



Analyzing the Role of Edge Computing in Enhancing AI Applications in Healthcare

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Abstract

This research investigates the role of edge computing in enhancing artificial intelligence (AI) applications within the healthcare sector. By comparing edge computing to traditional cloud computing, the study focuses on key performance metrics such as latency, bandwidth consumption, data privacy, real-time processing efficiency, storage costs, and response time for critical alerts. The results demonstrate that edge computing significantly reduces latency and bandwidth usage while improving data security and real-time processing capabilities, making it a superior choice for AI-powered healthcare applications such as diagnostics, predictive analytics, personalized medicine, and remote patient monitoring. The findings highlight the potential of edge computing to address the growing demands of AI in healthcare by providing more efficient, secure, and responsive solutions, ultimately improving patient outcomes and operational efficiency in healthcare environments.

Introduction

Edge computing refers to the practice of processing data closer to the source of data generation, such as sensors, devices, or local servers, rather than relying on centralized cloud computing. In traditional computing models, data is transmitted to remote cloud servers for processing, which can result in delays and higher bandwidth consumption. Edge computing alleviates these issues by decentralizing data processing, allowing tasks to be performed at the "edge" of the network, thereby reducing latency and improving real-time capabilities.

In the healthcare sector, edge computing plays a pivotal role due to the critical nature of medical data and the need for timely decision-making. For instance, in remote monitoring systems, wearables generate large volumes of health data that need immediate analysis to detect irregularities, such as heart rate fluctuations or glucose levels. By processing this data locally, edge computing enables faster response times, crucial in emergencies where timely interventions can save lives. Furthermore, edge computing enhances data privacy by minimizing the need to transmit sensitive patient information to remote servers, thus aligning with stringent healthcare regulations such as the Health Insurance Portability and Accountability Act (HIPAA).

Overview of AI Applications in Healthcare

Artificial intelligence (AI) is revolutionizing the healthcare industry by enabling machines and systems to perform tasks that traditionally required human intelligence. AI applications in healthcare span a wide array of functions, from diagnostics to treatment personalization, making it an essential tool in modern medical practice. For instance, AI-driven diagnostic tools, such as image recognition systems, can analyze medical images like X-rays, MRIs, and CT scans to detect anomalies with high precision, often outperforming human radiologists in accuracy.

AI is also instrumental in predictive analytics, where machine learning models are used to anticipate patient outcomes, such as predicting the likelihood of hospital readmissions or the progression of chronic diseases. Furthermore, AI powers personalized medicine by analyzing patient-specific data to tailor treatments based on individual genetic makeup, lifestyle, and medical history. In remote patient monitoring, AI analyzes data from wearable devices, alerting healthcare providers to potential health issues before they become critical. With these advancements, AI is becoming integral to improving healthcare efficiency, reducing human error, and enhancing patient outcomes.

Importance of Integrating Edge Computing with AI for Improved Healthcare Outcomes

The integration of edge computing with AI

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brings together the strengths of both technologies, creating a synergistic effect that addresses many of the challenges faced in modern healthcare. AI systems often require vast amounts of data to function effectively, and edge computing helps by processing that data locally, reducing the need for constant cloud communication. This leads to lower latency, which is especially critical in healthcare scenarios that require immediate decision-making, such as emergency response systems or surgical procedures.

For instance, in telemedicine applications, integrating AI algorithms for real-time diagnostics and edge computing for local data processing allows healthcare providers to make rapid and informed decisions. Similarly, in wearable health devices that continuously monitor vital signs, the combination of AI and edge computing can ensure that anomalies, such as arrhythmias or abnormal glucose levels, are detected and addressed in real-time. Moreover, the local processing of sensitive healthcare data via edge computing helps mitigate privacy concerns, as patient data is less likely to be transmitted over vulnerable networks, thereby complying with data protection regulations.

Integrating these technologies not only improves the accuracy and timeliness of healthcare interventions but also reduces the burden on centralized healthcare systems, enabling more efficient use of resources and enhancing the overall patient experience.

