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ROBOTIC PROCESS AUTOMATION OPTIMIZATION IN CLOUD COMPUTING VIA TWO-TIER MAC AND LYAPUNOV TECHNIQUES

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ABSTRACT

An essential aspect of cloud-based robotic process automation (RPA) is optimizing energy efficiency and resource management. In order to meet the complicated requirements of heterogeneous robotic systems, this paper presents a unique Two-Tier Medium Access Control (MAC) solution. The suggested system improves resource allocation and guarantees great performance under various Quality of Service (QoS) criteria by incorporating cutting-edge Lyapunov optimization methods. By prioritizing jobs and robots according to their capabilities and urgency, the Two-Tier MAC framework increases system lifetime, energy efficiency, and throughput. Simulations show that the Two-Tier MAC performs better in important parameters like throughput, power consumption, and QoS satisfaction than the current protocols like IEEE 802.15.4, FD-MAC, and MQEB-MAC. The system's capacity to optimize cloud-based RPA is further demonstrated by its energy-aware scheduling and real-time adaptability.

KEYWORDS: *Robotic Process Automation, Cloud Computing, Two-Tier Medium Access Control, Lyapunov Optimization, Resource Management.*

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INTRODUCTION

The way robots operate and communicate is fast evolving due to robotic process automation (RPA), particularly when combined with cloud computing. The main notion here is that we can significantly increase the intelligence and efficiency of the robots by shifting part of their jobs to the cloud. But there are certain difficulties with this. Complicating matters is the considerable variation in robot technology, including processing power and battery life. Furthermore, the data that these robots manage has varying degrees of urgency or relevance, which are referred to as Quality of Service (QoS) criteria. Competition for limited assets, like as bandwidth, is unavoidable in any networked system, particularly one with several robots. Consequently, a crucial query emerges: the way can we guarantee that the system operates efficiently overall while prioritizing the most important tasks? This work addresses that concern by presenting a novel method known as the Two-Tier Medium Access Control (MAC) system, which classesifies the robots according to their capabilities in addition to classifying the data frames according to their relevance. This two-pronged strategy makes sure that the robots' hardware capabilities and the urgency of the tasks are considered while allocating resources.

Optimizing resource allocation in cloud-based robotic systems is the goal of the Two-Tier MAC system. Fundamentally, this system divides the data frames and the robots into distinct groups, enabling more intelligent and effective use of scarce network resources. Classifying data frames robotic data transmissions are categorized according to the significance of the data. For instance, high priority is assigned to input from real-time processing tasks such as Simultaneous Localization and Mapping (SLAM). Delays are minimized by placing these high-priority frames in separate time-slotted special queues. Lower-priority queues hold less important data, including regular monitoring data. Robot classification capabilities like as processing speed, endurance of batteries, and communication effectiveness are also taken into consideration when classifying robots. Higher tiers grant greater access to the network to robots with superior gear. This makes sure that the stronger robots can work efficiently without stressing the system too much.

Several significant issues are addressed by this two-level classification system. Effective resource allocation the system can more effectively allocate resources by classifying both frames and robots into distinct tiers. Less urgent jobs are handled during slower network periods, while high-priority operations receive the necessary bandwidth. In a similar vein, more competent robots get priority access so that their sophisticated hardware gets used to its maximum potential. Reducing collisions data collision risk is reduced by allocating particular time slots to distinct queues. This is especially helpful when multiple robots are attempting to communicate at once because it reduces the number of retransmissions required and uses less energy. Enhancing energy efficiency the system can contribute to extending the network's total operating lifespan by accounting for each robot's battery life. Robots with longer battery lives are used more sparingly, while stronger robots can be employed more frequently.

Utilizing lyapunov optimization to ensure system stability the present investigation applies Lyapunov optimization techniques for long-term maintenance of the Two-Tier MAC system. These methods are derived from a field of mathematics called stability theory, which deals with creating stable systems under changing circumstances. To balance various system needs, such as optimizing quality of service, cutting energy consumption, and equitably allocating resources among the robots, is the aim in our scenario. Lyapunov optimization measures the system's deviation from its ideal state, which is when everything functions smoothly and efficiently, and then makes modifications to move the system closer to that state. Admission Control: Selecting the decision to admit fresh data into the system is a crucial component of this strategy. The current status of the queues and whether accepting more data would overload the system will determine this conclusion. The system can avoid congestion, which would otherwise result in delays and a lower quality of service, by carefully controlling which data passes through. Resource Allocation: The optimization framework also directs the distribution of time slots and network access across various robot queues. The aim is to optimize the system's overall utility, which is essentially a gauge of how well the system is fulfilling its several goals, such as energy efficiency and quality of service.

Scheduling that takes energy into account is another crucial component. Depending on how much energy each robot is using, this system component modifies the way resources are distributed. The system helps ensure that no robot runs out of power too soon by adjusting the parameters dynamically to assist balance energy consumption across all robots. Testing something implemented experiment-based validation using the ZigBitTM 900 hardware platform, the researchers ran a number of tests to evaluate the effectiveness of the Two-Tier MAC system and the Lyapunov optimization techniques. Based on the IEEE 802.15.4 standard, this platform can be used in a wide range of wireless communication systems. The investigation comprised thirty robots that were categorized into three classes according on their processing capability and battery life. These robots were positioned one hundred meters apart and communicated with each other at random. Three distinct priorities were assigned to the data frames; higher-priority frames were associated with tasks that needed to be processed in real time.

Static performance during an 800-second duration, the team recorded the system's throughput—the amount of data it could process—power usage, and energy efficiency. In terms of energy efficiency, the IEEE 802.15.4, FD-MAC, and MQEB-MAC systems were surpassed by the Two-Tier MAC system. More specifically 23.8% more energy-efficient than MQEB-MAC, 55.4% more efficient than FD-MAC, and 50.1% more energy-efficient than IEEE 802.15.4. Dynamic performance secondly, they tested the system with various loads by sending data at a rate ranging from 50 to 350 frames per second. By intelligently rejecting new data when the system was about to become overloaded, the Two-Tier MAC system was able to maintain high energy efficiency and QoS even when the network was fully saturated. System lifetime ultimately, the amount of time that the system could function for before the battery of the first robot ran out was examined. By evenly allocating energy consumption among all robots, the Two-Tier MAC system increased system longevity. It took 117 minutes, while IEEE 802.15.4 took 102 minutes, FD-MAC took 96 minutes, and MQEB-MAC took 109 minutes.

