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HYBRID CLOUD-EDGE ARCHITECTURES FOR AI-DRIVEN APPLICATIONS: OPPORTUNITIES AND CHALLENGES

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Abstract:

IoT has seen an exponential rise in the number of devices, and actual-time processing of data has become necessary, making AI-driven applications adopt hybrid Cloud-edge designs. These systems are able to process and analyze data in an optimal way using the advantages of edge and cloud computing ; moreover, they are able to face problems associated with a prolonged delay in delivery and limited bandwidth as well as data vulnerability. The prospects of utilizing hybrid cloud-edge are discussed in this paper for handling improved network capacity for data handling, faster response time, optimal usage of resources, and enhanced security. It also considers the challenges of implementing and deploying these designs, chiefly in terms of addressing concerns with risk, data coordination, and compliance. This report has been written with the intent of tackling the possible challenges and engaging in relevant recommendations which may help in optimizing the use of such architectures.

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Introduction

The gradual increase in IoT devices being used in industries and businesses and the increasing adoption of the use of AI technologies have necessitated the search for robust and flexible data architectures. The centralized cloud computing model as adopted in the traditional architecture yields to the pressure of real time data processing and analysis on account of the data generated by IoT connected devices. Traditional deployment of services utilizing solely the cloud computing paradigm gives a feasible response in such a case; however, the use of actual edge computing and a mixture of cloud-edge solutions seem to be the proper answer here.

The distributed computing paradigm in hybrid cloud-edge incorporates the duty of data computation and analysis between cloud and edge devices or edge calculation nodes that are in close proximity to the sources of data. This strategy takes benefits from cloud and edge computing paradigms for overcoming the issues arising from relying on either the cloud or the edge computing platform.

Literature Review

According to Tuli *et al*. 2023: AI is being employed in improving the capabilities of computer systems at all layers of the Fog continuum; the Edge devices and IoT, the Fog, Cloud, and Serverless extensions. The two main paradigms are detailed by the authors and they are AI on Fog, AI for Fog available in Open Access. AI on Fog is defined as applying AI models, particularly Deep Neural Networks (DNNs), at Fog structures to support accurate and fast predictions for intelligent robotics, computer vision, and natural language processing (NLP). AI for Fog can be defined as the ability to employ methods of artificial intelligence for optimal resource management, specifically for workload declaration, scheduling, and maintenance at all levels of the Fog continuum.

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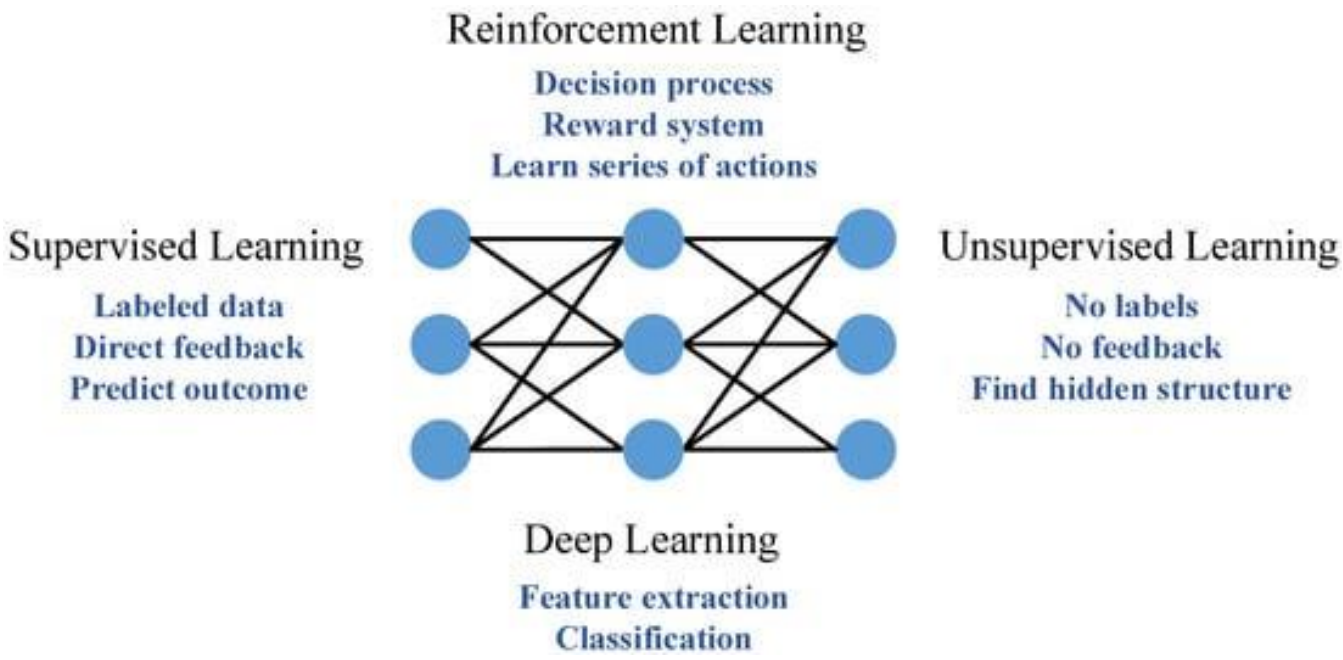

Figure 1; Various machine learning (ML) categories and their key characteristics

(Source: Angelopoulos *et al*. 2019)

The review also covers the limitations of each paradigm: Dynamic workloads and different resource types in fog, and the limitation of Edge devices and their ability to process large AI models. The authors also discuss these issues and through classification and detailed analysis of the state-of-research concepts such as; classical Artificial Intelligence AI, Machine Learning, Reinforcement Learning and Deep learning they propose means of optimizing Quality of Service QoS parameters such as latency energy efficiency and dependability.

