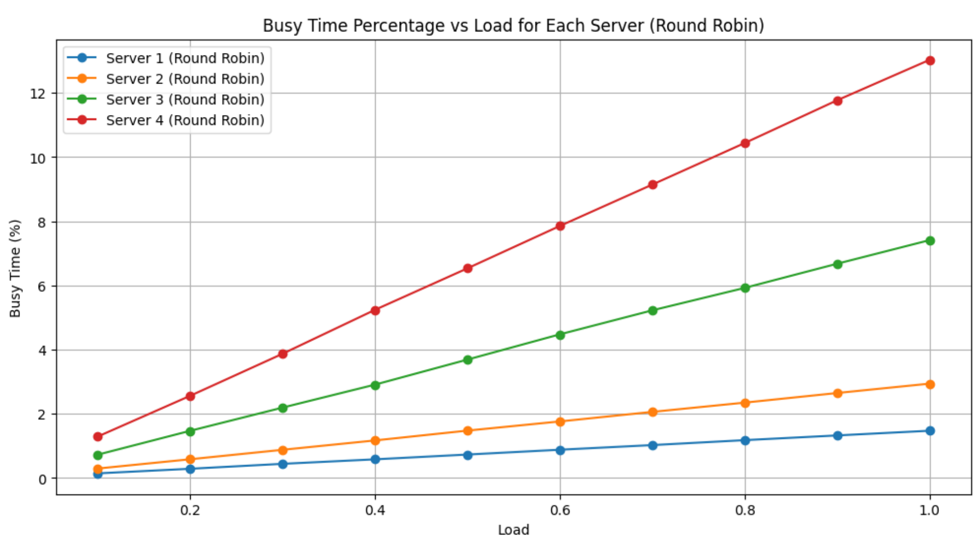
The simulation considers the following parameters:

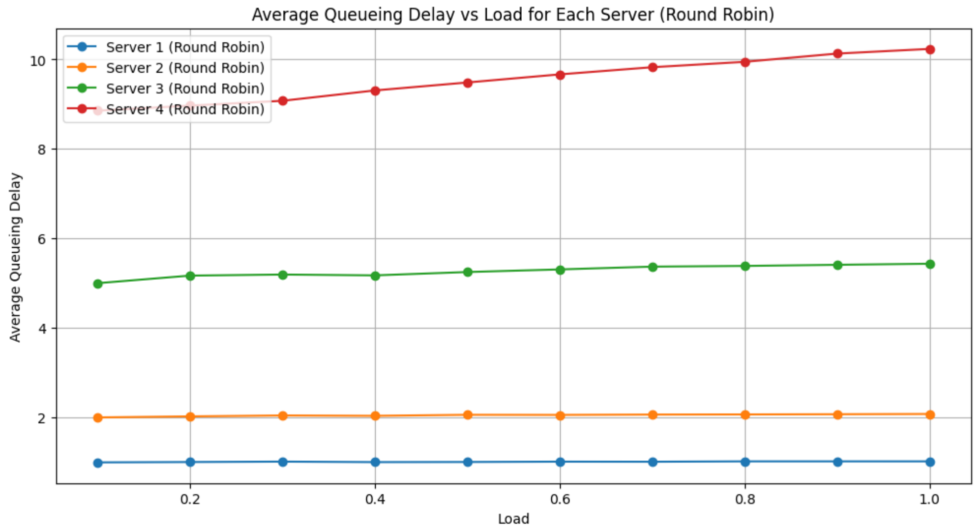
- **Service Rates**: Different for each server (1.0, 2.0, 5.0, and 9.0 packets per second).
- **Arrival Rate**: Varies to test different load conditions.
- **Simulation Time**: 2,000,000 time units.

Results

Round Robin

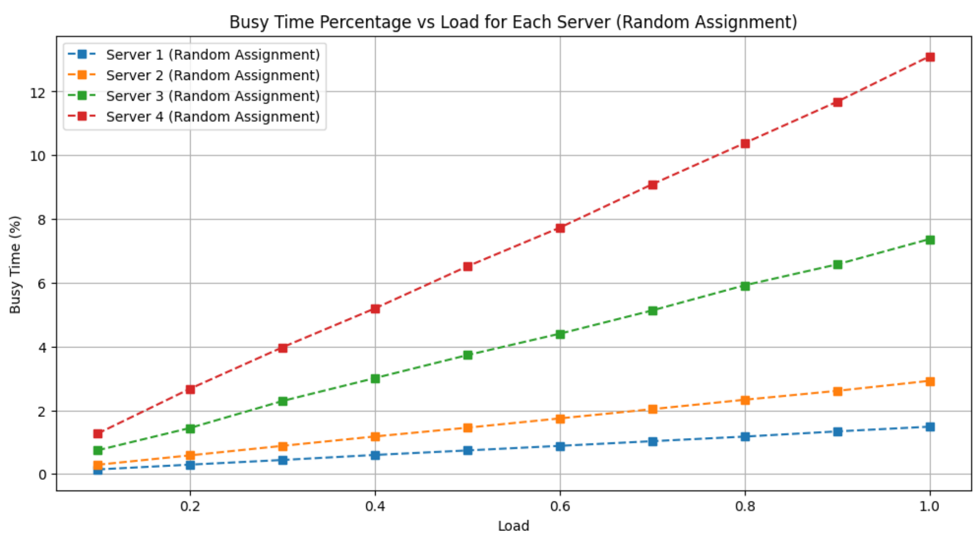
- Round-robin assignment distributes the load cyclically among servers and provides a balanced load distribution with predictable performance.
- Utilizes faster servers more efficiently, leading to lower delays.