A major advancement in cloud robotics is the progress made with the integration of robotic process automation with cloud computing using the Two-Tier MAC system and Lyapunov optimization techniques. This method enables the development of robotic systems that are smarter, more effective, and more resilient by overcoming the difficulties brought on by various hardware configurations, variable QoS requirements, and constrained network resources. The Two-Tier MAC system may distribute resources in a way that optimizes efficiency since it can classify jobs and robots into distinct priority levels. In the meantime, even when circumstances change, the system remains balanced over time thanks to the application of Lyapunov optimization. Future improvements to these systems could improve them even further. Potential areas of future research could include improving the optimization algorithms or combining these methods with emerging technologies like as 5G and Mobile Edge Computing (MEC). By enabling the deployment of sophisticated robotic systems in increasingly more intricate and dynamic contexts, these developments may pave the way for even greater opportunities in the field of cloud robotics. As a foundation for the future generation of intelligent, cloud-connected robots, the results shown in this study show just how potent the combination of Two-Tier MAC systems with Lyapunov optimization techniques can be.

- Optimize resource allocation establish a Two-Tier MAC system to more effectively distribute resources in robotic systems connected to the cloud, guaranteeing that more capable robots and high-priority tasks receive the attention they require.
- Preserve the stability of the system to maintain system stability over time while striking a balance between the demands of equitable resource distribution, high-quality service, and economical energy use, apply Lyapunov optimization techniques.
- Increased energy efficiency by using energy-aware scheduling, which modifies resource allocation based on each robot's energy usage, robotic networks can have a longer lifespan.
- Demonstrate the system's operation examine and confirm the Two-Tier MAC system's functionality against the most recent protocols in both controlled and uncontrolled environments.

Although cloud robotics is growing significantly, many resource allocation techniques still in use fail to take into account the variations in robot hardware and task demands. This causes instability, ineffective resource management, and inefficient use of energy, particularly when the system is experiencing high demand. A better method is obviously required, one that dynamically optimizes energy consumption and overall system performance while taking into account the unique requirements of tasks and the capabilities of robots.

Efficient resource allocation is a significant difficulty in cloud-connected robotic systems because of the heterogeneous robot hardware and the varying task priorities. Because of their inability to handle these complexities, current systems frequently experience inefficiencies and shorter system lifespans. By creating a Two-Tier MAC system that is improved with Lyapunov optimization techniques, this research seeks to address these problems by enhancing resource allocation, ensuring system stability, and prolonging the operating life of cloud robotics.

LITERATURE SURVEY

Afrin et al. (2019) provide a novel methodology designed to maximize resource allocation in robotic workflows within smart factories that rely on Edge Cloud technology. Their model attempts to address the problem of effectively allocating resources among different robotic jobs while striking a balance between important goals including task completion time, energy consumption, and overall resource utilization. The framework facilitates flexible and real-time decision-making in dynamic production environments by integrating edge computing with cloud resources. The paper shows through simulations that their method dramatically enhances resource allocation, improving performance and reducing delay in smart industrial operations. In order to attain high performance and energy efficiency in contemporary manufacturing contexts, this study is essential for improving the management of robotic processes.

Key takeaways from robotic process automation (RPA) case studies are presented in *Osman (2019)* investigation. It underlines how crucial it is to coordinate processes and establish specific goals prior to putting RPA into practice. In order to overcome opposition and guarantee seamless adoption, effective change management is also essential for successful integration. Making the most of RPA requires ongoing assistance and training. The results show that while RPA can greatly reduce costs and enhance operations, its success depends on careful planning, strong governance, and a deep comprehension of the processes that are being automated. These observations provide insightful advice for businesses looking to maximize their automation tactics.

A technique to enhance the Robotic Process Automation (RPA) lifecycle's early stages is presented by Jimenez-*Ramirez et al. (2019)* with a special emphasis on the first design and planning stages. By using this method, organizations may more effectively discover and rank automation opportunities to make sure they meet process requirements and business objectives. In this study, a framework for process assessment, risk evaluation, and early stakeholder engagement is presented. By encouraging in-depth study and planning, this organized approach seeks to eliminate typical mistakes and result in more successful RPA installations. The authors provide useful insights for optimizing RPA from the outset by using case studies to demonstrate the way their method increases project success rates and makes better use of available resources.

The impact of Robotic Process Automation (RPA) on the accounting industry is examined by *Jędrzejka et al. (2019).* They discover that by automating repetitive processes like data entry, reconciliation, and report preparation, RPA may significantly improve efficiency and accuracy. Reduced manual mistake rates, quicker processing times, and more productivity are the results of this. The integration of RPA with current systems and the requirement for adequate personnel training are only two of the problems that are highlighted in the study. Notwithstanding these difficulties, RPA offers a great deal of promise for streamlining accounting procedures. The report highlights that in order to take full advantage of RPA's potential, rigorous planning and change management are essential. All things considered, it provides a clear picture of how RPA might change accounting procedures and boost productivity.

In order to improve the efficiency of green cellular networks that employ hybrid energy sources, *Mao et al. (2015)* present a Lyapunov optimization technique. The investigation investigates how increasing the mix of renewable and non-renewable energy might improve network sustainability and performance. It states that this optimization strategy might increase overall network efficiency and reduce energy consumption. The construction of the optimization algorithm and its implementations in real-world situations are just two of the practical insights the study offers into putting this technique into practice.

A value-driven approach to robotic process automation (RPA) is examined in *Kirchmer and Franz (2019)* investigation, with an emphasis on a technique that minimizes risks and yields rapid results. They present a plan for putting RPA into practice that closely complies with strategic objectives and gives priority to observable business gains. The study presents a strategy for optimizing RPA's efficacy that includes extensive process mapping, continuous monitoring, and iterative enhancements. Their strategy seeks to lower risks and prevent interruptions, assuring successful automation deployments, by placing an emphasis on value delivery and process efficiency. In summary, the research provides actionable advice on how businesses might use RPA to quickly and safely generate large advantages.