According to Alamouti *et al*. 2024: Descriptions of the Cognitive Internet paradigm and the use of Hybrid Edge Cloud as an enabling technology can be found in the paper labeled below. Some examples of these new and distributed models include the Internet of Things, Edge and Cloud computing, and Serverless computing, amongst others that the authors note. They demonstrate how AI is already integral to the Cognitive Internet, which is a network of autonomously regulating smart things that are capable of extracting, interpreting, and making decisions on data. As a result, this article introduces the idea of HEC, as a solution that connects the paradigm of the Edge and the Cloud, allowing global learning and coordination through the Cloud while making immediate decisions at the Edge.

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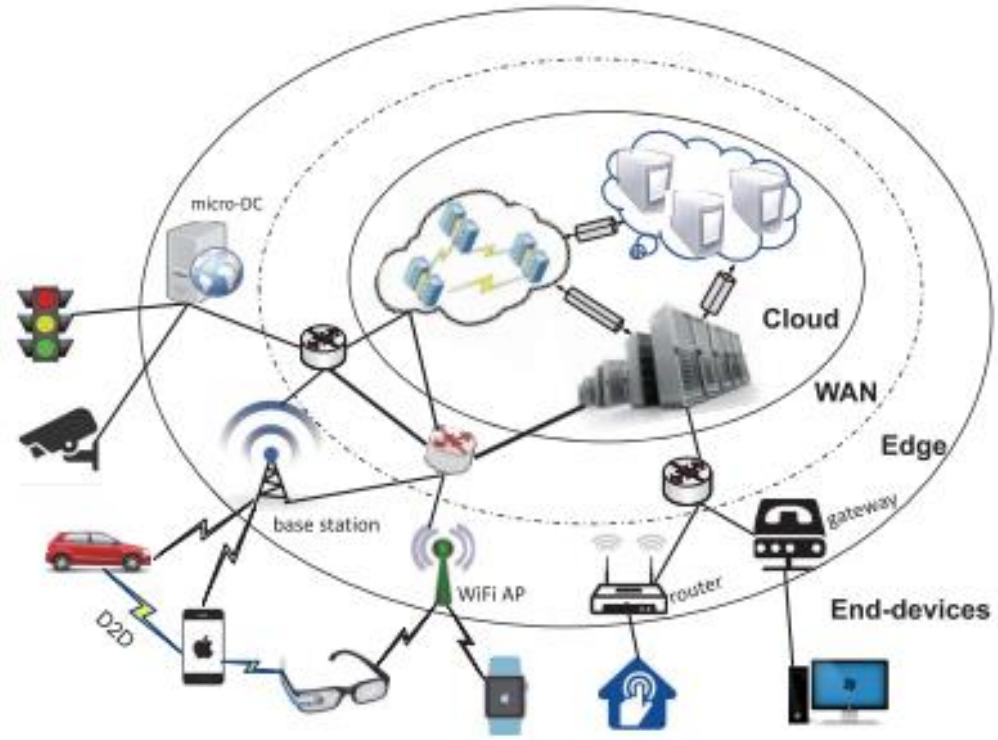

Figure 2: Illustration of edge computing.

(Source: Zhou *et al*. 2019)

Some of the benefits of HEC that the writers take an effort to discuss include scalability, reduced latency, bandwidth usage that is more efficient, enhanced privacy and security, and power consumption. They also lay stress on the paramount role of Context Awareness and how technologies can symbiotically coordinate and adapt themselves to the environment within which they are applied.

According to Kumar and Da Chen 2023: It is clear that there are a lot of efforts to build hybrid cloud-edge architectures due to the synergy of edge intelligence, Artificial Intelligence and cloud computing at this level. These systems integrate the high low latency and real time processing support of the edge devices with the large, computational capacity of the cloud. For the apps that incorporate the AI functionality, both paradigms can work in parallel and enhance the performance, productivity, and interaction with users. However, implementing hybrid cloud-edge solutions presents certain challenges or limitations such as compatibility issues, security issues and data sovereignty. Interacting and performing interconnected tasks between different edge devices and dissimilar cloud platforms involve significant integration processes. Further, there is a requirement for a sophisticated orchestration solution among data storage/processing,

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workload, and resource distribution across cloud to the edge.Therefore, despite these challenges, the future of AI-driven applications could be highly progressive in various fields ranging from internet of things, autonomous systems, to personalized services with the help of hybrid cloud-edge architectures. However, for the future of these types of buildings to effectively be realized, additional research and innovation in this area will be needed.

