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IoT and Edge Computing for Contemporary Applications: A Conceptual Study

Krishnakant Singh[1], Dr. Manju Pandey[2] and Dr. Sunil Pandey[3]
[1-3]National Institute of Technology, Raipur, India
Email: ksingh.phd2024.ca@nitrr.ac.in, {mpandey.mca, sys_admin}@nitrr.ac.in

***Abstract*— The application of Internet of Things (IoT) in combination with edge computing (EC) is examined in this study for various effective Contemporary Applications. It explores principles, architecture, communication protocols, and case studies from the real world illustrating how these technologies improve responsiveness. The study emphasizes the capabilities of EC and IoT to create resilient, real-time, and efficient systems.**

***Index Terms*— Edge Computing (EC), Internet of Things (IoT), Real-Time Data Processing, Predictive Analytics, Communication Protocols, Edge Computing Technologies.**

I. INTRODUCTION

IoT is transforming the physical world into a digital realm. It is connecting the various everyday objects over internet to avoid or to reduce human to machine interactions for performing various everyday task whereas the EC provides very swift and effective response for the reducing the time taken for computational task based on data collected by various IoT sensors and single board computers.
IoT and Edge Computing (IoEC) together can provide a very quick and effective solution in various sectors where real time response is needed. Let us give a very quick overview on these:

A. Internet of Things (IoT)

The Internet of Things, or "IoT," is a network of physical objects that have been integrated with sensors, software, and other tools to facilitate the exchange of data and the establishment of online connections with other systems and devices.
The importance of IoT lies in its capability to create a vast and interconnected network of devices, generating and utilizing data to enhance decision-making processes across various domains [1].
Industrial automation, smart homes, healthcare, transportation, and agriculture are just a few of the sectors in which IoT finds extensive use.

B. Edge Computing (EC)

EC is a distributed computing concept that performs collection and storage of data near to the data source. When compared to typical cloud computing, this closeness to data sources lowers latency, speeds up processing, and eases bandwidth restrictions [2].
Edge computing enhances the real-time insights and responsiveness of Internet of Things applications by processing data close to the network's edge.

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C. Intergration of IoEC

IoEC deployment can revolutionize computation, analytics, and edge technologies like Real-Time Actuation, Edge-based decision making, etc. IoEC can reduce sensor data processing time. IoEC integration addresses cloud-centric IoT architectural limitations. This integration uses edge computing's real-time processing and cloud computing's vast storage and analytical power to handle IoT devices' vast data[3]. This hybrid technique boosts IoT system efficacy, scalability, and reactivity. IoT sensors can track energy use, traffic, and air quality in smart cities. EC can interpret data locally to provide real-time insights, such as adjusting traffic signals in real-time to make it less intense. Aggregated data can be analyzed on the cloud to aid future planning and policymaking.

II. IoT Data Computation

Data computation of various data generated through IoT devices can be done in various ways. This section will address the approach to cloud and edge data computation.

A. Cloud based Computation

Cloud-based computation involves utilizing centralized data centres to process and store data generated by IoT devices. This approach provides significant computational power and scalability, allowing for complex data analysis and machine learning tasks [4]. The capacity of cloud-based computation to manage enormous volumes of data from several IoT devices is one of its main benefits. Despite its benefits, cloud-based computation can suffer from high latency and bandwidth constraints, especially in scenarios requiring real-time processing.