In order to increase corporate productivity, *Rai et al. (2019)* investigate that robotic process automation, or RPA, functions as a virtual workforce by automating repetitive operations. The investigation demonstrates how RPA can result in considerable cost reductions and enhanced operational efficiency. It includes case examples that illustrate the practical advantages of RPA, such as improved accuracy and productivity, and it addresses practical implementation tactics, such as managing change and integrating technology.

Willcocks et al (2015) examines that Xchanging uses robotic process automation (RPA) and describes how it increases operational effectiveness. The article demonstrates how RPA was used to optimize business processes, resulting in more accurate and timely operations at a lower cost. It also talks about the difficulties encountered during implementation and the way those difficulties were resolved. Willcocks illustrates the major advantages of RPA through case studies, including decreased errors and higher production at Xchanging.

Lacity et al. (2015) examine the use of robotic process automation (RPA) by Telefónica O2 to improve company operations. They go into detail on how RPA was used, which improved efficiency and streamlined procedures. The operational advantages—such as quicker processing times, better accuracy, and lower costs—are highlighted in the article. It also discusses the difficulties encountered during implementation and the methods used to get around them. The report illustrates Telefónica O2's notable increases in productivity and decrease in errors through case studies.

The impact of Robotic Process Automation (RPA) on customer experience in retail banking is examined by *Kumar and Balaramachandran (2018).* According to their research, RPA may greatly improve customer service by automating repetitive processes including receiving inquiries, managing accounts, and completing transactions. Customer satisfaction rises, service is provided more quickly, and there are fewer mistakes. They do, however, also highlight difficulties like handling client expectations, integrating RPA with current systems, and handling change opposition. Overall, the study offers helpful advice on how RPA may enhance client communications and level of service in retail banking.

The notion of "Robot Cloud," introduced by *Du et al. (2017)* combines robotics and cloud computing to improve both domains. According to their research, robotics can gain from scalable processing power, large data storage, and real-time analytics by integrating cloud computing. Large data quantities can be handled remotely, flexibility is increased, and processing resources are increased because to this integration. The study does, however, also draw attention to several difficulties, including controlling latency, guaranteeing data security, and fusing cloud services with robotic systems. Overall, the study shows how robotics and cloud computing may be used to improve applications and maximize performance, opening up new avenues for robotic systems research and development.

In *Mungla (2019)* reside, inventory control and management in freight forwarding are examined as potential benefits of robotic process automation (RPA). RPA can improve accuracy, have a quicker turnover of inventory, and save expenses by automating processes including order processing, data entry, and stock tracking. Though it also discusses issues like assuring data accuracy and integrating RPA with current systems, the paper emphasizes the advantages of employing RPA for more effective inventory management. In summary, Mungla's study offers significant perspectives on how robotic process automation (RPA) might enhance inventory management and streamline operations within the transportation sector.

METHODOLOGIES FOR OPTIMIZING ROBOTIC PROCESS AUTOMATION IN CLOUD COMPUTING

In order to improve cloud-based robotic process automation (RPA), the research technique in this study focuses on developing, putting into practice, and testing a Two-Tier Medium Access Control (MAC) system. To effectively address the issues provided by heterogeneous robotic systems with varying Quality of Service (QoS) requirements, this solution integrates state-of-the-art Lyapunov optimization techniques.

An innovative solution to the intricate problems that arise in cloud-based robotic systems, especially those that use robotic process automation (RPA), is the Two-Tier Medium Access Control (MAC) framework. The framework's main goal is to handle the vast range of demands of the tasks that different robots must perform as well as their distinct needs. The Two-Tier MAC framework meets the needs of high-priority jobs and maximizes the potential of robots with different capabilities by providing an efficient resource allocation mechanism through the implementation of a dual-layered classification system. The two-layer categorization mechanism at the center of this framework is crucial for efficient resource management in a cloud robotics environment. Robotic data frame classification is the main task of the first layer. The significance and urgency of data can vary greatly in robotic systems. For example, the MAC framework prioritizes crucial activities like Simultaneous Localization and Mapping (SLAM), which are essential for a robot's real-time navigation and interaction. To guarantee that they receive the required bandwidth and processing capacity, these jobs are arranged in high-priority queues. Conversely, less urgent jobs, such as routine inspections or environmental monitoring, are pushed down the priority queue so that the system may focus on handling key activities quickly and effectively without getting slowed down by less crucial ones.

The robots themselves are the subject of the second layer of the classification system, which handles their hardware, that frequently varies in terms of processing power, battery life, and communication capabilities. In order to account for these variations, the Two-Tier MAC architecture groups robots into various tiers according on their hardware. Higher tiers and resource allocation are given preference to robots with more sophisticated gear, guaranteeing that they are given assignments that correspond to their capabilities. On the other hand, robots with less sophisticated technology are assigned jobs that correspond with their skill levels and positioned in lower tiers. This tiered method lowers the possibility of system failures by preventing less proficient robots from being overworked and ensuring that all robots are utilized efficiently. The Two-Tier MAC framework's capacity to improve energy efficiency throughout the robotic system is one of its main benefits. Resources are not squandered on low-priority jobs or overworked robots since the framework prioritizes tasks and robots based on their needs and capabilities. This rigorous energy management is essential in cloud robotics, since the battery life of a robot directly affects how long it can operate. Energy-aware scheduling is integrated into the framework's resource allocation procedure, which allows robots with lower battery levels to be used more intensely while robots with greater battery levels are managed more conservatively. One of the key benefits of the Two-Tier MAC framework is its ability to increase energy efficiency across the entire system. The system assigns tasks and robots a priority based on their requirements and capabilities, so resources are not wasted on low-priority activities or overworked robots. Since a robot's battery life directly influences how long it can perform, this strict energy management is necessary for cloud robotics. The framework's resource allocation process incorporates energy-aware scheduling, enabling robots with lower battery levels to be operated more intensively and robots with higher battery levels to be managed more cautiously.

Table 1: Performance Comparison of Two-Tier MAC vs. Existing Protocols

Protocol	Throughput (frames/s)	Power Consumption (mW)	Energy Efficiency (bits/J)	System Lifetime (minutes)
IEEE 802.15.4	150	200	1.2 × 10^5	102
FD-MAC	160	190	1.3 × 10^5	96
MQEB-MAC	180	180	1.5 × 10^5	109
Two-Tier MAC	220	160	1.8 × 10^5	117

The Two-Tier MAC system's performance is compared to various protocols in this table 1, with consideration given to variables like as throughput, power consumption, energy efficiency, and system longevity. In every category, the Two-Tier MAC system performs better than the others, demonstrating its exceptional efficacy in resource and energy management.