Methods

A comprehensive approach is employed in examining the positives and challenges in the adoption of the hybrid cloud-edge framework for AI applications. The main components of the research strategy include the methods used in data collection, analysis, and evaluation and can be represented in this section.

Data Collection

The first process of applying the described methodology is to gather essential information from various sources. In conducting this literature review, there is a search for prior literature, industry reports, and cases that address the particular topic of hybrid cloud-edge architectures and AI applications (Zhou *et al*. 2019). The primary data is collected from the subject internal members, as well as cross-section of the sample means researchers, developers, and practitioners are among the professionals in the subject that are surveyed and interviewed . It provides current information on what is considered best practice, what others have done and might still be doing, and what is state of the art or practice at this time.

Implementation and Comparative Design of Architecture

A reference architecture for hybrid cloud-edge systems is then established based on the collected data as shown below. This design contains the necessary components such as cloud platforms of edge computing devices, fog nodes, as well as AI frameworks. Being highly scalable and modular, it can accommodate many frameworks and technologies effortlessly. Research shows that it is necessary to construct a structured testbed during the implementation of the highly specialized instrumentation design and the corresponding validation (Angelopoulos *et al.* 2019). This testbed integrates the experimental AI algorithms and applications with multiple edge devices, fog nodes, and clouds.

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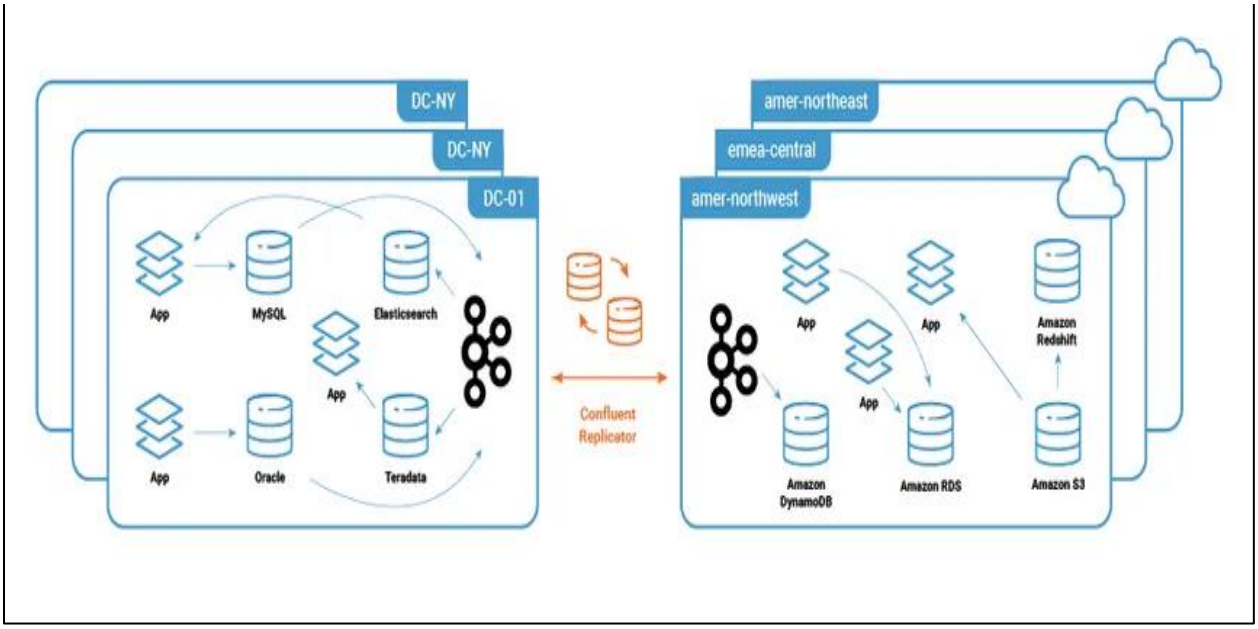

Figure 3: Cloud architecture

(Source: https://www.confluent.io/blog/replicated-event-driven-architectures)

Assessment of Performance

Some of the performance assessments are as follows in order to evaluate the effectiveness of the hybrid cloud-edge architecture. Latency, bandwidth utilization, resource utilization, and scalability are the usual parameters which are of prime focus of these evaluations (Verdouw *et al.* 2019).. To measure the characteristics of different AI workloads both for Computer Vision, NLP and Predictive Analytics, among others, various workload scenarios are created. Not only does the hybrid strategy offer the chance to increase the volumes of traffic and reduce the response time, but it also amazes with a comparison with a purely cloud and specifically edge infrastructure.