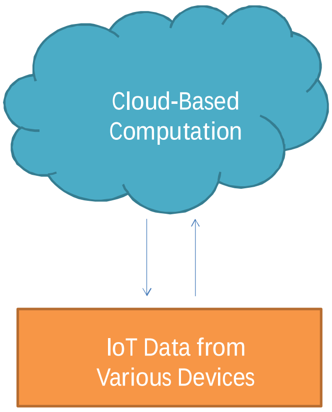

Figure 1. Cloud-Based Computation in IoT

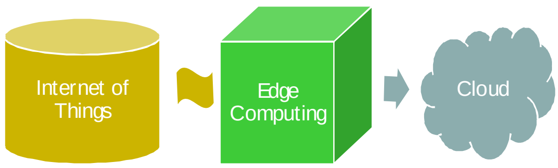

Figure 2. Edge-Based Computation in IoT

B. Edge based Computation

The limits of cloud-based computation are addressed by edge-based computation, which processes data locally on edge devices such edge servers, routers, or gateways. By limiting the quantity of data transferred across the network, this method lowers latency, saves bandwidth, and improves data security [5]. Edge-based computing is very useful for applications that need to make decisions in real time. By distributing computational tasks across edge devices, organizations can achieve a more efficient and resilient IoT infrastructure. Edge-based computation also reduces the dependency on centralized cloud resources, increasing the system's overall reliability. The data that has been processed can sent to the cloud in order to store data backups or to make the data accessible to other data users.

III. IoT Functional Overview

The IoT functional architecture consists of a various of layers and components, all of which are essential to the smooth functioning of internet-wide networks. Each layer and its constituent parts are elaborated in detail in this section.

The Device Layer is the physical foundation, responsible for gathering environmental data and executing commands from higher layers. The Communication Layer manages data routing and addressing between devices and gateways, ensuring data integrity and optimizing network performance through error handling and flow control. The Service Organization Layer handles service discovery, composition, orchestration, and management to ensure reliable and seamless operation of IoT services. The Security and Authorization Layer addresses critical security aspects, including authorization, identity management, and authentication, to protect IoT systems from unauthorized access and malicious activities. The Virtual Entry Layer bridges the gap between physical devices and applications by mapping devices to their virtual counterparts, monitoring performance, and defining data semantics for consistent interpretation. Finally, the Application Layer supports applications that utilize IoT data to provide valuable insights and functionalities, including the management and execution of business processes dependent on IoT data.

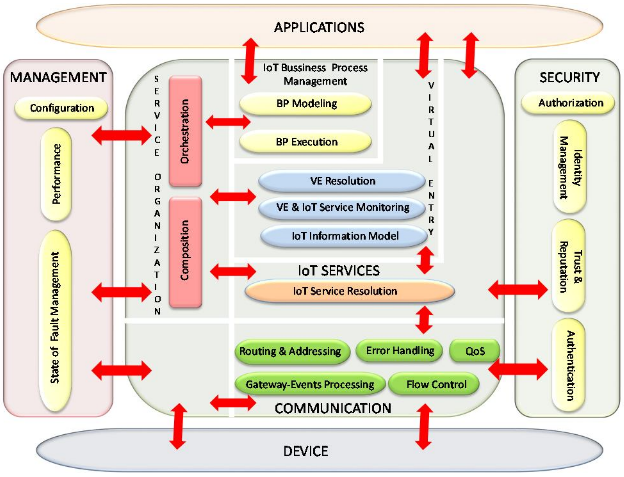

Figure 3. Functional Overview of IoT [6]

IV. IoT-Edge-Cloud Architecture

The IoEC-Cloud architecture is organized in a tiered structure with multiple layers of computing nodes. Each layer performs specific tasks such as data aggregation, processing, and decision-making. This architecture typically includes the following layers:

- Sensor Layer: Physical layer where all sensors are deployed.
- Device Layer: The layer where data is collected.
- Edge Layer: A layer consists of various Edge Nodes where data is processed locally.
- Cloud Layer: Centralized server performing data backups or to make data available for various other consumers of data.