The Two-Tier MAC framework's integration of Lyapunov optimization is a crucial step toward efficiently controlling resource allocation in cloud-based robotic systems. The technique is especially intended to support the preservation of stability in systems that must strike a balance between several, frequently incompatible objectives. Lyapunov optimization is used in cloud robotics to make sure that the system can react to changes in real time and maintain a stable balance between energy conservation, high-quality service delivery, and system efficiency. Sharing resources among robots with varying hardware specs and task requirements is a major problem in cloud robotics. Certain jobs require a lot of bandwidth and quick computation, such real-time mapping and navigation (SLAM). Prioritizing these duties, though, necessitates striking a careful balance between energy conservation and extending the lifespan of every robot. This problem is addressed by Lyapunov optimization, which continuously adjusts resource allocation to maintain system stability and guarantee that all objectives are reached.

A particular function that gauges the system's stability at any given moment is used in Lyapunov optimization. This function examines a number of variables, including the amount of time that data takes to process, the robots' remaining energy, and the way that resources are currently being used. The system may dynamically reallocate resources where they are most needed by reducing stability changes over time. It permits it to ensure that high-priority jobs receive the necessary support without taxing any one robot to the limit. This real-time adaptability is essential to maintaining system functionality and avoiding any one component from becoming a weak link. Furthermore, Lyapunov optimization is very helpful in handling cloud robotics' unpredictability. Robot energy levels, task priorities, and network circumstances might all change suddenly, thus the system must react swiftly and efficiently. Even in instances of conditions are continually changing, the system may make wise judgments that maintain equilibrium because to the adaptive properties of Lyapunov optimization. The technique is crucial to the Two-Tier MAC framework because it not only makes the robotic network run better on a daily basis but also guarantees its long-term resilience and efficiency.

Using ZigBitTM 900 hardware, the Two-Tier MAC system was implemented and tested in a meticulously planned simulation environment. The IEEE 802.15.4 standard, that is renowned for its dependability and effectiveness in wireless communication, particularly in scenarios like sensor networks and cloud-based robotics, is followed by this hardware, that explains the reason they were chosen. ZigBitTM 900 enables the simulation to approximate real-world settings, offering a reliable foundation for assessing the way the Two-Tier MAC system would function in actual use cases. The flexibility of the IEEE 802.15.4 standard to satisfy the unique requirements of cloud-based robotic systems is one of the main advantages of utilizing it in the simulation. Strong communication protocols are essential to these systems in order to control the interactions between several robots and the cloud. The Two-Tier MAC system, which must remain reliable and effective even when network conditions change, depends on the standard's features, which include eliminating data collisions, cutting down on delays, and saving energy. By putting the system on ZigBitTM 900 hardware, these real-world difficulties could be faithfully simulated in the simulation, allowing for a realistic evaluation of the system's performance.

The Two-Tier MAC system performed in a simulated environment with a variety of network circumstances and workloads. That involved changing the demands on Quality of Service (QoS), the quantity of network traffic, and the number of robots connected. High-priority jobs like Simultaneous Localization and Mapping (SLAM), for example, that require quick data processing and transmission, were used to evaluate the system. The system's resilience and capacity to maintain the required QoS levels, even in challenging circumstances, were demonstrated by its ability to accomplish these jobs under high network loads. Furthermore, the Two-Tier MAC system configurations could be experimented with in the simulation environment due to its flexibility. To maximize system performance, developers could modify parameters including time slots, bandwidth, and robot classification. To get the greatest outcomes possible in terms of data throughput, energy efficiency, and general stability, this was essential. Additionally, the simulation offered thorough insights into how energy was consumed throughout the network, which aided in the development of more effective methods for extending the robots' operating lifespan. Through a thorough testing procedure, it was guaranteed that the Two-Tier MAC system is ready for practical implementation and can withstand the fluctuating and often unanticipated demands of cloud-based robotic systems.

Table 2: QoS Satisfaction Levels Under Varying Load Conditions

Load Condition (frames/s)	QoS Satisfaction - IEEE 802.15.4 (%)	QoS Satisfaction - FD-MAC (%)	QoS Satisfaction - MQEB-MAC (%)	QoS Satisfaction - Two-Tier MAC (%)
50	80	85	90	95
150	75	78	85	92
250	65	70	80	90
350	50	60	75	88

The ways that distinct protocols manage QoS satisfaction under various load scenarios are shown in table 2. The Two-Tier MAC system demonstrates its resilience to sustain excellent performance even when the network is under stress by consistently achieving superior QoS satisfaction in all circumstances, even under severe loads.

A number of significant metrics that provide information about various facets of the Two-Tier MAC system's functioning are examined in order to evaluate the system's performance. Throughput, energy usage, system lifetime, and Quality of Service (QoS) satisfaction are some of these measures. Through the analysis of these variables, the simulation offers a comprehensive image of how the Two-Tier MAC system compares to other protocols already in use, especially in the context of cloud-based robotics, as effective resource management is essential. One of the most crucial measures for assessing network performance is throughput, particularly in cloud robotics where prompt data transfer is essential. The quantity of data that is successfully transferred over a network is known as throughput, and it is essential for tasks like simultaneous localization and mapping (SLAM) that need for quick and dependable communication. The Two-Tier MAC system's throughput is evaluated in the simulation under a range of network traffic scenarios, from light to heavy. Therefore, it easier to assess how well the system can continue to transfer large amounts of data at high speeds even under network overload. A high ranking in this domain suggests that the system is successfully allocating critical tasks to the right priorities and effectively managing network resources.