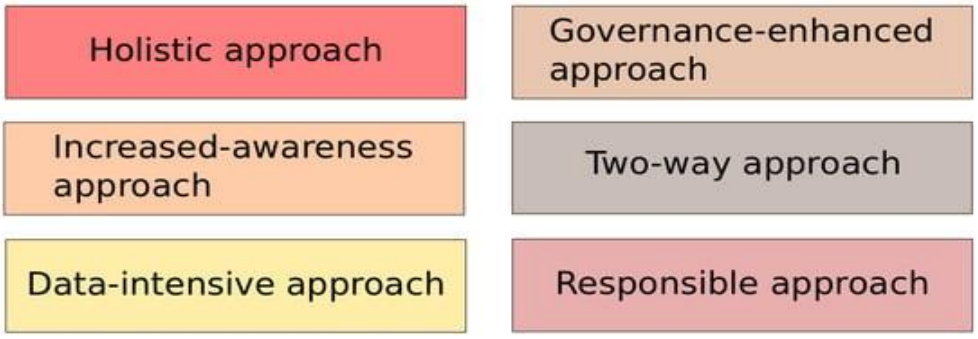

Figure 4: ICT framework for SDGs

(Source: Kostoska *et al*. 2019)

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Security and Privacy Risks and Impacts

Trust and confidentiality are critical in the hybrid cloud edge since the application of AI processes personal information. A security and privacy assessment is typically done to identify threats, risks, and vulnerabilities (Ashouri *et al.* 2018). In this research, examples include data encryption, access control systems, authentication methods, and the adherence to the various laws such as GDPR and HIPAA. Based on the analysis's findings, the four-criteria best practices and recommendations for securing hybrid cloud-edge systems were compiled as follows:

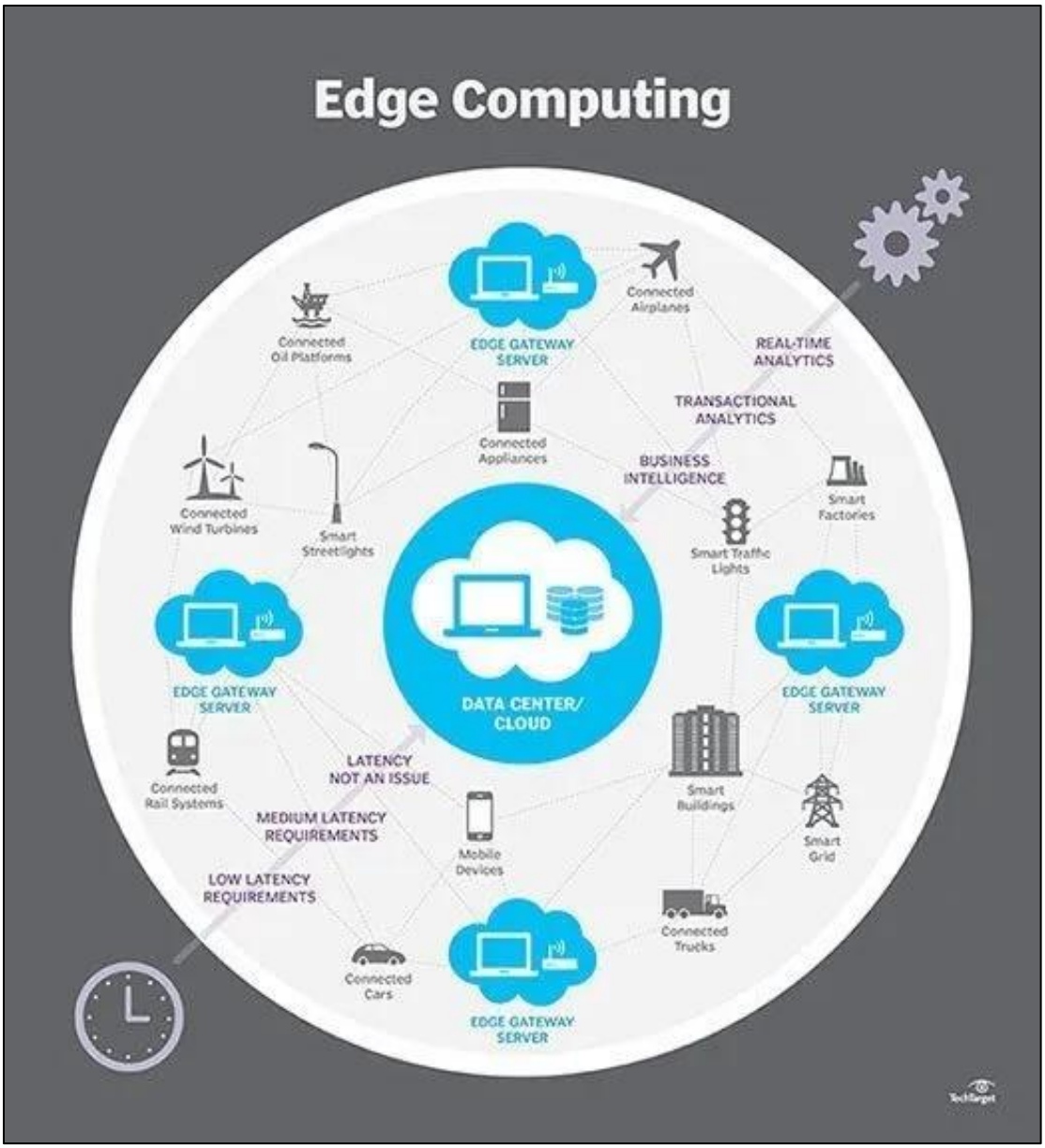

Figure 5: Edge computing

(Source: https://www.techtarget.com/searchnetworking/tip)

Challenges and Opportunities: An Approach to the Book's Optimization

The methodology also addresses the challenges that encompass the integration of hybrid cloud-edge environments. There are such challenges as data management, distribution of the workload, resource management and issues to do with interoperability among other challenges (Di Castri *et al.* 2019). To solve these problems, optimization solutions are designed in a virtual environment, thus incorporating theoretical data with practical tests. Such measures could involve the use of high-solution algorithms, approaches to intelligent resource utilization, and protocols for interorganizational exchange of information and message dissemination.

