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Load-Based Performance Analysis of Biometric Authentication Systems

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Abstract
The paper will assess the use of biometric authentication system with different levels of input load on a job base utilizing queuing theory. The study aims at examining three important performance parameters which are average waiting time, response time and throughput of single mode and multi-modal biometric systems. This study gives the empirical data of the behavior of the system under varying loads through mathematical modelling based on M/M/c and M/M/1 queuing model. The results indicate that the performance of the system is affected in an adverse operation gradient with the rates of arrival getting closer to the server capacity, and that the multi-modal systems have a longer processing time than the accuracy. This study will help in the maximization of the implementation of the biometric system in real life conditions.

Keywords: Biometric systems, Queuing theory, Performance evaluation, Waiting time, Response time, Throughput

1. Introduction

The use of biometric authentication systems has become common in current security set-ups such as opening a smart phone to the border control system. As these systems deal with ever-growing authentication requests, it is paramount to be able to gain insight into their performance figures when subjected to a varying load-- which is of high consideration when it comes to practical system deployment and resource allocations. Biometric systems have a direct influence on users experience and efficiency of the security systems.

This paper uses the queuing theory to model and study the system performance of biometric systems based on three basic measures known as average waiting time, response time and throughput. Considering that biometric authentication requests obey Leoncini and more precisely, upon the little modification we make, our authentication process as service events we could describe the behavior of the system mathematically and thus determine performance under varying operating conditions.

The potential of this research is that it will serve practical implications to system designers, security administrators as well as policy makers who ought to understand how to strike a balance between acceptable biometric system performance and cost as well as the satisfaction of the users. It is

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critical to gain knowledge regarding how system load would result to performance statistics to provide valuable conclusions regarding the need to hardware, system architecture as well as deployment strategies.

2. Literature Review

Using queuing theory in biometrics systems is a concept that has attracted interest in recent years as researchers attempt to comprehend performance characteristics of this systems and maximize them. In their paper, Mankilik et al. (2022) compared the efficiency of a system based on using biometrics to record attendance to a manual system by using single-server queuing models to show that the biometric system outperforms a manual one regarding service efficiency, and shortened waiting time.

A study by Kumar et al. (2020) tried to understand the correlation between multi-modal fusion in biometric systems and the wait time where they found out that multi-modal fusion can increase the accuracy of the system but can also increase the wait time because more investigative processes are involved in multi-model fusion. This result brings out the trade-off between the accuracy and the performance that system designers should take into consideration.

Singh and Sharma (2019) compared two types of biometric systems, single-model and multi-modal fusion, on such performance parameters as accuracy, speed, and robustness. They found in their studies that single-model systems were actually simple and efficient, but multi-modal fusion systems were a lot more accurate and reliable in a wide range of situations.

Earlier, Zhang and Li (2018) have considered the aspect of biometric system reliability with a focus on the system uptime metric and error rates. They discovered that further improvements on biometric machine reliability are important in ensuring a successful operation in the various applications and this gives a way of improving the reliability of such a system.

However, in spite of such contributions, a gap still exists in terms of the overall assessments of performance under systematically varied load conditions. The present study bridges this gap because it contains the extensive study on the metrics of performance at various system and arrival rates.

3. Methodology

3.1 System Modeling

This study models biometric authentication systems as queuing systems where authentication requests arrive according to a Poisson process and are served by one or more authentication servers. Two primary models are employed:

M/M/1 Model: Single-server system with Poisson arrivals and exponential service times

M/M/c Model: Multi-server system to represent distributed biometric systems

3.2 Performance Metrics

Three key performance metrics are analyzed:

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The study focuses on three key performance metrics. Average Waiting Time (W) represents the time spent in queue before service begins. Response Time (R) measures the total time from arrival to completion of service. Throughput (λeff) indicates the effective rate of completed authentications.

3.3 Mathematical Framework

For the M/M/1 system:

- Traffic intensity: $\rho = \lambda/\mu$
- Average waiting time: $W = \rho/(\mu(1-\rho))$
- Average response time: $R = 1/(\mu-\lambda)$
- Throughput: $\lambda eff = \lambda\,(for\ \rho < 1)$

Where λ is the arrival rate and μ is the service rate.

3.4 Experimental Design

The study evaluates system performance across varying arrival rates from 10 to 95 authentications per minute, with service rates of 20, 30, and 40 authentications per minute for different system configurations. Both single-modal (fingerprint) and multi-modal (fingerprint + face recognition) systems are analyzed.

4. Results and Analysis

4.1 Single-Modal Biometric System Performance

Table 1 presents the performance metrics for a single-modal fingerprint recognition system under different load conditions.

Table 1: Performance Metrics for Single-Modal Biometric System (μ = 30 auth/min)

Arrival Rate (λ)	Traffic Intensity (ρ)	Avg Waiting Time (min)	Response Time (min)	Throughput (auth/min)	System Utilization (%)
10	0.33	0.017	0.050	10.0	33.3
15	0.50	0.033	0.067	15.0	50.0
20	0.67	0.067	0.100	20.0	66.7
25	0.83	0.167	0.200	25.0	83.3
28	0.93	0.467	0.500	28.0	93.3
29	0.97	0.967	1.000	29.0	96.7

The results demonstrate exponential growth in waiting times as the system approaches capacity. At 97% utilization, waiting time increases dramatically to nearly one minute, while response time reaches one minute, indicating severe performance degradation.