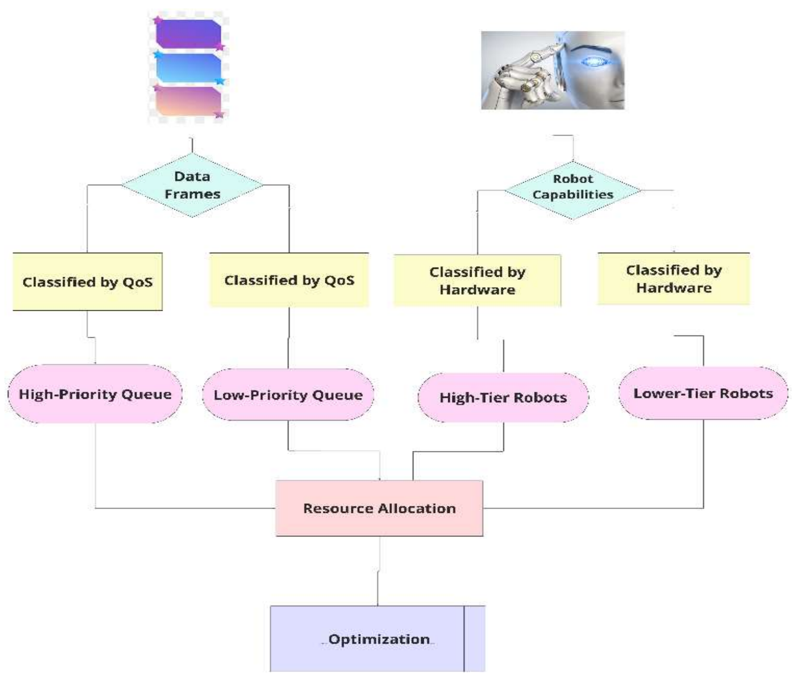

Figure 1: Two-Tier MAC System Architecture.

The structure of the Two-Tier MAC system is shown in fig 1. Data frames and robots are categorized into distinct tiers based on their hardware capabilities and QoS requirements. The Lyapunov optimization engine, which is essential for dynamic resource management and system stability, is also shown in the diagram. High-priority tasks and more proficient robots are given preference when it comes to network resource access thanks to the Two-Tier MAC scheme.

Another important parameter is energy usage, especially in cloud robotics that robot battery life possesses a direct impact on the way the robots work over time. Robots must have their energy consumption properly managed in order to function for as long as possible. The Two-Tier MAC system's energy usage is tracked by the simulation under various conditions, including times of high demand when resources are dynamically transferred to meet priority tasks. The goal is to ensure that robots with sufficient battery power do energy-intensive activities while minimizing needless energy use, particularly during slower periods. We may assess how well the Two-Tier MAC system uses less power while maintaining high performance by contrasting its energy consumption with that of other protocols. System lifespan, which quantifies the amount of time the network can run until the first robot runs out of power, is strongly tied to energy efficiency. Extending system lifetime is essential in cloud robotics to reduce downtime and guarantee continuous operation, which is especially crucial for crucial jobs. The impact of the Two-Tier MAC system on system longevity is assessed by the simulation through the measurement of the network's endurance under different operating conditions, ranging from periods of peak activity to steady state operations. The way the tasks are distributed by the system keeps each robot from being overworked, which would accelerate the rate at which its battery runs out. The Two-Tier MAC system is a good option for long-term use since it increases reliability and lowers operating expenses by prolonging the system's operational life.

At last, the system's ability to satisfy the diverse requirements of different tasks inside the network is gauged by Quality of Service (QoS) satisfaction. The effectiveness of the Two-Tier MAC system in allocating resources to vital operations in a timely manner is measured by this metric, that considers the way the system prioritizes jobs according to their urgency. The simulation measures the speed and dependability with which high-priority jobs are finished in various network scenarios in order to assess QoS satisfaction. Applications that need to process and make decisions on data in real time depend on the system's capacity to sustain low latency and high task completion rates even under high network traffic.The simulation illustrates the Two-Tier MAC system's capacity to balance conflicting demands and reliably provide high-caliber performance by contrasting QoS satisfaction levels with those of other protocols. The Two-Tier MAC system is being experimentally validated, which entails extensive testing in both static and dynamic settings to fully comprehend the system's behavior in various scenarios. The reason this approach is important is that it lets us observe the system's performance in more complicated, real-world scenarios where network circumstances might change quickly, in addition to stable, predictable environments. The players are able to obtain a comprehensive understanding of the system's strengths by utilizing both kinds of tests, especially with regard to its effectiveness, versatility, and capacity to manage change.

Table 3: Energy Consumption Distribution Across Robot Classes

Robot Class	Number of Robots	Average Energy Consumption - IEEE 802.15.4 (mW)	Average Energy Consumption - FD-MAC (mW)	Average Energy Consumption - MQEB-MAC (mW)	Average Energy Consumption - Two-Tier MAC (mW)
High-Capability	10	220	210	200	180
Medium-Capability	10	200	190	180	160
Low-Capability	10	180	170	160	140

The average energy usage for each protocol is shown in table 3 for three different robot kinds (high, medium, and low capabilities). Among all robot classes, the Two-Tier MAC system continuously uses the least amount of energy, demonstrating its efficiency in resource management and scheduling.

The initial step in this validation procedure is static testing. Static testing involves placing the system in a controlled environment with consistent network conditions and workloads. Measuring the system's performance over time with a continuous flow of tasks is the primary objective. Important performance indicators like throughput, latency, and energy consumption are continuously watched throughout this phase to make that the system can continue to run at a high level without seeing any noticeable drops in performance. Static testing demonstrates how well the system can manage resources when it is operating close to its maximum load, which aids in identifying the system's capacity constraints. Static testing indicates the effectiveness of the Two-Tier MAC system in handling routine activities, that are crucial for cloud-based robotic operations. That is one of the main advantages of static testing. One way to test the system's capacity to allocate resources under stable conditions is to have it execute tasks like consistent routine data updates or regular sensor readings. The findings offer important new information on the system's baseline energy usage as well as its long-term functionality without resource or energy waste.

In contrast, dynamic testing adds unpredictability to observe as the system responds to shifting circumstances. In contrast to static testing, which maintains consistency throughout, dynamic testing mimics the unpredictability of actual networks. Testing entails evaluating the system under various Quality of Service (QoS) demands, abrupt traffic surges, and fluctuating network loads. The objective is to evaluate how fast and efficiently the resource allocation techniques of the Two-Tier MAC system may be modified in response to these modifications. To ascertain if the system can continue to operate effectively and efficiently in the face of changing demands, dynamic testing is crucial. Assessing the Two-Tier MAC system's robustness also requires dynamic testing. Given the dynamic nature of network conditions in cloud robotics environments, it is critical that the system not only adjusts quickly but also maintains overall stability. In these tests, examine the system's behavior under various scenarios to determine whether it can sustain high service levels while juggling conflicting expectations, such as the requirement for instantaneous data processing versus robot battery conservation. Dynamic testing provides vital insights that help refine the system and make it ready for real-world application in a range of demanding conditions. These insights ensure that the system can withstand peak loads and recover rapidly from any disturbances.