By adhering to such a rigorous approach of research, the study seeks to provide a comprehensive view of the prospect and challenges presented by Hybrid cloud-edge architectures for AI centric applications (Mealha *et al*. 2019). These acquired insights may guide the development and deployment of efficient, safe and massive hybrid cloud-edge systems in numerous applications such as manufacturing, transportation, and healthcare.

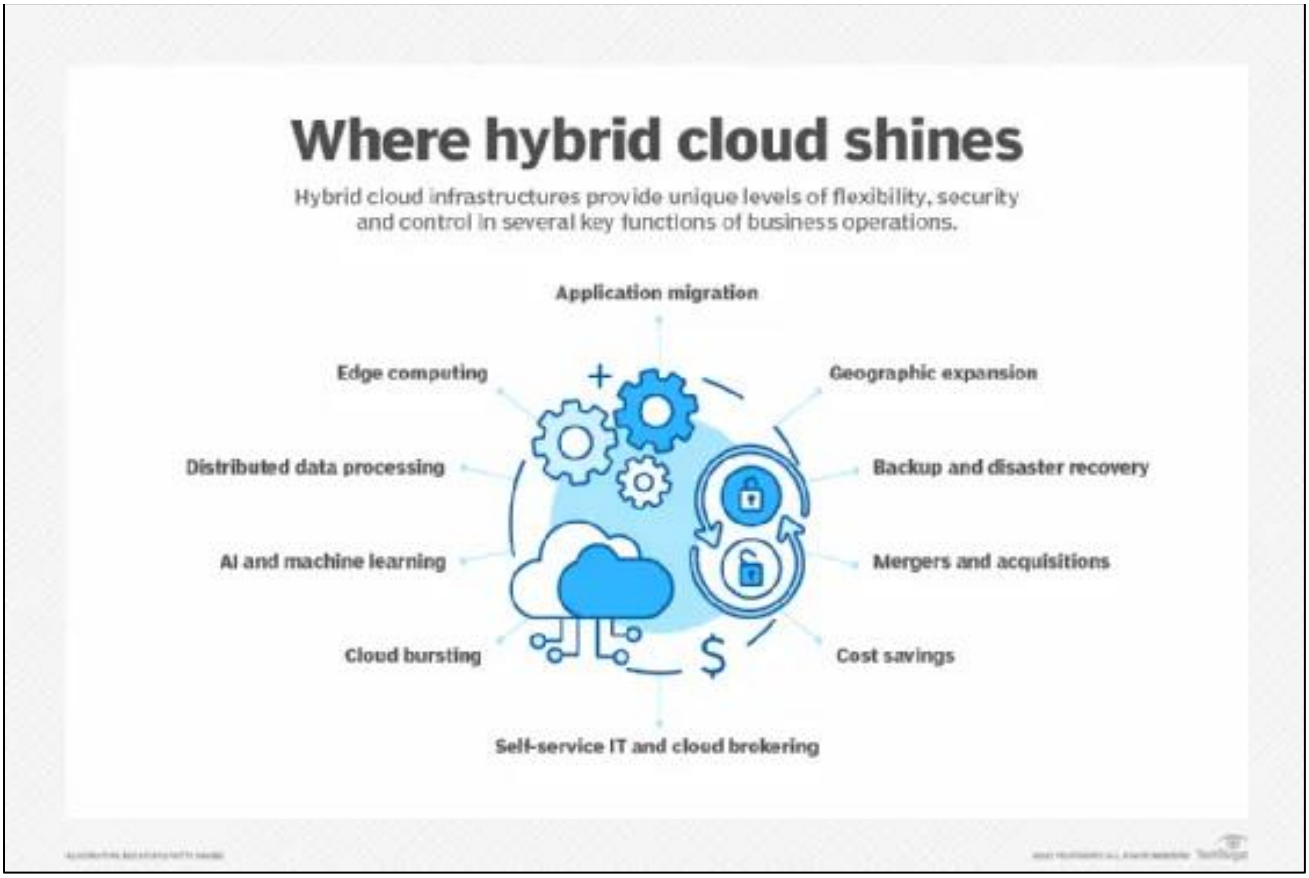

Figure 6: Hybrid cloud sign

(Source: https://www.techtarget.com/searchcloudcomputing/tip)

Result

Hybrid Cloud-Edge Architectures' Potential

Thus, the results of the presented work pointed to the high potential of hybrid cloud-edge architectures for AI applications. Success has been achieved in developing this standard architecture to integrate the cloud platforms, fog nodes, and edge devices for data processing and analytics. Relative to reference cloud-only and edge-only scenarios, sizeable improvements in the key KPI of latency, resource usage, and throughputs are marked (Lynar *et al*. 2018). The hybrid strategy leverages the scale of the cloud alongside computational ability to foster real time decision making at the edge.