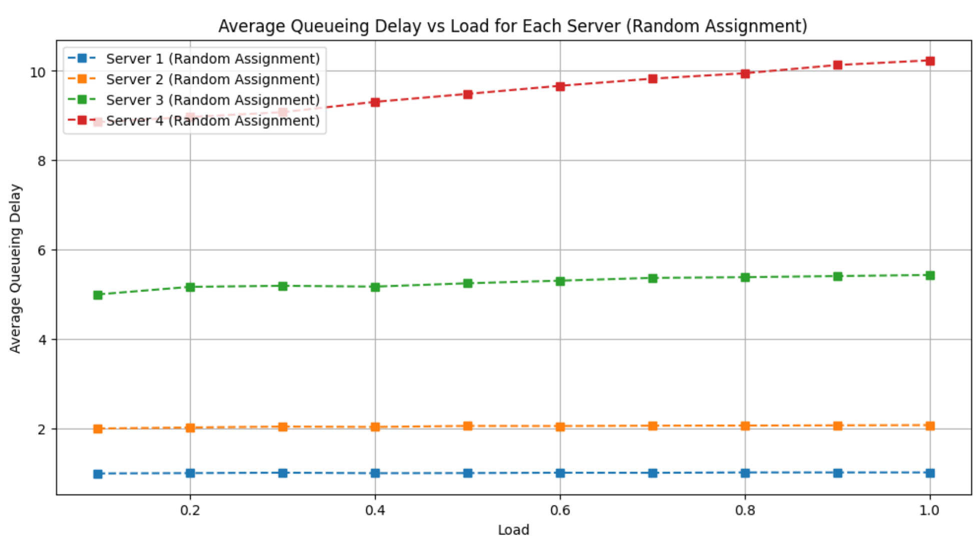




Random Assignment

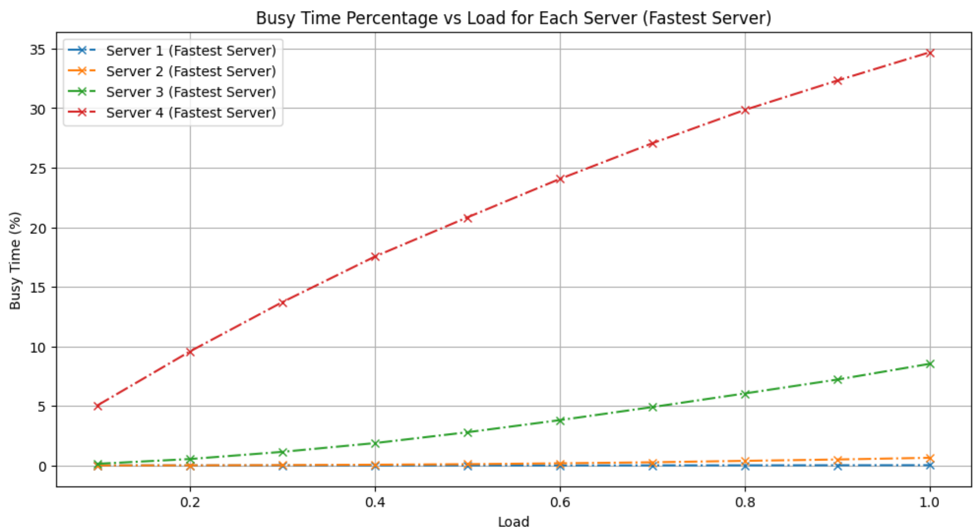
- Results in uneven load distribution and higher variability in performance metrics.
- Can lead to unpredictable queueing delays and often higher queueing delays due to uneven load distribution.

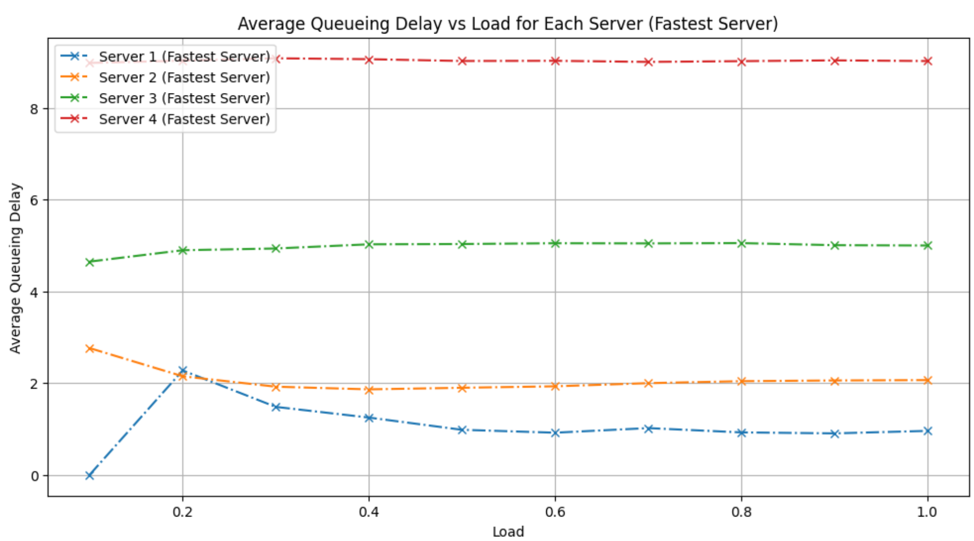




Fastest Server Assignment

- Concentrates load on the fastest server, leading to imbalanced utilization. The fastest server handles the majority of the load, while slower servers are underutilized
- Minimizes queueing delays for light to moderate loads but can cause bottlenecks under heavy load conditions.
- While this algorithm minimizes queueing delay for requests handled by the fastest server, it can lead to higher overall delays under heavy load due to the bottleneck effect.





Conclusion

The round-robin assignment algorithm offers the most balanced and predictable performance among the tested strategies, effectively utilizing faster servers and maintaining lower average queueing delays. Random assignment introduces variability and unpredictability, while the fastest server assignment can optimize delays under light loads but risks bottlenecks under heavy traffic.

Task 4

Introduction

In Task 4, we analyze the impact of different service time distributions on the performance of a single drone equipped with a base station featuring a single antenna (N = 1, m = 1). Specifically, we compare the traditional M/M/1 queue (exponential service time) with M/G/1 queues, where the service times follow different distributions, such as uniform and normal distributions. The goal is to observe how these distributions affect key performance metrics: average waiting time and loss probability.