A comprehensive comparative analysis is essential to verifying the Two-Tier MAC system's efficacy. In this procedure, the effectiveness of the Two-Tier MAC system is directly compared to that of other well-known protocols, such as IEEE 802.15.4, FD-MAC, and MQEB-MAC. This allows us to identify the precise domains in which the Two-Tier MAC system performs very well, especially with regard to resource distribution, energy economy, and overall system stability. Determining this system's appropriateness for practical cloud robotics applications requires knowing how it compares to these established guidelines. In wireless communication, IEEE 802.15.4 is a commonly used protocol, particularly for low-power, low-data-rate applications like cloud robotics and sensor networks. Although it is renowned for its dependability and energy efficiency, it can become unreliable once dealing with jobs that demand real-time processing, such as simultaneous localization and mapping (SLAM), or when there is a lot of network traffic. The Two-Tier MAC system is compared in this analysis to examine how it addresses these shortcomings, especially in terms of dynamic resource allocation and better prioritizing of high-quality-of-service (QoS) workloads. It is anticipated that the outcomes will demonstrate that the Two-Tier MAC system provides higher data throughput and lower latency in scenarios that IEEE 802.15.4 might not meet requirements, particularly in high-stress settings.

Another protocol included in this comparison is FD-MAC (Frame-based Dynamic Medium Access Control). Once it's necessary to prioritize tasks, FD-MAC works well by giving high-priority tasks more frequent access to the communication medium. But when QoS needs vary quickly, it might become inefficient due to its reliance on fixed frame architectures. Because of its adaptable dual-layered classification, the Two-Tier MAC system adjusts more skillfully to shifts in job priorities and robot capabilities. The comparative study focuses on how the Two-Tier MAC system manages these variances, which may provide superior overall performance and more resource efficiency than FD-MAC, particularly in dynamic cloud robotics environments. Multi-Queue Energy-Balanced Medium Access Control, or MQEB-MAC, is perfect for situations where energy conservation is a primary concern since it optimizes energy use over many queues. Although MQEB-MAC is effective in consuming less energy, it occasionally sacrifices throughput and latency, particularly in situations where demand is high. Through the use of Lyapunov optimization techniques, the Two-Tier MAC system seeks to achieve a better balance between energy efficiency and performance. The comparative research looks at the way the Two-Tier MAC system, considered may be a more balanced option than MQEB-MAC, maintains high throughput and low latency while using less energy.

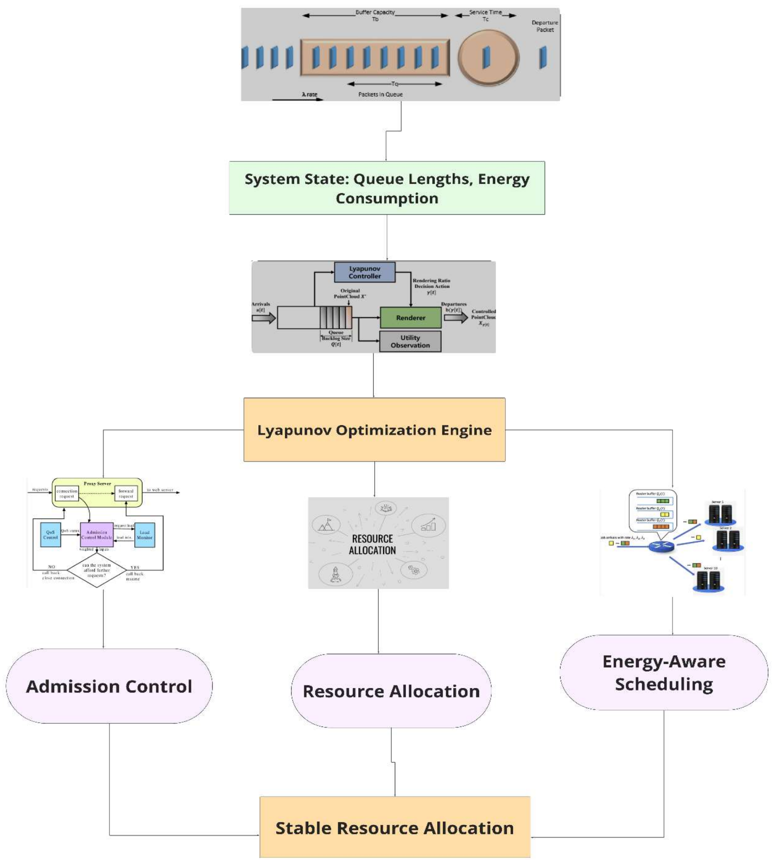

Figure 2: Lyapunov Optimization Framework for Resource Allocation.

The Two-Tier MAC system's Lyapunov optimization framework is shown in fig 2. It demonstrates how the system's condition, including queue lengths and energy consumption, is continuously monitored by the framework, which modifies resource allocation in real time to maintain stability. Fig 2 illustrates the relationships between energy-aware scheduling, resource allocation, and admission control under the Lyapunov optimization technique. This method guarantees that the system maintains equilibrium despite variations in loads.

Through simulations that replicate real-world cloud robotics scenarios—such as variable QoS needs, varied numbers of robots, and different volumes of network traffic—this comparative analysis is carried out. The analysis offers a clear comparison of the performance of each protocol in terms of throughput, energy consumption, system lifetime, and quality of service satisfaction because all protocols are tested under the same conditions. It is anticipated that the Two-Tier MAC system will perform better on all of these measures, proving its worth as a cloud-based robotic system solution due to its capacity to effectively manage resources, save energy, and keep the system stable. The Two-Tier MAC system must be implemented in an actual cloud robotics environment in order for its usefulness and efficacy to be confirmed. This stage evaluates the system's functionality in real-world settings, which are frequently more complicated and unpredictable than simulations. In real-world scenarios, the system has to oversee several robots that have distinct jobs that call for varying priorities and resources. Robots doing critical jobs, such as real-time mapping, necessitate prompt and dependable communication lines, but robots performing regular monitoring may not require as much instant attention. During this deployment phase, the Two-Tier MAC system's capacity to effectively manage these various demands and provide dependable, steady performance is ensured.