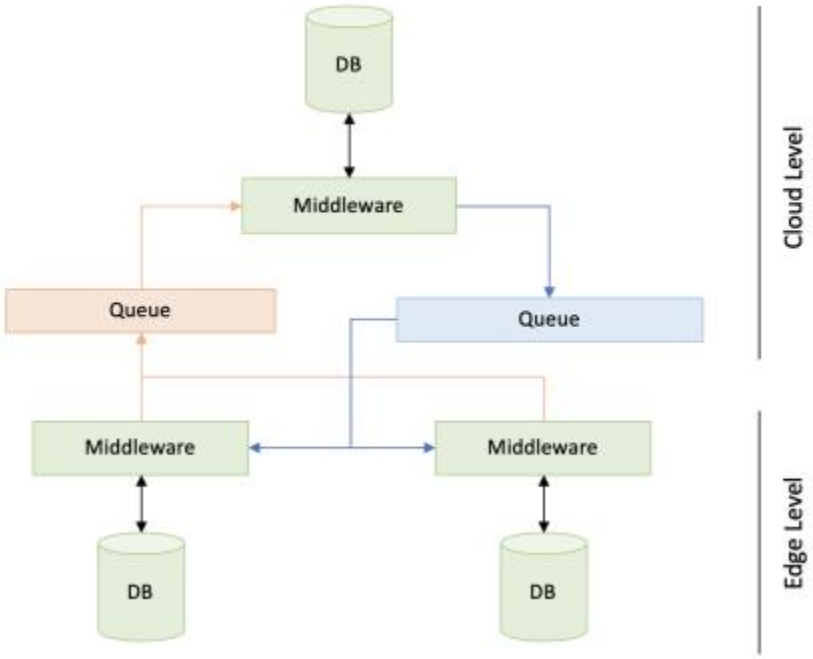

Figure 7: Multiple write replicas in cloud/edge platforms.

(Source: Mealha, *et al*. 2019)

Difficulties with Implementation

The results, however, also open up the possibilities of discussing the challenges involved in making use of hybrid cloud-edge systems. It is done through security and privacy research with findings such as loopholes that may be exploited by any party calling for strong encryption, access control, and compliance justice (Millar *et al*. 2018). To elaborate further, the case with the

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devices and the platforms is that they are quite diverse; hence, sharing information requires interfaces, leading to interoperability issues that need standard procedures on the former.