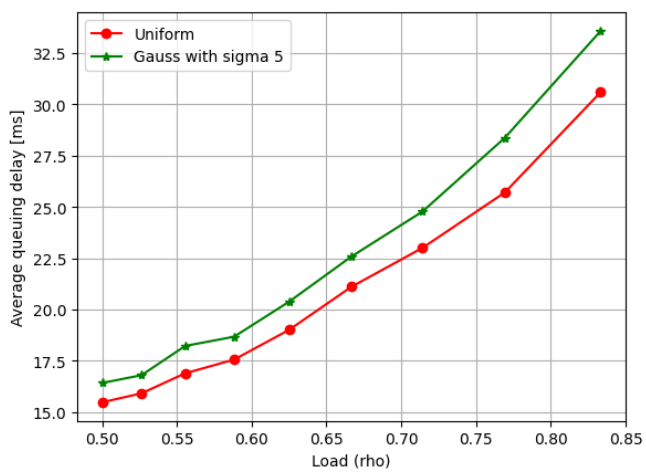
Simulation Details

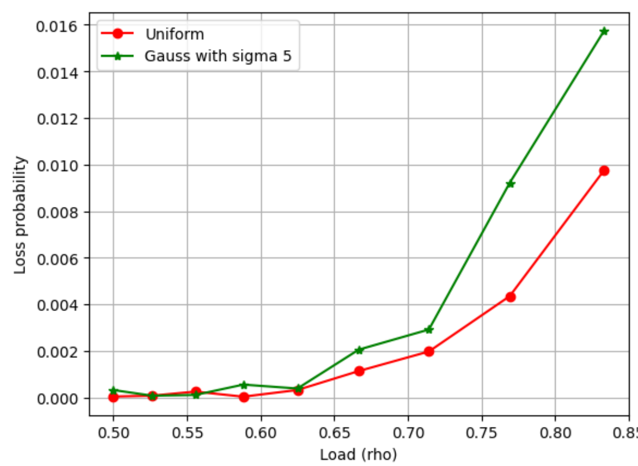
The simulation considers the following parameters:

- **Service Rate**: 10 packets per second.
- **Arrival Rate**: Varied to test different load conditions.
- **Simulation Time**: 500,000 time units.
- **Service Time Distributions**:
  Uniform Distribution: Service time is uniformly distributed between 5 and 15 units.
  Normal Distribution: Service time is normally distributed with a mean of 10 and a standard deviation of 5 units.

Results

	Uniform Distribution	Normal Distribution (σ = 5)
Average Queueing	- The average queueing delay increases gradually with the load. - The uniform distribution provides a predictable and consistent delay, as all service times are bounded between 5 and 15 units.	- The average queueing delay is higher than the uniform distribution, especially at higher loads. - The normal distribution introduces more variability in service times, resulting in higher delays. - The occasional long service times due to the normal distribution's tail increase the average delay.
Loss Probability	- The loss probability increases with load but remains relatively lower than with the normal distribution. - The bounded nature of the uniform distribution ensures that service times are predictable, reducing the chances of buffer overflow.	- The loss probability is higher compared to the uniform distribution. - The higher variability and occasional long service times of the normal distribution led to increased buffer occupancy and higher loss probabilities.





Conclusion

The simulation results indicate that the choice of service time distribution significantly impacts the performance of the UAV-based communication system. The uniform distribution offers more predictable performance with lower delays and loss probabilities, while the normal distribution introduces higher variability, leading to increased delays and loss probabilities. These insights are crucial for designing UAV-based communication systems to optimize performance under different service time conditions. In summary, we can say:

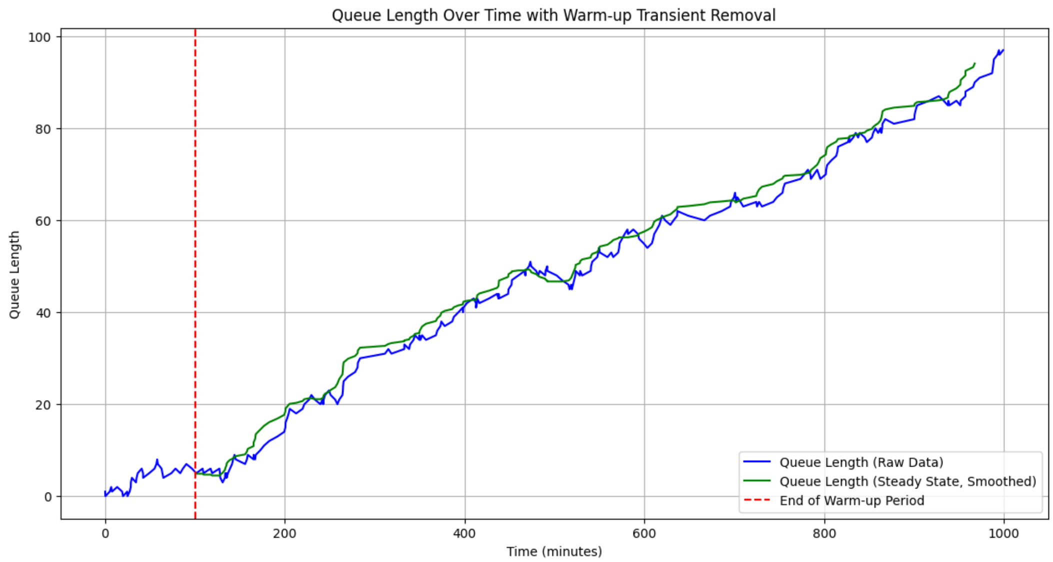
- **Uniform Distribution**:
  - Provides more predictable and consistent performance.
  - Lower average queueing delays and loss probabilities compared to the normal distribution.
- **Normal Distribution**:
  - Introduces higher variability in service times.
  - Results in higher average queueing delays and loss probabilities due to the occasional long service times.

Lab 2

Task1

a) Observe the System Behavior During the Warm-up Transient Period

In this task, we observed the behavior of a single drone system during the warm-up transient period to identify the transition to the steady state. The system was simulated using a discrete-event simulation approach. The following results were obtained from the simulation. Note that the blue line is just a hypothetical line comparing the Steady-state situation (green line) to the Raw data (blue line).



The plot includes:

- The raw queue length data over the entire simulation period (blue line).
- The smoothed queue length data after removing the warm-up period (green line).
- A vertical red dashed line indicates the warm-up period's end at 100 minutes.
- The queue length was plotted over time to visualize the system's behavior.
- As seen in the plot, the queue length gradually increases during the initial period, indicating a transient state.
- The transition to the steady state can be observed once the queue length stabilizes and follows a more predictable pattern.

b) Method to Remove the Warm-up Transient

To remove the warm-up transient, we applied a method of ignoring the initial transient period based on visual analysis and the “moving average smoothing” Function. The specific steps taken were:

1. **Identifying the Warm-up Period**: Based on the initial analysis, the warm-up period was determined to be the first 100 minutes of the simulation.
2. **Removing Warm-up Data**: Data points corresponding to the first 100 minutes were excluded from the analysis.
3. **Smoothing the Steady State Data**: To further reduce noise and fluctuations, a moving average smoothing function was applied to the remaining data, providing a clearer view of the steady state behavior.