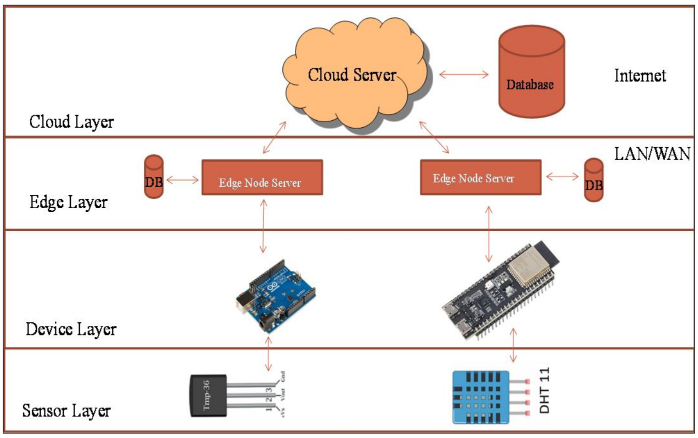

Figure 4. IoT-Edge-Cloud Architecture

This multi-layered architecture enables a balanced distribution of computational tasks, implementing the Cloud and edge computing's respective advantages. The sensor layer includes sensors, actuators, etc. that generate data. The device layer consists of single board microcontroller embedded device used for data collection. The edge layer consists of several edge nodes with gateways, routers, and servers that do local data analysis and provide instant insights and decision-making capabilities. The cloud layer provides additional storage, processing power, and advanced analytics, enabling long-term data analysis and strategic planning and data backup.

V. IoT-Edge Communication Protocol

Edge computing protocols are crucial for managing processing of data and communication at the network's edge. These help in reducing latency, improving real-time data handling, and ensuring data security by efficiently coordinating tasks between edge devices and central servers. Following are the different types of edge computing protocols:

A. Message Queue Telemetry Transport (MQTT)

Based on the TCP/IP protocol, MQTT delivers messages in the correct order and simplifies machine-to-machine communication via a publish-subscribe architecture [9]. It is suitable for Applications for the IoT that need reliable communications in low-bandwidth environments due to its ability to function with constrained devices and networks. Publisher, broker, and client make up MQTT where Publishers publish broker-collected data and broker organizes topic-related data. It uses a hierarchical string called topic to categorize messages and route them between publishers and subscribers.

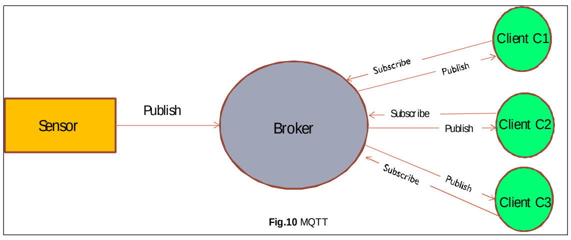

Figure 5. Representation of MQTT

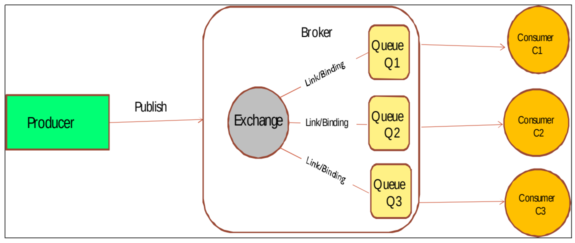

Figure 6. Working of AMQP

B. Advanced Message Queuing Protocol(AMQP)

In edge computing, AMQP is particularly useful due to its robust features which include ensuring reliable communication even while network outages are occurring. It supports message delivery confirmation and transactions, making it appropriate for uses requiring high reliability and security. AMQP's flexibility allows it to handle various messaging patterns and its ability to work over the internet and within private networks makes it a versatile choice for edge computing environments [10].

C. Constrained Application Protocol(CoAP)

CoAP is a specific transfer protocol of web which was created to be used with IoT restricted networks and nodes. It is made to convert to HTTP/HTTPS with ease, making web integration easier, while maintaining a small footprint suitable for edge computing scenarios operating over UDP, providing simplicity and minimal overhead, which are crucial for devices with limited processing power and memory [10]. In edge computing, CoAP is advantageous due to its ability to provide efficient, low-latency communication. It supports multicast, making it effective for group communications often required in sensor networks. CoAP's observe mode allows clients to stay updated with the latest state of a resource, making it suitable for real-time applications in EC where timely data delivery is critical.