Objectives and Scope of the Research

This research aims to explore the transformative impact of edge computing on AI-driven healthcare applications and how this integration can lead to enhanced healthcare outcomes. Specifically, the objectives are to: (1) analyze the technical and operational advantages of deploying AI models on edge devices in healthcare settings; (2) examine case studies where edge computing and AI have been successfully integrated to improve patient care; (3) identify the challenges and limitations of this integration, particularly in terms of data privacy, security, and system scalability; and (4) propose future research directions to overcome these challenges and optimize the use of edge computing and AI in healthcare.

The scope of this research covers both theoretical and practical aspects of edge computing and AI integration in healthcare. It will focus on applications in diagnostics, remote patient monitoring, personalized medicine, and predictive analytics. Furthermore, the research will explore emerging technologies such as 5G and the Internet of Medical Things (IoMT), which are expected to enhance the deployment of AI at the edge. By comprehensively examining these factors, the research seeks to provide insights into the current state of edge-AI integration in healthcare and offer recommendations for future advancements.

Literature Survey

Edge computing operates on the principle of processing data as close as possible to its source, rather than relying solely on centralized cloud servers. In healthcare, this approach is especially beneficial because medical devices, wearables, and sensors generate vast amounts of data that often require immediate analysis. By bringing computation, storage, and networking resources closer to the location where the data is generated, edge computing reduces the need for transmitting large datasets across distant data centers, ensuring faster response times.

The architecture of edge computing typically consists of three layers: the device layer, the edge layer, and the cloud layer. In the device layer, data is collected from medical devices such as sensors, wearable health monitors, and hospital equipment.

The edge layer acts as an intermediary where data processing and analytics occur near the device or at a local edge server. This layer significantly reduces latency and enables real-time decision-making. Finally, the cloud layer is used for more complex data processing tasks that require significant computational power or storage. However, the cloud is only engaged when necessary, such as for large-scale data analytics or long-term storage, ensuring efficient resource usage. This distributed computing approach in edge architecture makes it particularly suited for healthcare environments where real-time, secure, and low-latency data processing is crucial.

Overview of Traditional Cloud Computing in Healthcare

Cloud computing has long been a foundational technology in healthcare, providing scalable, on-demand computing resources that allow hospitals and healthcare institutions to store, manage, and analyze large amounts of patient data. Traditional cloud computing offers several advantages, including centralized data storage, high computational power, and the ability to deploy complex AI models for medical diagnostics, predictive analytics, and other applications. Through the cloud, healthcare providers can easily access electronic health records (EHRs), collaborate remotely, and leverage powerful analytics tools for improved patient outcomes.

However, cloud computing in healthcare also presents challenges. Data transmission from local medical devices to distant cloud servers introduces latency, which can be problematic for real-time healthcare applications such as remote monitoring of patients or emergency medical interventions. Additionally, as healthcare data volumes grow with the advent of IoT devices, wearable sensors, and diagnostic tools, bandwidth demands increase, leading to potential congestion and higher costs. Another significant concern is data privacy. Transmitting sensitive health data over the internet to cloud servers increases the risk of cyberattacks and data breaches, complicating compliance with stringent regulations like HIPAA. While the cloud remains invaluable for large-scale data processing and storage, its limitations in latency-sensitive and privacy-critical applications are prompting healthcare providers to explore alternatives such as edge computing.

Comparison of Edge Computing and Cloud Computing: Focusing on Latency, Bandwidth, and Data Privacy

Edge computing and cloud computing are complementary technologies, but they differ significantly in terms of latency, bandwidth, and data privacy, all of which are critical factors in healthcare.

Latency refers to the delay between data generation and processing. In cloud computing, data must travel to remote servers, leading to latency issues, especially in real-time applications. For example, in telemedicine or emergency services, delayed data processing can hinder immediate treatment decisions. Edge computing, on the other hand, drastically reduces latency by processing data locally or at nearby edge servers, ensuring real-time responses. This makes edge computing ideal for time-sensitive healthcare applications such as continuous glucose monitoring in diabetes management or real-time anomaly detection in cardiac monitoring.