Task 2

a) Design Drone Scheduling Schemes

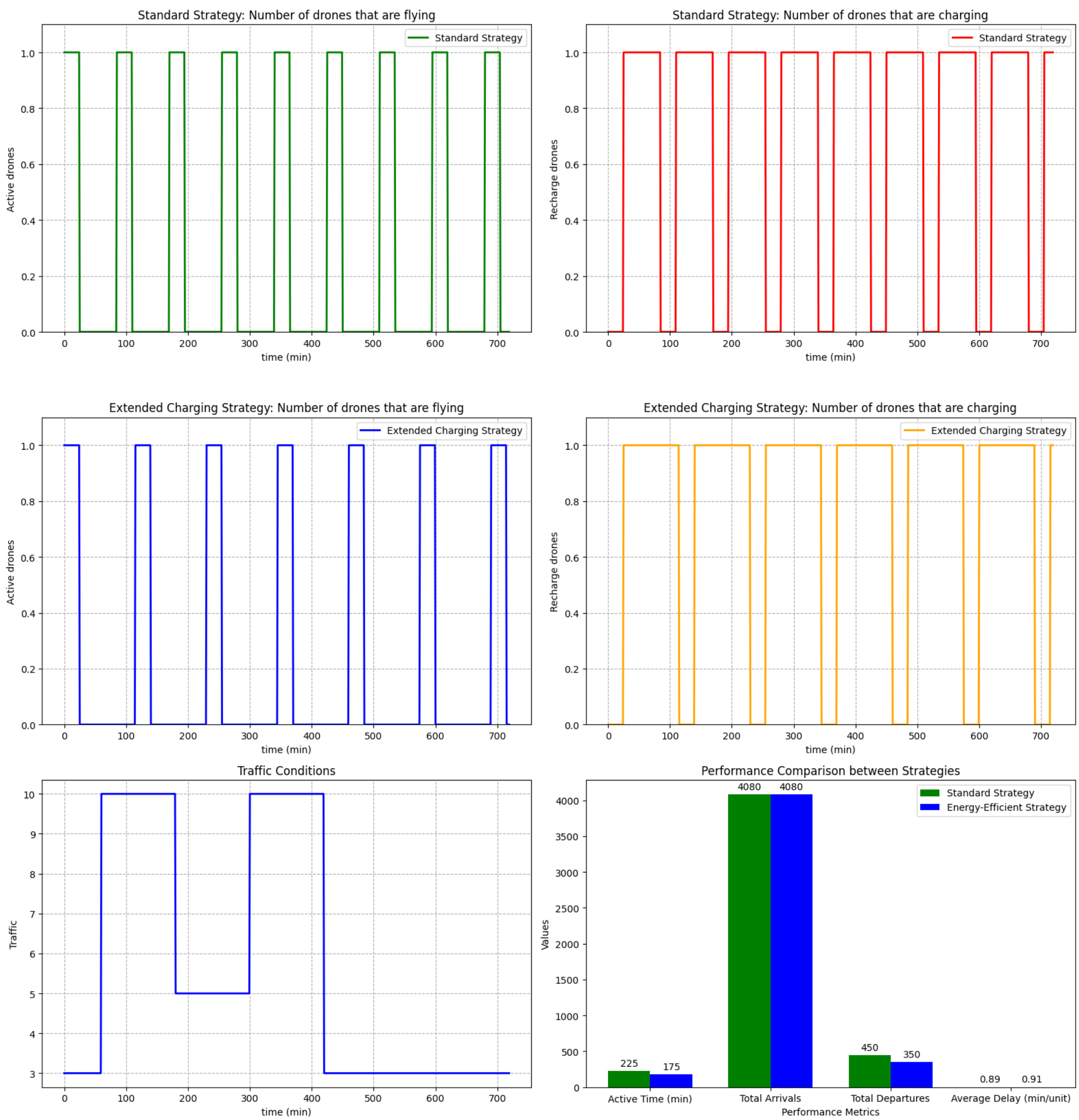
The code simulates drone operations with two strategies:

- **Standard Strategy:** 25 minutes active time, 60 minutes charging time.
- **Extended Charging (or energy efficient) strategy:** 25 minutes active time, 90 minutes charging time.

Key performance metrics which were analyzed in this lab from this task to the end are:

- **Active Time:** The cumulative time period during which the drone is operational and handling traffic.
- **Total Arrivals:** The total number of traffic units that arrive in the system over the simulation period.
- **Total Departures:** The total number of traffic units successfully handled and offloaded by the drone.
- **Average Delay:** The average time each traffic unit spends in the system before being handled by the drone.

Also, as mentioned in the lab instructions, analysis was performed from 8 a.m. to 8 p.m. However, the chosen peak hours were 8 a.m. to 11 a.m. and 1 p.m. to 3 p.m.



Conclusion

Standard Strategy: This strategy allows for more frequent drone activity due to shorter charging times. It is recommended to use this strategy during peak hours to maximize the drone's active time and handle more traffic.

Extended Charging Strategy: This strategy results in longer downtimes for the drone but can be useful if prolonged operational periods are needed. Due to reduced active time, it might be less effective during peak hours.