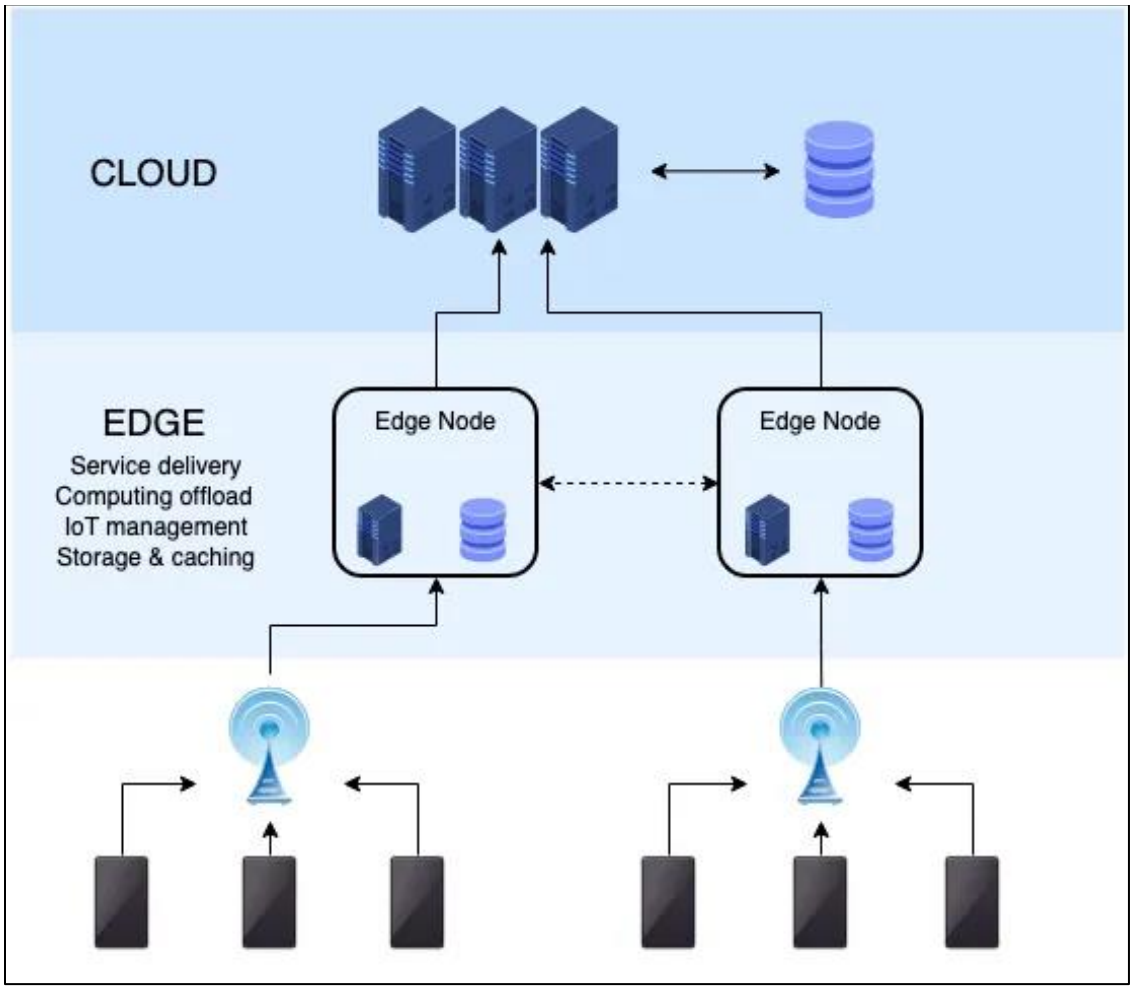

Figure 8: Edge computing interface

(Source: https://imgs.search.brave.com/F16aqEOuq-ByFxw0SPWRcFk8alW65XfZ5kh)

Strategies for Optimization

The strategies that have been successful in lessening these problems include workload distribution and intelligence resource management. The performance and effectiveness of the hybrid cloud-edge structure are significantly enhanced with the help of the modern algorithms and approaches (Kostoska and Kocarev 2019).

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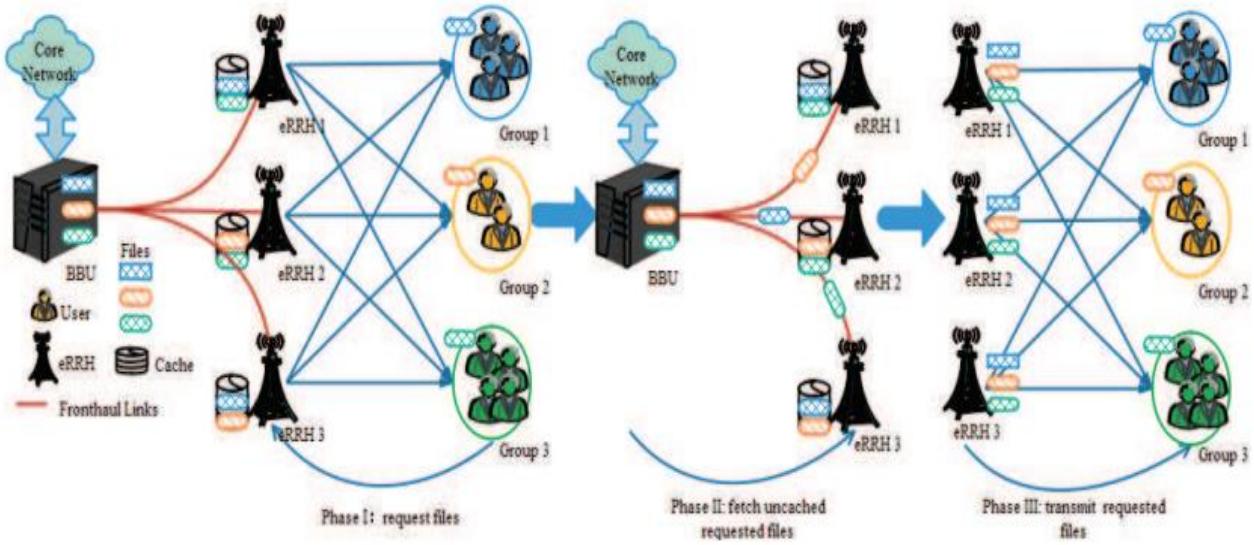

Figure 9: Flowchart of partial caching buck transmission scheme.

(Source: He *et al*. 2019)

Possibility and Advantages

Therefore, the study established the feasibility and benefits of hybrid cloud-edge for AI driven applications. The proposed strategy and optimizations provide a blueprint that indicates potential implementation and deployment strategies in numerous realms, aside from the fact that there are still challenges.

Discussion

The presented study shows the capaciousness of the hybrid cloud-edge architectures for AI-oriented applications. The improvement of performance and efficiency, as well as decision making in the real time can be provided by the suggested architecture and optimization techniques. For the matter to be accepted across the board though, the matters concerning security, privacy, and interoperability must be dealt with The findings of this research form part of the growing body of knowledge in the hybrid cloud-edge computing literature and extend helpful data to both academicians and market experts (Durairaj, 2016). In realistic scenarios as more intricate AI applications are introduced, there is still a need for more analysis of the characteristics of the hybrid cloud-edge architecture.