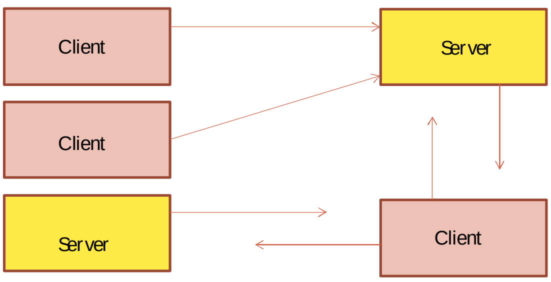

Figure 7. Representation of CoAP

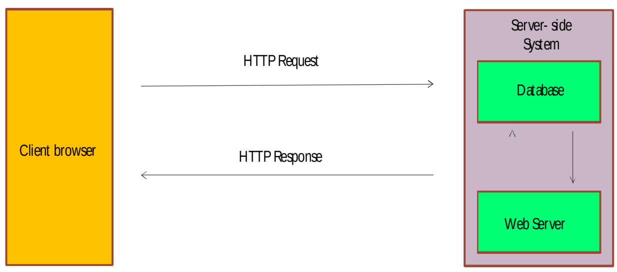

Figure 8. HTTP/HTTPS communication

D. HTTP/HTTPS

In the context of edge computing, HTTP/HTTPS is commonly used for its compatibility with existing web technologies and ease of integration with various services and platforms. However, it is important to note that HTTP/HTTPS can be resource-intensive, as it requires more overhead compared to other lightweight protocols like CoAP and MQTT [10]. HTTP/HTTPS's primary advantage is its ubiquity and ease of use. However, due to its higher overhead compared to protocols like CoAP, HTTP/HTTPS may not be suitable for highly constrained devices or scenarios requiring minimal latency and bandwidth consumption.

E. Data Distribution Service (DDS)

DDS middleware protocol aims to improve publisher-subscriber data exchanges in distributed systems to be interoperable, scalable, dependable, real-time, and high-performance [11]. DDS is especially suitable for vital systems for task and edge computing environments where real-time data distribution is crucial. DDS is designed to support real-time applications by providing predictable, low-latency communication. In EC, DDS plays a vital role by enabling efficient data exchange between edge devices and systems. DDS's ability to provide low-latency communication makes sure the real-time handling of data at the edge, obviating the need to send data to a central cloud. Edge environments can be unpredictable, with potential for network disruptions and hardware failures [12].

F. Lightweight Broadcast Authentication Protocol (LBAP)

The LBAP is a novel protocol designed to address the security and efficiency needs of edge-based IoT applications. Traditional centralized authentication systems are often unsuitable for IoT due to their latency, high computational requirements, and reliance on distant cloud servers. LBAP, on the other hand, uses EC concepts to improve security and performance by providing a decentralized authentication process that is closer to the data sources [13]. LBAP employs cryptographic techniques specifically chosen to be light-weight, making it appropriate for devices with less memory and processing power. The protocol utilizes hash chains and authenticated encryption to ensure message integrity, confidentiality, and forward secrecy.

VI. EDGE TECHNOLOGIES

Edge technologies enable various technologies for data processing and analysis close lowering latency and bandwidth consumption and enhancing real-time decision-making near to source of data and operational efficiency. These technologies are essential for applications requiring quick response times and enhanced data security.

A. Edge Analytics

An innovative strategy in the IoT space is edge analytics, which permits data analytics and processing near the data sources. instead of depending exclusively on centralized data centers. This technique improves real-time decision-making skills by drastically lowering latency and bandwidth consumption. The rapid increase of IoT devices generating massive data streams necessitates efficient edge analytics to manage the amount and velocity of data. Edge analytics involves deploying machine learning models at edge nodes, where they utilizing central servers to be trained and synchronized on a regular basis [14]. This approach not only optimizes resource utilization but also improves privacy by transmitting model parameters instead of raw data.

B. Artificial Intelligence at Edge

Instead of depending exclusively on centralized cloud infrastructure, edge AI entails implementing AI algorithms on devices at the network's edge. By evaluating data locally, this technique lowers latency, improves privacy, and increases the performance of AI applications.

Real-time data processing and decision-making are now possible thanks to Edge AI applications that have been extended across industries including healthcare, automotive, and agriculture thanks to recent advances in AI and IoT.

As a result of the transition from early edge computing paradigms, such as content delivery networks, specialized hardware and devices that support complex AI operations with the least amount of latency and bandwidth consumption have been developed.

This shift towards localized AI processing is supported by the increasing availability of data from IoT devices, as well as the improved connectivity and reduced latency offered by next-generation networks like 5G and 6G [15].