b) Compare System Performance

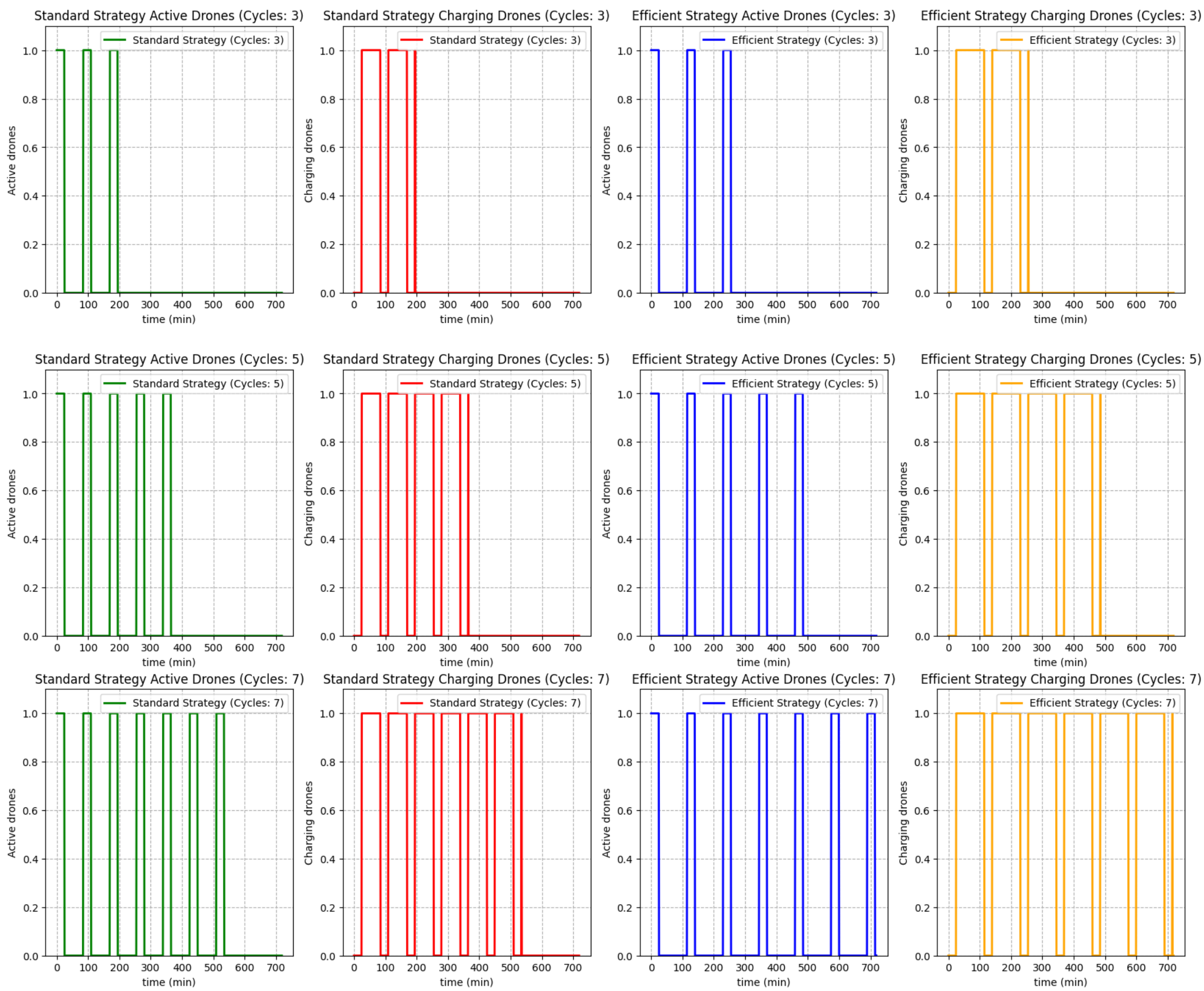
In this part, the system performance was compared using different scheduling strategies, and the scheme that handles the largest traffic volume was identified.

Conclusion

The Standard Strategy has a higher active time and total departures, handling a larger fraction of traffic volume during the day compared to the Extended Charging Strategy. The Standard Strategy's average delay is slightly lower, indicating better Service Quality.

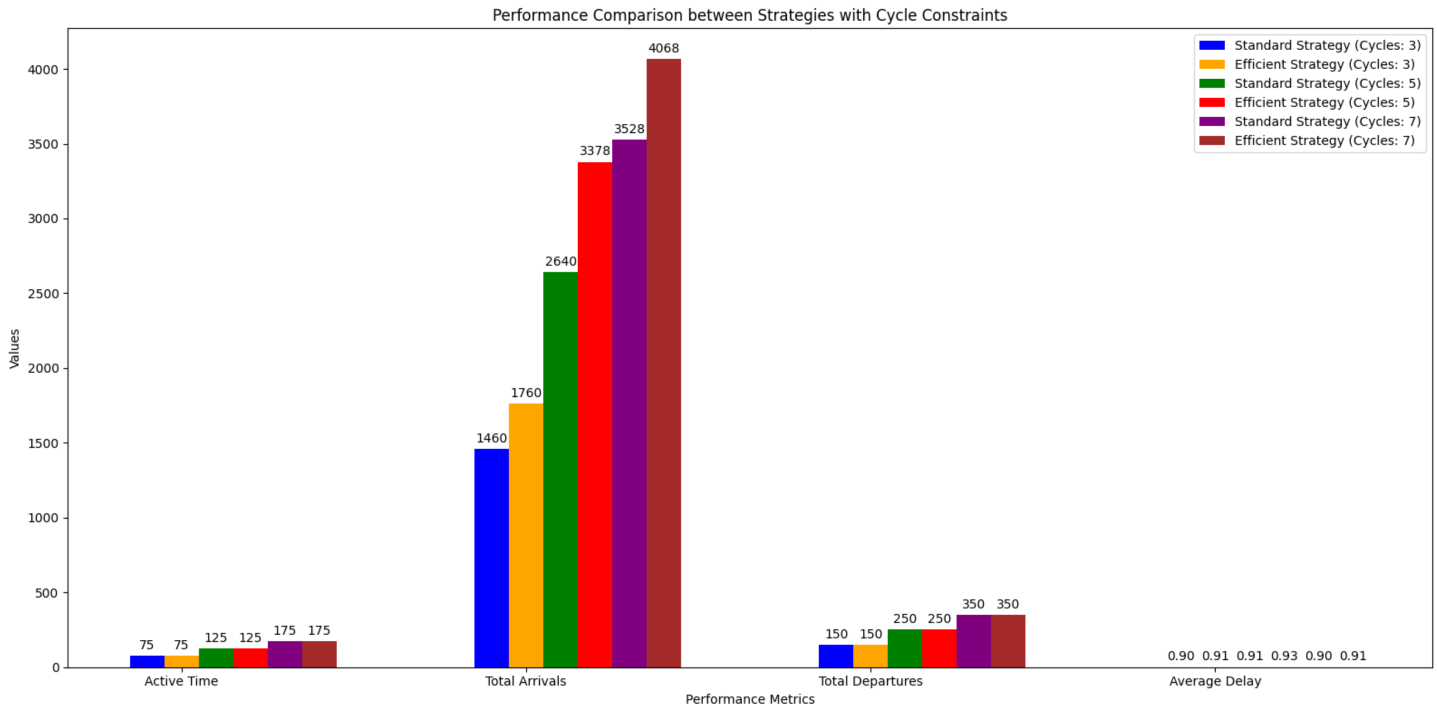
c) Introduction of Cycle Constraints

To limit battery degradation, a constraint on the maximum number of battery charging/discharging cycles is introduced. The system performance is evaluated under different thresholds: 3, 5, and 7 cycles per day.