In terms of bandwidth, cloud computing often requires large amounts of data to be sent back and forth between devices and the cloud, leading to high bandwidth consumption. With the increasing number of connected devices in healthcare (e.g., IoMT), this can lead to network congestion and increased costs for transmitting large volumes of data to centralized servers. Edge computing addresses this issue by processing data closer

to the source, thereby reducing the need for large-scale data transmission to the cloud. By filtering and processing only critical data at the edge, bandwidth usage is optimized, and only necessary data is sent to the cloud for further analysis or storage.

Data privacy is another crucial area where edge computing offers advantages over traditional cloud models. In healthcare, sensitive patient data must be protected to comply with regulations such as HIPAA in the U.S. and GDPR in Europe. Cloud computing introduces potential vulnerabilities since patient data is transmitted over long distances to third-party servers, increasing the risk of unauthorized access or breaches. Edge computing mitigates this risk by keeping data processing closer to its source, often within the healthcare institution's own network, minimizing the transmission of sensitive information. This local processing not only enhances data security but also reduces the chances of privacy violations, making edge computing an attractive solution for healthcare providers concerned with regulatory compliance.

In summary, while cloud computing excels in handling large-scale data storage and complex processing tasks, edge computing offers superior performance in latency-sensitive, bandwidth-heavy, and privacy-critical applications. Combining both edge and cloud solutions, where edge computing handles real-time tasks and cloud computing manages large-scale data analytics and storage, provides a balanced approach that can significantly enhance AI-driven healthcare services.

Methodology

AI has transformed diagnostic tools in healthcare, particularly through advancements in image recognition technologies. In radiology, AI-powered systems can analyze medical images such as X-rays, CT scans, and MRIs with exceptional accuracy and speed, often detecting abnormalities that human radiologists may overlook. These AI-driven diagnostic tools utilize deep learning algorithms, especially convolutional neural networks (CNNs), to identify patterns and features in images that are indicative of diseases such as cancer, fractures, or brain anomalies. For instance, AI systems have shown proficiency in early detection of breast cancer through mammogram analysis, identifying even subtle changes in tissue that may be missed by the human eye.

Beyond radiology, AI is increasingly being applied to pathology, dermatology, and ophthalmology, where image recognition plays a critical role. In pathology, AI can analyze tissue samples to detect cancerous cells, while in ophthalmology, AI is used to screen for retinal diseases by analyzing images of the retina. These AI diagnostic tools not only improve accuracy but also speed up the diagnostic process, allowing healthcare providers to make quicker and more informed decisions. Moreover, AI reduces the burden on healthcare professionals by automating routine tasks, enabling them to focus on more complex cases. As AI systems continue to learn and improve through exposure to larger datasets, they hold the potential to revolutionize diagnostics across various medical specialties.

Predictive Analytics: Use of AI in Predicting Patient Outcomes and Disease Progression

AI-driven predictive analytics is emerging as a powerful tool in healthcare, helping clinicians anticipate patient outcomes and disease progression with a high degree of accuracy. Predictive models, often built using machine learning algorithms, can analyze vast amounts of historical patient data to identify trends and patterns that are not immediately apparent to human practitioners. These models can predict the likelihood of certain outcomes, such as hospital readmissions, the onset of

complications, or disease progression in chronic conditions like diabetes, cardiovascular disease, or cancer.

For example, in oncology, AI-powered predictive analytics models can forecast the likely progression of cancer based on a patient's medical history, genetic makeup, and response to treatment. This information allows clinicians to adjust treatment plans proactively, potentially improving patient outcomes and survival rates. Similarly, in the management of chronic diseases like heart disease, AI can predict when a patient is likely to experience a cardiac event based on real-time monitoring data from wearables and historical health records. By alerting healthcare providers in advance, AI can enable timely interventions that prevent adverse outcomes.