Edge AI represents a transformative shift in the field of artificial intelligence, bringing computational power closer to where data is generated and utilized.

This paradigm change creates new opportunities for innovation in a variety of industries while also enhancing the effectiveness and performance of AI applications.

Edge AI adoption is predicted to pick up speed as technology develops, leading to major improvements in how we use and interact with intelligent technologies in our daily lives.

VII. Case Study for Various Application Domain

Implementation of IoEC have several use cases, below case studies demonstrate how bringing computation closer to data sources improves performance and efficiency in real-world applications. These examples highlight the practical benefits and challenges of implementing edge computing solutions.

A. Disaster Management

EC has emerged as a crucial technology in improving the efficiency and reliability in practical implementation of edge computing in disaster management scenarios, particularly focusing on the integration of UAV-mounted mobile edge nodes (UAVMEC) and LoRaWAN gateways [16]. Along with this the system architecture involves user devices in affected areas, which typically include smartphones and laptops, which are used by individuals to communicate, access the internet, and transmit data during disasters over LoRaWAN gateways, UAVMEC facilitates communication in places without conventional infrastructure. User device data is forwarded by drones to LoRaWAN gateways, which subsequently send it to cloud or central servers. Because it provides emergency communication networks in cases where conventional infrastructure is disrupted, this system is essential for disaster management.

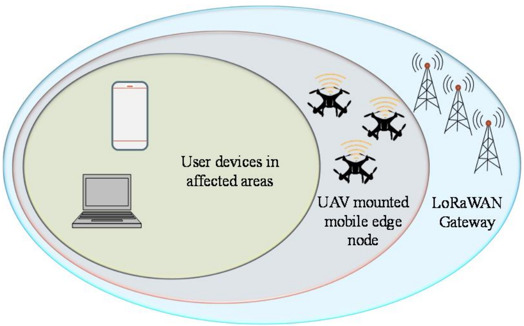

Figure 9. UAVMEC for Disaster Management[16]

Even across vast, impacted areas, effective connectivity and uninterrupted data flow are ensured by UAVs equipped with mobile edge computing capabilities. These drones process and temporarily store data.

B. Smart Oil Fields

A "Smart Oil Field" integrates modern technology with edge computing to enhance oil extraction operations. Traditional oil rigs are upgraded with smart wells and advanced sensors, including subsea sensors for measuring pressure, temperature, and flow rates, and well sensors for monitoring extraction efficiency. Drones and ships, equipped with cameras and sensors, contribute additional data. This information is processed locally by edge computing systems, allowing for real-time analysis and optimization of extraction processes. By enabling immediate issue detection and data-driven improvements, edge technology enhances operational efficiency, safety, and environmental protection, setting a new standard in the oil industry [17].

C. Weather Monitoring

Edge computing greatly improves weather forecasting by processing data locally, reducing bandwidth usage and latency. It enables real-time decision-making, which is crucial for accurate predictions [20]. From several places, Internet of Things sensors gather meteorological data, including humidity, wind speed, temperature, and air pressure. Fast and accurate forecasts are ensured by the local processing of this data at the edge. By pre-processing and filtering data, edge computing reduces bandwidth costs and improves dependability to meet weather forecasting difficulties. To further improve forecasts and lower mistakes and computational strain on central servers, methods such as anomaly detection on edge devices are used. In order to lessen the effects of extreme weather events and to support companies that depend on accurate weather information, this strategy increases the efficiency and accuracy of weather predictions.

D. Agriculture

Smart agriculture is made possible by the transformation of networking through the convergence of cloud computing and EC. For instance, AgriTalk, an IoT platform for smart agriculture, uses fog/edge computing to improve applications such as rice blast detection and piglet crushing avoidance. Delays are cut in half when using fog/edge computing as opposed to conventional cloud techniques.

By enabling farmers to design and maintain their own apps, AgriTalk's low-code/no-code methodology enhances accessibility and scalability. This integration shows notable gains in productivity and creativity in smart farming by addressing issues such sensor calibration, device integration, big data management, and data privacy [19].

E. Health Monitoring

Edge computing is used in smart health monitoring to improve responsiveness and efficiency in the medical field. Edge computing makes real-time analysis possible by locally processing data from medical equipment, which is essential for managing chronic illnesses or emergency medical circumstances [21].