Conclusion

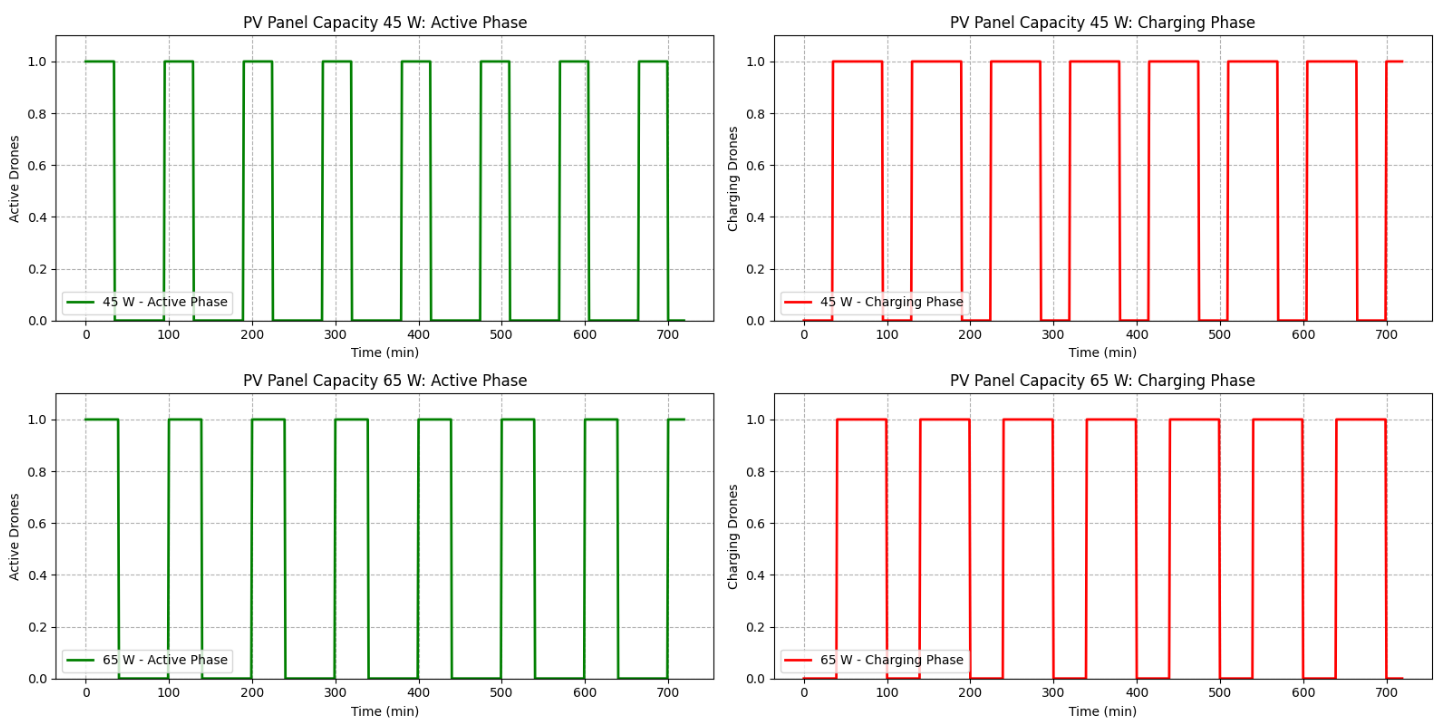
Based on the simulation results above and the performance metrics in the plot below, the **Efficient Strategy** consistently outperforms the **Standard Strategy** in terms of handling a higher total arrival volume across all cycle constraints. Despite having a slightly higher average delay, the Efficient Strategy allows for greater offloading of traffic, making it the preferable choice for maximizing the volume of traffic handled during peak periods and overall performance under cycle constraints.