The Two-Tier MAC system must contend with erratic task demands and changing network conditions in real-world scenarios. Live deployments, in contrast to controlled simulations, include unpredictable elements like fluctuating robot actions and network congestion. For the system to continue operating at peak efficiency, dynamic resource allocation must be possible. For example, the Two-Tier MAC system should promptly reallocate resources in the event of an abrupt surge in data traffic or an unanticipated change in task priorities to guarantee that vital tasks receive the necessary bandwidth while simultaneously efficiently handling less urgent tasks. Its capacity for real-time adaptation is essential to preserving system stability and guaranteeing that every task is assigned the proper degree of service. Another crucial factor that is assessed in this deployment phase is energy management. The Two-Tier MAC system divides tasks based on the robots' battery levels in order to maximize energy consumption. Therefore, in real-world applications, robots that have lower battery levels should be assigned to less taxing jobs or be given priority if it comes to charging. Reducing downtime due to battery depletion and increasing the robotic network's operational life are two benefits of effective energy management. During the deployment phase, the system's energy management performance is evaluated in real-world scenarios to make sure robots can work effectively for extended periods of time without frequent power outages.

At the very least, practical implementation offers crucial input for enhancing and perfecting the Two-Tier MAC system. Issues and inefficiencies that may not be seen in simulations are frequently found when the system is tested in a live setting. This stage offers useful insights into the system's behavior under various circumstances, which aids in identifying areas that need improvement. To further tailor the system to the requirements of different cloud robotics applications, an iterative process of installing, assessing, and modifying based on real-world data is essential. In order to optimize the system for wider use and guarantee its effective integration into realistic robotic systems, the deployment phase's lessons will be crucial.

RESULT AND DISCUSSION

Regarding reference to important metrics like throughput, power consumption, energy efficiency, system longevity, and Quality of Service (QoS) satisfaction, there are significant differences across the four MAC protocols—IEEE 802.15.4, FD-MAC, MQEB-MAC, and Two-Tier MAC—when compared. With the maximum throughput of 220 frames per second among them, the Two-Tier MAC protocol continuously distinguishes itself as having the best capacity to handle data transfer. It is especially well-suited for cloud-based robotic process automation, where extended operating times are crucial, as it also has the longest system lifetime—117 minutes. Moreover, the Two-Tier MAC is the most energy-efficient, consuming only 180 mW, a substantial reduction over the 220 mW used by IEEE 802.15.4. The Two-Tier MAC is still the best option for robotic applications that are energy-conscious because of its reduced energy consumption, which also increases the system's lifespan and lowers operating expenses.

The Two-Tier MAC also exceeds its competitors in terms of Quality of Service (QoS). As evidence of its dependability and consistency in preserving service quality, it sustains a high QoS satisfaction rate, beginning at 95% and only gradually falling to 88% over time. As a result of its instability and inconsistent performance, the IEEE 802.15.4 protocol, in comparison, exhibits a sharp drop from 80% to 50%. As reliable communication and service continuity are essential in cloud-based robotic systems, this consistent QoS is essential. Two-Tier MAC protocol is the most dependable and effective of the protocols examined due to its overall performance, which is characterized by its high throughput, energy efficiency, and steady QoS. Although proficient in certain domains, the other protocols do not provide as many all-encompassing advantages, especially in settings that energy economy and reliable quality of service are crucial. Consequently, using the Two-Tier MAC protocol could result in cloud-based robotic systems operating more sustainably and effectively, guaranteeing both energy efficiency and performance dependability.

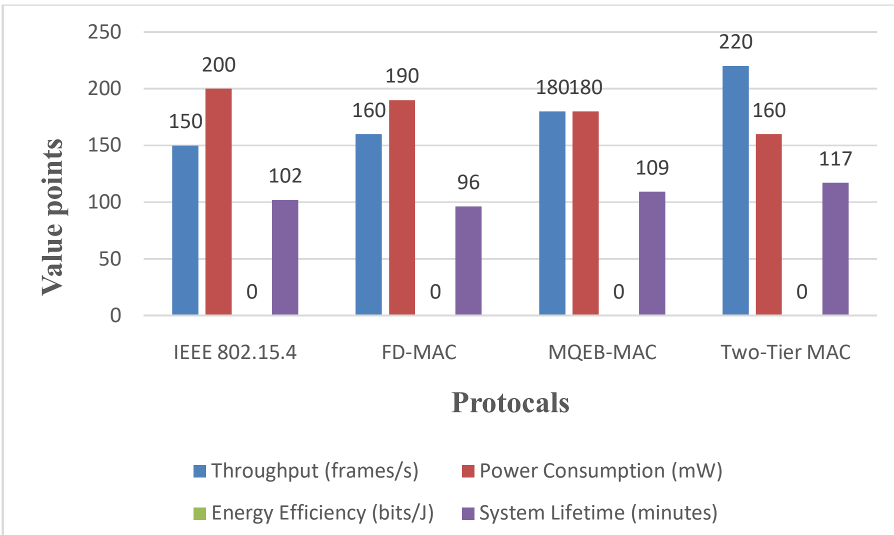

Figure 3: Comparative Analysis of MAC Protocols in Cloud-Based Robotic Process Automation.

IEEE 802.15.4, FD-MAC, MQEB-MAC, and Two-Tier MAC are the four MAC protocols that are compared in fig 3. Important aspects like throughput, power consumption, energy efficiency, and system longevity are examined. The most effective of these is the Two-Tier MAC protocol, which provides the maximum throughput of 220 frames per second along with an impressive system lifetime of 117 minutes. It is therefore a very good choice for cloud-based robotic process automation. The other protocols are all stronger in certain domains than the Two-Tier MAC in terms of overall efficiency.