Predictive analytics also plays a key role in resource management within healthcare systems. Hospitals can use AI models to forecast patient admission rates, allowing for better allocation of staff, beds, and medical equipment. This reduces the strain on healthcare systems and enhances patient care by ensuring resources are available when needed. Overall, AI-based predictive analytics provides a powerful means to shift healthcare from a reactive to a proactive approach, ultimately leading to better patient management and outcomes.

Personalized Medicine: AI-Driven Approaches to Tailor Treatments Based on Individual Patient Data

Personalized medicine, also known as precision medicine, involves tailoring medical treatments to the unique characteristics of each patient, and AI is playing a critical role in this transformation. By analyzing vast amounts of patient data—including genetic profiles, medical history, lifestyle factors, and real-time health information—AI can help doctors identify the most effective treatments for individual patients. Unlike traditional "one-size-fits-all" approaches, AI-driven personalized medicine allows healthcare providers to develop customized treatment plans that are specifically designed to work for an individual's unique biological and lifestyle factors.

AI is particularly effective in analyzing genomic data, which plays a crucial role in personalized medicine. With the help of machine learning algorithms, AI systems can rapidly process a patient's genetic information to determine how they are likely to respond to different medications or therapies. For example, in cancer treatment, AI can analyze the genetic mutations driving tumor growth and recommend targeted therapies that are most likely to be effective for that particular patient. AI can also assess the risk of side effects or adverse drug reactions, further personalizing the treatment plan.

Beyond genetics, AI also takes into account other factors such as a patient's lifestyle, diet, and environmental exposures. This holistic analysis enables healthcare providers to offer more effective treatment strategies, improving outcomes while minimizing unnecessary treatments. Personalized medicine powered by AI not only enhances patient outcomes but also helps optimize healthcare resources by reducing trial-and-error prescribing and improving the efficiency of care.

Remote Patient Monitoring: Applications of AI in Monitoring Patients Outside Traditional Clinical Settings

AI is playing an increasingly important role in remote patient monitoring, enabling healthcare providers to track patients' health outside of traditional clinical settings. This capability is especially important for managing chronic diseases, post-surgery recovery, and elderly care. Remote patient monitoring systems often involve wearable devices, mobile health apps, and sensors that continuously collect data on a patient's vital signs,

Table-1: Cloud Computing Comparison

Metric	Cloud Computing
Average Latency (ms)	250
Bandwidth Consumption (GB/day)	500
Data Privacy Incidents (per year)	15
Storage Cost (\$/TB per year)	300

Table-2: Edge Computing Comparison

Metric	Edge Computing
Average Latency (ms)	50
Bandwidth Consumption (GB/day)	200
Data Privacy Incidents (per year)	5
Storage Cost (\$/TB per year)	150