By lowering latency and bandwidth consumption, this method guarantees quicker and more dependable responses.

Furthermore, by reducing the necessity to send private information to remote cloud servers, it improves security by utilizing cutting-edge encryption and access controls. Scalability is another benefit of edge computing, which makes it possible to manage massive data from linked devices and enable machine learning models for predictive analytics.

This makes healthcare more proactive and enhances patient outcomes.

VIII. Challenges in IoT-Edge

EC introduces several challenges that has to be taken care of in order to reach its full potential. Majorly these include the heterogeneity of devices and infrastructure, difficulty in standardization and resource management which results in limiting scalability, maintaining trust and security, and managing globally dispersed resources [22][23].

Apart from this, some of the challenges in IoEC are:

- IoT and edge computing expand data points and transmission paths, risking data breaches. Edge devices and edge servers must protect data. Data protection involves encryption, secure communication, and regular security updates.
- The IoT uses numerous communication protocols and standards. Integrating these technologies with edge infrastructure is complex.
- Edge devices often have less memory, storage, and computing power than cloud servers. Processing complex data with minimal latency and limited resources is tough.
- IoT devices make edge infrastructure management and expansion harder. Effective orchestration, monitoring, and management solutions are needed to exploit edge resources and scale to meet growing demands without compromising performance.
- Data accuracy and quality from IoT devices are critical. Missing numbers, errors, and inconsistent data formats might hinder edge data processing and analysis. Error correction, normalization, and validation ensure data quality. Edge devices gather energy or use batteries. Energy efficiency and continuous data processing are hard to balance. For longevity, edge devices need energy-efficient hardware, power management, and low-power communication protocols.
- Advanced edge analytics and machine learning require skill. Edge-specific analytical models that function with edge device resources are difficult to develop and install. These models must be updated and optimized for changing data and conditions.
- Data governance and regulatory compliance are difficult when handling sensitive data across jurisdictions. Companies must establish data handling, storage, and processing policies under GDPR, HIPAA, and other laws. Includes data anonymization, access limits, and audit trails.

III. Conclusions

In conclusion, we examined how IoEC might improve modern applications' efficiency, responsiveness, and security. IoEC can construct robust systems for real-time data processing and decision-making, decreasing bandwidth and latency compared to cloud-based alternatives.

Healthcare monitoring and industrial automation require rapid responses; therefore, edge computing brings data storage and computation closer to data sources. Edge computing concerns include managing diverse devices, data security, and work offloading to edge nodes. Successful EC implementation requires sophisticated algorithms to balance computational loads and ensure energy efficiency.

Integrating IoEC into healthcare, agriculture, smart oil fields, and disaster management has huge potential. By utilizing the strengths of both technologies, it is possible to build resilient, efficient, and real-time systems to improve operational effectiveness and decision-making processes.

REFERENCES

[1] T. Higashino, H. Yamaguchi, A. Hiromori, and A. Uchiyama, "Edge Computing and IoT Based Research for Building Safe Smart Cities Resistant to Disasters," 2023.

[2] M. Satyanarayanan, "The Emergence of Edge Computing," Computer, vol. 50, no. 1, pp. 30-39, 2017.

[3] M. Chiang and T. Zhang, "Fog and IoT: An Overview of Research Opportunities," IEEE Internet of Things Journal, vol. 3, no. 6, pp. 854-864, 2016.

[4] H. Ning et al., "A Survey on Fog Computing: Architecture, Key Technologies, Applications, and Open Issues," Journal of Network and Computer Applications, vol. 98, pp. 27-42, 2017.

[5] G. Premsankar, M. Di Francesco, and T. Taleb, "Edge Computing for the Internet of Things: A Case Study," IEEE Internet of Things Journal, vol. 5, no. 2, pp. 1275-1284, 2018.

[6] M. L. Umashankar et al., "A survey on IoT protocol in real-time applications and its architectures," in ICDSMLA 2021: Proceedings of the 3rd International Conference on Data Science, Machine Learning and Applications, Singapore: Springer Nature Singapore, 2023.