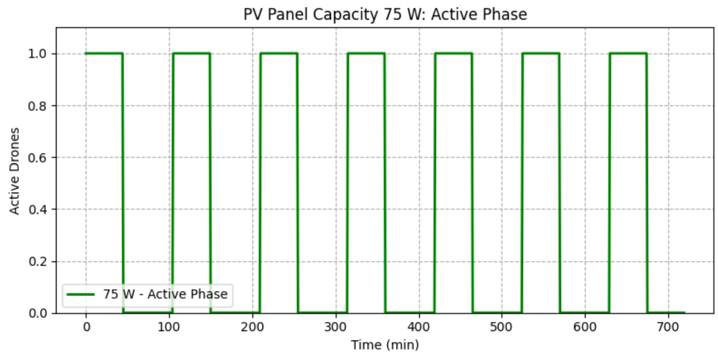


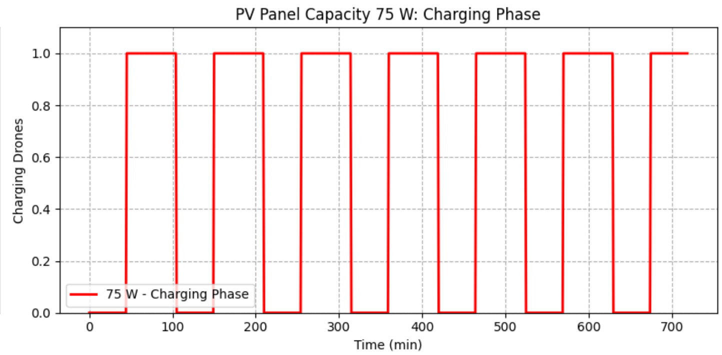
Task 3

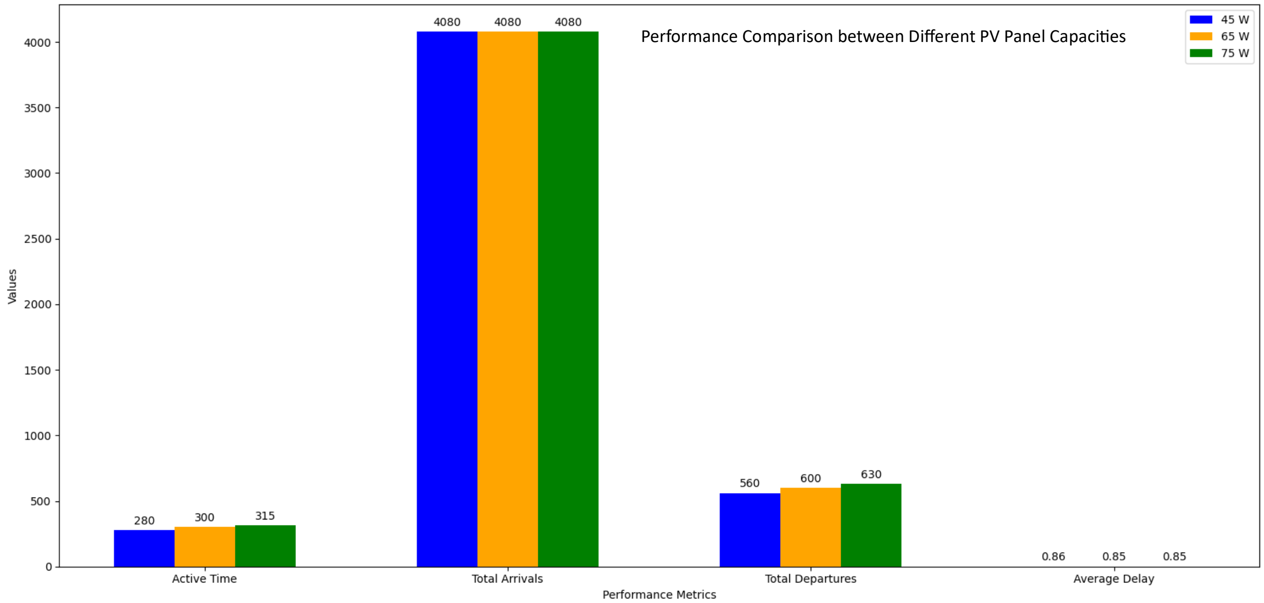
a) Effect of Varying PV Panel Capacity on Scheduling Schemes and System Performance

In this task, we analyze the impact of different PV panel capacities on the performance of a drone used to offload mobile traffic in a business area. The drone is equipped with a battery and a PV panel, and we investigate how varying the PV panel capacity (45 W, 65 W, and 75 W) influences the scheduling schemes and overall system performance.









Conclusion

Increasing the PV panel capacity improves the drone's active time and the total departures while maintaining a similar average delay. The 75 W PV panel configuration performs the best, with the highest active time and total departures, indicating more efficient traffic handling. This suggests that higher PV panel capacities allow the drone to stay active longer and handle more traffic, optimizing the offloading process in peak traffic areas.

b) Analysis of Traffic Volume Handled and Battery Cycles

We examined the fraction of traffic volume handled by the drone and the number of battery charging/discharging cycles for different PV panel capacities (45 W, 65 W, and 75 W). This analysis helps us understand the efficiency and sustainability of the drone's operations under varying energy capacities.

Conclusion

The results indicate that higher PV panel capacities enable the drone to handle a larger fraction of the traffic volume while requiring fewer battery charging/discharging cycles. Specifically, the 75 W PV panel configuration achieved the highest traffic handling efficiency (15.44%) with the lowest number of battery cycles (6). This suggests that increasing the PV panel capacity not only improves the drone's ability to manage traffic but also reduces the frequency of battery cycling, potentially extending the battery's lifespan and enhancing the overall sustainability of the drone's operations. Reducing the number of charging cycles implies less downtime for the drone, allowing it to remain operational for longer periods and, thus, better serve the needs of the area. The 75 W configuration demonstrates the best balance between energy efficiency and operational capacity, making it the most effective choice among the three options.