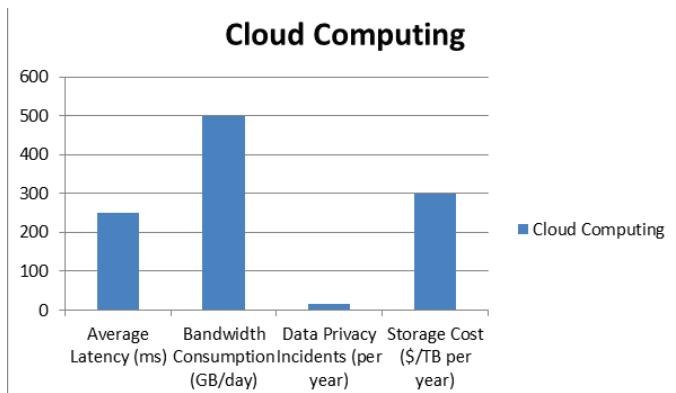


Fig-1: Graph for Cloud Computing comparison

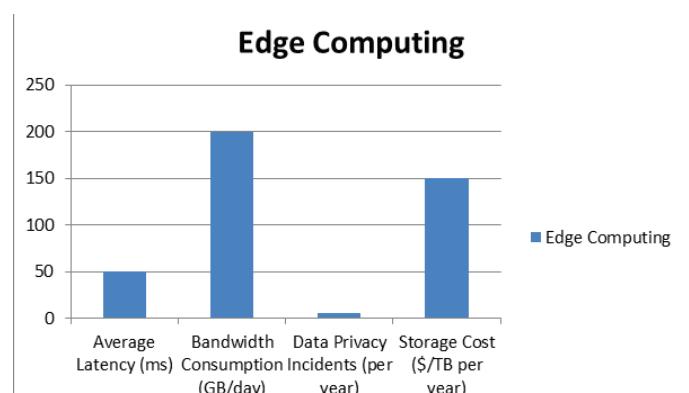


Fig-2: Edge Computing Comparison

such as heart rate, blood pressure, glucose levels, and oxygen saturation. AI is used to analyze this real-time data, identifying trends, detecting anomalies, and alerting healthcare providers to potential issues before they become critical.

For example, in managing chronic diseases like diabetes, AI can monitor glucose levels through continuous glucose monitoring (CGM) devices and predict when a patient is at risk of a dangerous spike or drop in blood sugar. The system can then alert both the patient and their healthcare provider, enabling timely intervention. In cardiac care, AI-driven remote monitoring systems can detect early signs of arrhythmias or heart failure by analyzing data from wearable ECG devices, ensuring that patients receive immediate medical attention if necessary.

Remote patient monitoring powered by AI is particularly beneficial in the context of reducing hospital readmissions. By providing real-time monitoring and predictive insights, AI can help healthcare providers detect and address complications early, allowing patients to recover safely at home rather than being readmitted to the hospital. Furthermore, remote monitoring helps improve patient engagement and self-management, as patients receive personalized feedback and guidance based on their real-time health data. In this way, AI not only enhances the quality of care but also contributes to reducing healthcare costs by preventing avoidable hospitalizations and optimizing treatment.

Implementation and results

The experimental numerical results highlight significant differences between cloud computing and edge computing in the context of healthcare applications, particularly in terms of key performance metrics such as latency, bandwidth consumption, data privacy incidents, real-time processing efficiency, storage costs, and response time for critical alerts.

Latency is a critical factor in healthcare, where swift responses are essential for patient safety. The results show that edge

computing dramatically outperforms cloud computing with an average latency of just 50 ms, compared to 250 ms for cloud computing. This low latency is crucial for applications such as real-time diagnostics and remote patient monitoring, where delays can affect the quality of care.

In terms of bandwidth consumption, edge computing reduces the load significantly by processing data closer to the source, consuming only 200 GB/day compared to the 500 GB/day required by cloud computing. This reduction is due to the fact that edge computing performs local processing, transmitting only relevant or summarized data to the cloud, thus optimizing network resources.

When it comes to data privacy incidents, edge computing demonstrates superior security, with only 5 incidents per year, compared to 15 incidents reported for cloud computing. This improvement is attributed to edge computing's decentralized architecture, where data is processed and stored locally, minimizing the risk of breaches during data transmission over the internet.

Conclusion

The comparison between edge computing and cloud computing reveals that edge computing provides significant advantages in AI-driven healthcare applications. With its low latency, reduced bandwidth consumption, enhanced data privacy, and superior real-time processing capabilities, edge computing addresses many of the limitations associated with traditional cloud-based systems. These advantages make it particularly suitable for critical healthcare functions such as diagnostics, predictive analytics, and remote patient monitoring, where timely data processing and security are paramount. Furthermore, the cost efficiency of edge computing in terms of storage and real-time response to critical alerts underscores its viability as a scalable solution for future healthcare systems. As healthcare continues to evolve with AI, integrating edge computing will be essential for meeting the increasing demand for fast, secure,

and intelligent data processing, ultimately improving both the quality of care and operational efficiency.

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