[7] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A Survey on Enabling Technologies, Protocols, and Applications," IEEE Communications Surveys & Tutorials, vol. 17, no. 4, pp. 2347-2376, 2015. doi: 10.1109/COMST.2015.2444095.

[8] D. Bandyopadhyay and J. Sen, "Internet of Things: Applications and Challenges in Technology and Standardization," Wireless Personal Communications, vol. 58, pp. 49-69, May 2011. doi: 10.1007/s11277-011-0288-5.

[9] S. Yi, Z. Hao, Z. Qin, and Q. Li, "Fog Computing: Platform and Applications," in Proceedings of the 3rd Workshop on Hot Topics in Web Systems and Technologies, pp. 37-42, 2015.

[10] E. Al-Masri et al., "Investigating Messaging Protocols for the Internet of Things (IoT)," IEEE Access, vol. 8, pp. 94880-94911, 2020.

[11] A. Tolk, O. Valverde, and S. Y. McCann, "Applicability of OMG's Data Distribution Services to Enhance Simulation Interoperability," in 2022 Simulation Innovation Workshop, Orlando, FL, 2022.

[12] L. Broering, P. Calyam, and M. Popescu, "DDS-based Edge Computing for Real-Time Data Distribution in IoT," IEEE Internet of Things Journal, vol. 7, no. 12, pp. 11770-11779, Dec. 2020.

[13] M. Nakkar, R. AlTawy, and A. Youssef, "Lightweight Broadcast Authentication Protocol for Edge-Based Applications," IEEE Internet of Things Journal, vol. 7, no. 12, pp. 11766-11769, Dec. 2020.

[14] A. Aral, M. Erol-Kantarci, and I. Brandić, "Staleness Control for Edge Data Analytics," Proceedings of the ACM on Measurement and Analysis of Computing Systems, vol. 4, no. 2, pp. 1-24, 2020.

[15] R. Singh and S. S. Gill, "Edge AI: A Survey," Internet of Things and Cyber-Physical Systems, vol. 3, pp. 71-92, 2023.

[16] J. Xu, K. Ota, and M. Dong, "Big Data on the Fly: UAV-Mounted Mobile Edge Computing for Disaster Management," IEEE Transactions on Network Science and Engineering, vol. 7, no. 4, pp. 2620-2630, 2020.

[17] R. F. Hussain et al., "Federated Edge Computing for Disaster Management in Remote Smart Oil Fields," in 2019 IEEE 21st International Conference on High Performance Computing and Communications; IEEE 17th International Conference on Smart City; IEEE 5th International Conference on Data Science and Systems (HPCC/SmartCity/DSS), IEEE, 2019.

[18] "CoAP Protocol," Nordic Developer Academy, Available: https://academy.nordicsemi.com/courses/cellular-iot-fundamentals/lessons/lesson-5-cellular-fundamentals/topic/lesson-5-coap-protocol/. Accessed: 23 July 2024.

[19] Y.-B. Lin, W.-E. Chen, and T. C.-Y. Chang, "Moving from Cloud to Fog/Edge: The Smart Agriculture Experience," IEEE Communications Magazine, vol. 61, no. 12, pp. 86-92, 2023.

[20] Ş. M. Kaya et al., "An Intelligent Anomaly Detection Approach for Accurate and Reliable Weather Forecasting at IoT Edges: A Case Study," Sensors, vol. 23, no. 5, p. 2426, 2023.

[21] A. Singh and K. Chatterjee, "Edge Computing Based Secure Health Monitoring Framework for Electronic Healthcare System," Cluster Computing, vol. 26, no. 2, pp. 1205-1220, 2023.

[22] L. Fotia, F. Delicato, and G. Fortino, "Trust in Edge-Based Internet of Things Architectures: State of the Art and Research Challenges," ACM Computing Surveys, vol. 55, no. 9, pp. 1-34, 2023.

[23] G. K. Walia, M. Kumar, and S. S. Gill, "AI-Empowered Fog/Edge Resource Management for IoT Applications: A Comprehensive Review, Research Challenges and Future Perspectives," IEEE Communications Surveys & Tutorials, 2023.