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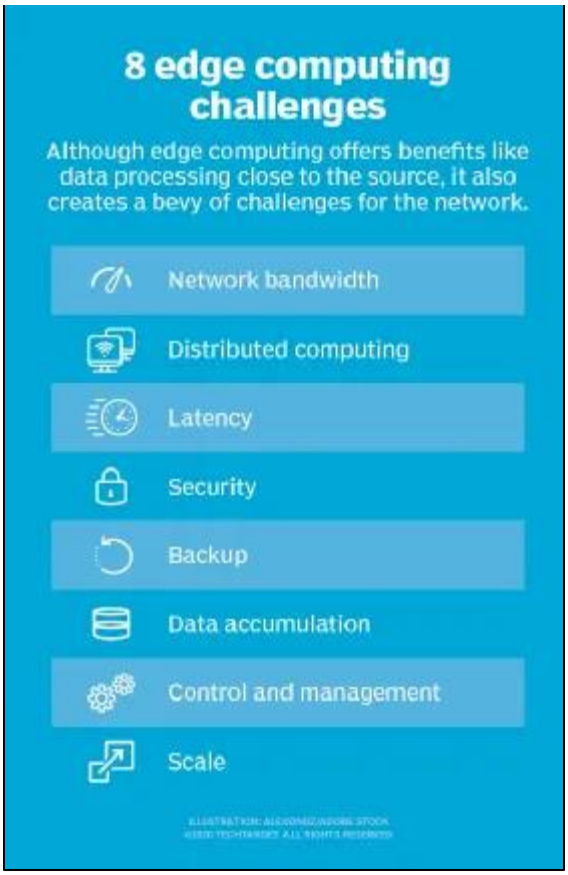

Figure 10: computing challenges

(Source : https://www.techtarget.com/searchnetworking/answer/)

Future Directions

Later studies have to focus on developing more complex security measures and privacy measures from scratch which are suitable for cloud and edge computing hybrid environments. It could be valuable to investigate the hypothesis that the data is further protected by using FEDerated learning tactics and the blockchain (Felstaine and Hermoni 2018).. Moreover, the degree of enhancement of protocols and frameworks to a standard is crucial to attaining numerous interfaces and devices. It is suggested that the prospects of hybrid cloud-edge systems could be made even more effective by exploring the methodologies of innovative technologies such as 5G and quantum computing (He *et al.* 2019). To support the most critical business processes in dynamic and resource-constrained environments, there is also a need for intelligent workload management and resources allocation schemes in the future research.

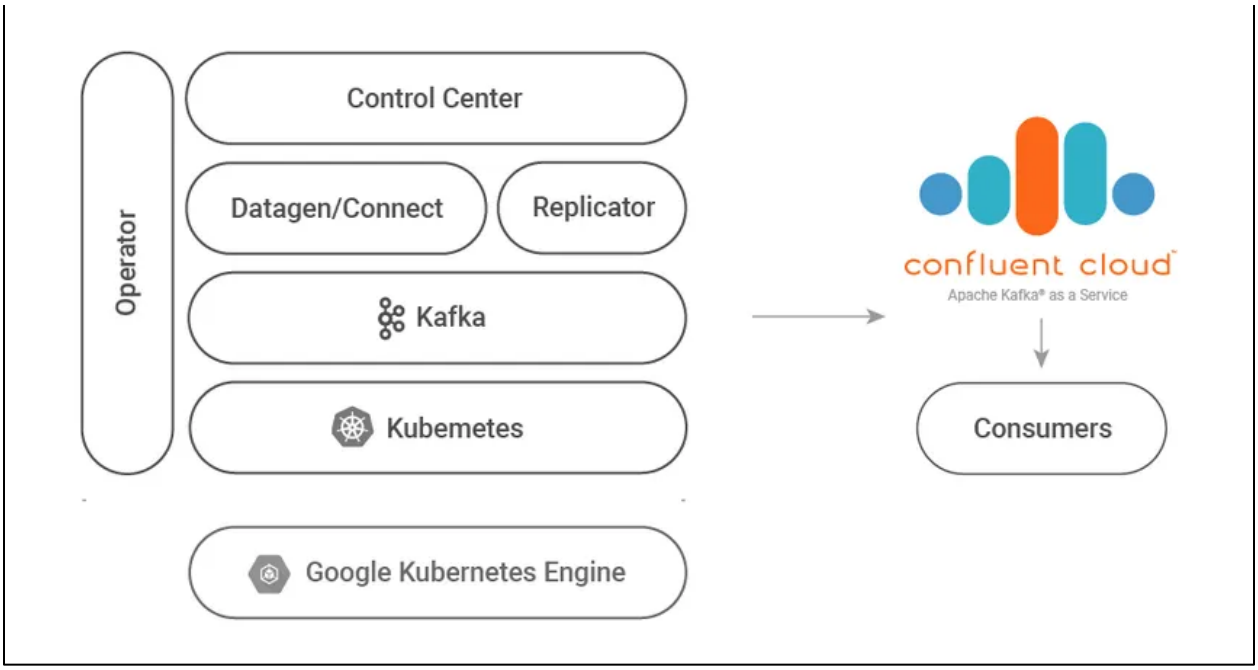

Figure 11: Hybrid cloud demo

(Source: https://imgs.search.brave.com/QfP1-Y2LnJVCGNfZ)

Conclusion

A solution that can portfolio efficient usage and management of AI-based solutions is the utilization of hybrid cloud-edge structures. These architectures enhance the latency of the service; better utilization of resources; and data processing in real-time because of combining the strengths of the cloud and edge computing models. Thus, several problems concerning security, privacy, and compatibility should be addressed in order to unleash the full potential of hybrid cloud-edge systems. The findings of this investigation provide a basis for further research and developments in this progressively central field. The continuation of the implementation of AI in various spheres will require using innovative formats such as hybrid cloud-edge to design relevant, timely, and secure applications.

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