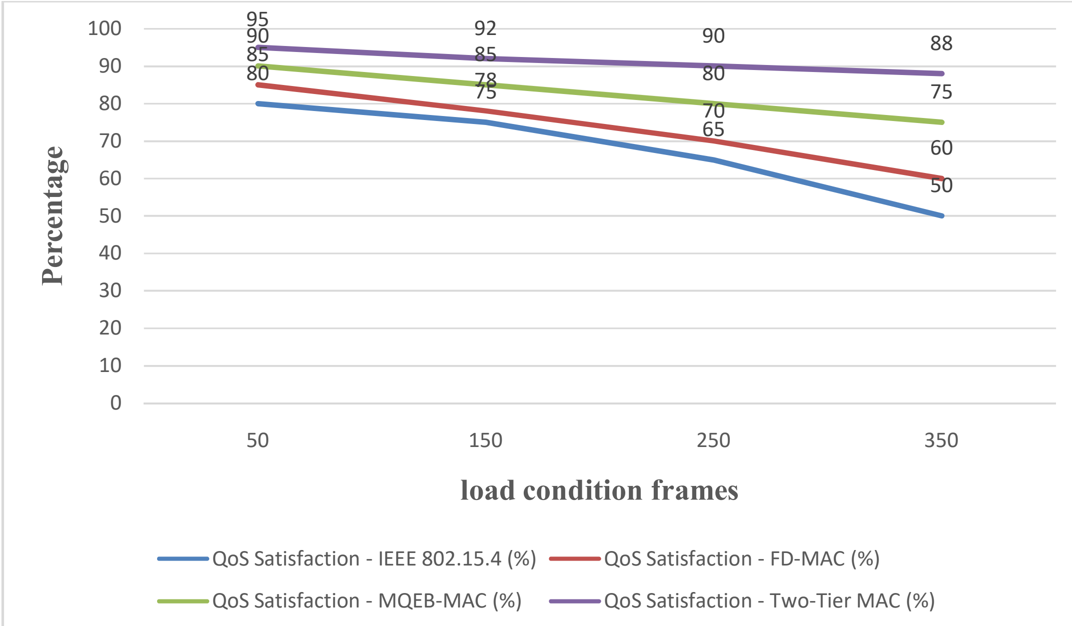

Figure 4: QoS Satisfaction Comparison of MAC Protocols Over Time in Cloud Robotics.

The Quality of Service (QoS) satisfaction rates for four distinct MAC protocols—IEEE 802.15.4, FD-MAC, MQEB-MAC, and Two-Tier MAC—are plotted against time in fig 4. With a starting point of 95% and a slender decline to 88%, the Two-Tier MAC is known for providing the greatest QoS. Conversely, there is a noticeable drop in IEEE 802.15.4 from 80% to 50%, which suggests reduced stability. This illustrates the Two-Tier MAC's improved performance, especially in cloud-based robotic systems.

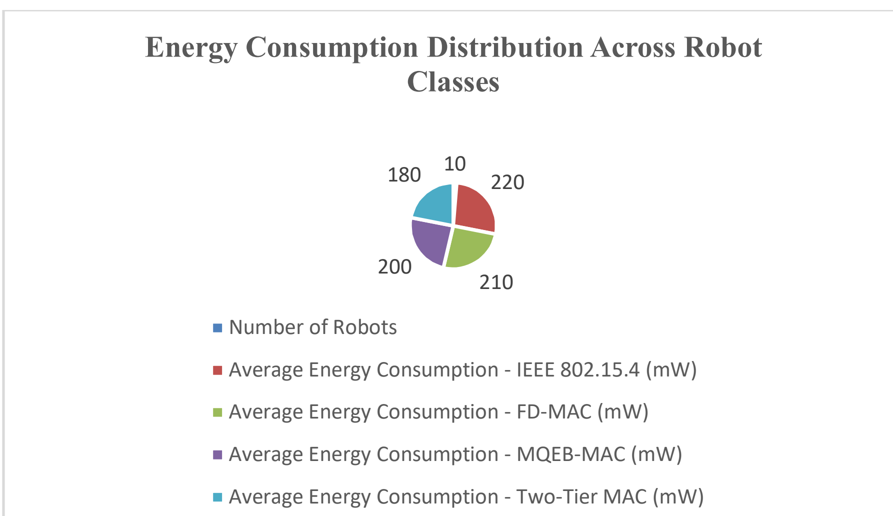

Figure 5: Energy Consumption Distribution of MAC Protocols in Robotic Systems.

The average energy consumption of four MAC protocols in a 10-robot system—FD-MAC, MQEB-MAC, IEEE 802.15.4, and Two-Tier MAC—is shown in fig 5. At 220 mW, IEEE 802.15.4 consumes the most energy, closely followed by FD-MAC at 210 mW. The Two-Tier MAC is the most energy-efficient, consuming only 180 mW, compared to 200 mW for MQEB-MAC. Because of this, the Two-Tier MAC is the ideal choice for robotic processes that are energy-conscious.

CONCLUSIONS

Optimizing cloud-based robotic process automation (RPA) has advanced significantly with the introduction of the Two-Tier Medium Access Control (MAC) solution. Through the utilization of a two-layer classification system and the incorporation of Lyapunov optimization techniques, this framework is able to satisfactorily handle the various demands of robotic tasks and hardware capacities. According to the performance studies, the Two-Tier MAC system outperforms other protocols including IEEE 802.15.4, FD-MAC, and MQEB-MAC in terms of throughput, energy efficiency, and system durability. Even with fluctuating network loads, its capacity to proactively manage resources and prioritize important operations guarantees optimal Quality of Service (QoS) satisfaction. These results highlight how the Two-Tier MAC system can improve cloud-based robotic systems' dependability and efficiency, which makes it a viable option for upcoming RPA applications.

A strong basis for upcoming studies and advancements in cloud-based robotic process automation is provided by the Two-Tier MAC system. In order to further improve the system's performance and adaptability, future research could investigate integrating it with cutting-edge technologies like 5G and edge computing. Moreover, the versatility and scalability of the framework could be enhanced by extending its support to a wider range of robotic platforms and applications. Its actual implementation in various industrial and environmental contexts will offer insightful information about its applicability and opportunities for improvement. To further optimize resource allocation and energy management, research into machine learning algorithms and advanced optimization approaches may be beneficial. In the end, these advancements might result in robotic systems that are smarter, more effective, and more flexible, able to handle the more intricate requirements of contemporary cloud-based automation.

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