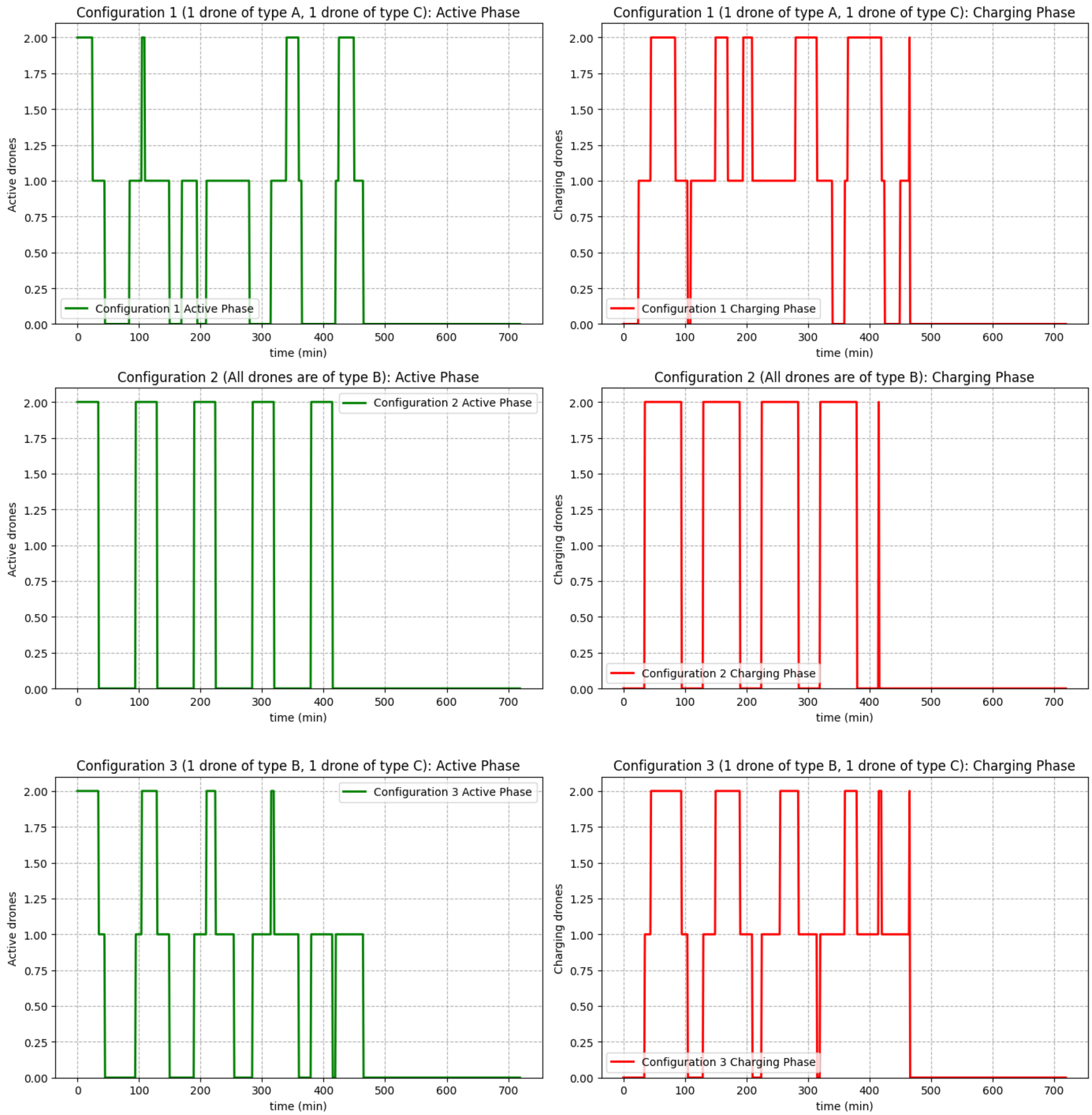
Task 4

a) Drone Scheduling Strategy for Different Drone Configurations

In this task, we evaluate the performance of three different drone configurations. Each configuration includes drones of different types to maximize the traffic volume handled during peak periods.

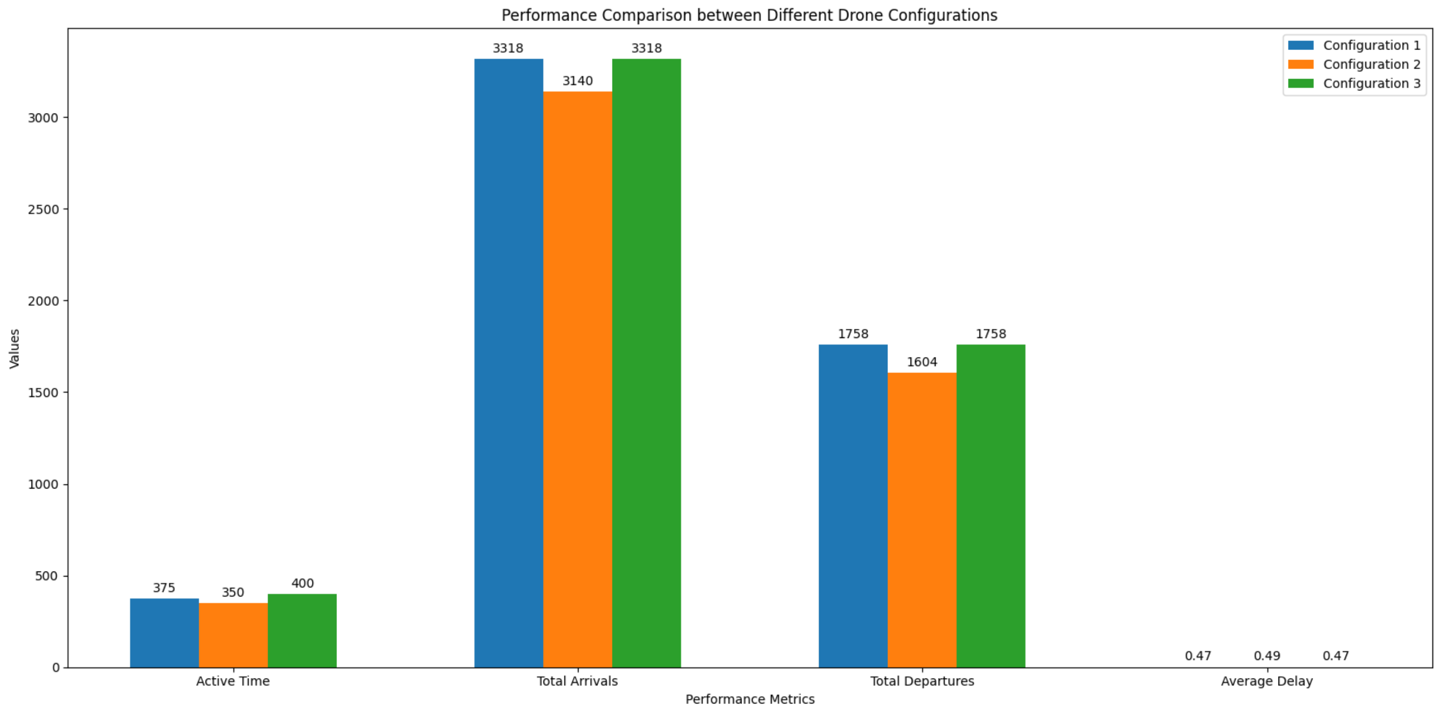
Configurations:

- **Configuration 1:** 1 drone of type A, one drone of type C
- **Configuration 2:** All drones are of type B
- **Configuration 3:** 1 drone of type B, one drone of type C



Conclusion

According to the performance metrics plot below, configuration 3, with one drone of type B and one of type C, showed the best performance in terms of active time and total departures, handling 1758 traffic units with an average delay of 0.47 minutes/unit. Configuration 2, with two drones of type B, had the least active time and highest average delay, indicating less efficiency in handling peak traffic. Configuration 1 performed similarly to Configuration 3 but with a slightly lower active time. Overall, Configuration 3 is the most effective in maximizing the volume of traffic handled while maintaining a reasonable delay.



b) Analysis

Configuration 3, consisting of one drone of type B and one drone of type C, offers the best trade-off among the volume of traffic handled, the number of battery charging/discharging cycles, and the Quality of Service (QoS). This configuration handled a high traffic volume (1758 units) with the lowest average delay (0.47 minutes/unit). The type B drone, equipped with a PV panel, and the type C drone, with a larger buffer size, complement each other effectively, resulting in fewer charging cycles while maintaining high service rates.

Motivating Factors:

- **Volume of Traffic Handled**: Configuration 3 handled the highest traffic volume, equivalent to Configuration 1, but with better QoS, as indicated by the lower delay.
- **Battery Charging/Discharging Cycles**: The combination of types B and C drones in Configuration 3 allowed for a more balanced distribution of active and charging phases, reducing the frequency of battery cycles compared to Configuration 1, which used a type A drone with only battery power.
- **Quality of Service (QoS)**: The average delay in Configuration 3 was the lowest among all configurations, showing that this setup can handle high traffic volumes efficiently without compromising service quality.

Conclusion

Configuration 3, with one drone of type B and one drone of type C, provides the optimal trade-off, effectively balancing the volume of traffic handled, minimizing the number of battery cycles, and delivering superior QoS in terms of experienced delay.