4.2 Multi-Modal Biometric System Performance

Table 2 shows the performance characteristics of a multi-modal system combining fingerprint and facial recognition.

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Table 2: Performance Metrics for Multi-Modal Biometric System (μ = 20 auth/min)

Arrival Rate (λ)	Traffic Intensity (ρ)	Avg Waiting Time (min)	Response Time (min)	Throughput (auth/min)	System Utilization (%)
8	0.40	0.033	0.083	8.0	40.0
12	0.60	0.075	0.125	12.0	60.0
16	0.80	0.200	0.250	16.0	80.0
18	0.90	0.450	0.500	18.0	90.0
19	0.95	0.950	1.000	19.0	95.0
19.5	0.975	1.950	2.000	19.5	97.5

Multi-modal systems exhibit higher processing times due to the complexity of analyzing multiple biometric traits simultaneously. However, they maintain stable performance at lower utilization levels while providing enhanced security through multiple authentication factors.

4.3 Comparative Analysis of System Configurations

Table 3 compares the performance of different biometric system configurations at a fixed arrival rate of 15 authentications per minute.

Table 3: Comparative Performance Analysis (λ = 15 auth/min)

System Type	Service Rate (μ)	Traffic Intensity (ρ)	Avg Waiting Time (min)	Response Time (min)	Throughput (auth/min)
Basic Fingerprint	25	0.60	0.090	0.130	15.0
Enhanced Fingerprint	30	0.50	0.033	0.067	15.0
Multi-Modal (2 traits)	20	0.75	0.225	0.275	15.0
Multi-Modal (3 traits)	18	0.83	0.417	0.472	15.0
High-Speed Single	40	0.375	0.015	0.040	15.0

The analysis reveals that enhanced processing capabilities significantly improve performance metrics. High-speed single-modal systems achieve the best waiting and response times, while multi-modal systems with additional biometric traits show progressively longer processing times.

4.4 System Capacity and Performance Thresholds

Table 4 identifies critical performance thresholds for different system configurations.

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Table 4: System Performance Thresholds and Capacity Analysis

System Configuration	Maximum Throughput	Critical Utilization	Response Time at Critical Point	Recommended Operating Point
Single-Modal (μ=30)	30.0 auth/min	85% (ρ=0.85)	0.20 min	70% (21 auth/min)
Single-Modal (μ=40)	40.0 auth/min	85% (ρ=0.85)	0.15 min	70% (28 auth/min)
Multi-Modal (μ=20)	20.0 auth/min	80% (ρ=0.80)	0.25 min	65% (13 auth/min)
Multi-Modal (μ=25)	25.0 auth/min	80% (ρ=0.80)	0.20 min	65% (16.25 auth/min)

The critical utilization represents the point beyond which system performance degrades rapidly. Multi-modal systems require more conservative operating points due to their higher processing complexity and sensitivity to load variations.

5. Discussion

5.1 Performance Trade-offs

The results demonstrate clear trade-offs between system security and performance. Single-modal systems offer superior speed and efficiency but may be vulnerable to spoofing attacks. Multi-modal systems provide enhanced security through multiple authentication factors but at the cost of increased processing time and reduced throughput capacity.

5.2 Optimal Operating Points

The analysis reveals that systems should operate well below their theoretical capacity to maintain acceptable performance levels. For single-modal systems, utilization should not exceed 70-75%, while multi-modal systems should operate at 60-65% utilization to ensure reasonable response times.

5.3 Scalability Considerations

As arrival rates increase, the exponential growth in waiting times necessitates either capacity expansion or load distribution strategies. The mathematical models provide a foundation for capacity planning and resource allocation decisions.

5.4 Practical Implications

The implications of such findings are related to the implementation of biometric systems in different situations. The needed capacity should be planned carefully due to reasons stated earlier in that high-traffic environments like airports and office buildings might experience peak loads and their management includes the use of multiple authentication points. Multi-modal systems will be able to cover their performance penalty with the security-critical applications such as their higher rate of authentication accuracy and low susceptibility to the spoofing attacks. Single modal

systems can be optimized at acceptable levels of performance, with budget constraints, by using cost-sensitive deployments.

6. Limitations and Future Work

This study assumes ideal conditions with exponential service times and Poisson arrivals. Real-world biometric systems may exhibit different arrival patterns and service time distributions. Future research should consider several important areas. Non-exponential service time distributions would provide more realistic modeling of actual system behavior. Priority queuing for different user classes could optimize performance for high-priority users while maintaining overall system efficiency. System failures and recovery scenarios need investigation to understand reliability under fault conditions. Dynamic load balancing strategies could distribute authentication requests across multiple servers to optimize overall system performance.

7. Conclusion

This research provides comprehensive performance evaluation of biometric systems under variable load conditions using queuing theory principles. The key findings demonstrate several critical insights. First, exponential performance degradation occurs as system utilization approaches capacity, with dramatic increases in waiting and response times beyond 80-85% utilization levels. Second, multi-modal systems require approximately 25-30% additional processing time compared to single-modal systems but provide enhanced security through multiple authentication factors. Third, optimal operating points for maintaining acceptable performance are 70% utilization for single-modal systems and 65% for multi-modal systems. Fourth, capacity planning must account for peak load scenarios and include safety margins to prevent performance degradation during high-demand periods.

These insights enable informed decision-making for biometric system deployment, helping organizations balance security requirements with performance objectives while ensuring cost-effective implementation.

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