Edge Computing for Critical Infrastructure Delay Sensitive Applications: Current Trends and Future Directions

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Abstract— **Internet of things as an emerging technology is increasing into various aspects of our lives with several smart applications ranging from grid, cities, homes and healthcare. The IOT gadgets numbering in Billions are linked to the Internet regularly with projection of the devices expected to reach 500 billion by the year 2030. Produced data by the IOT gadgets are communicated constantly from sensors to the main storage platform designated at the remote cloud server. Several delay sensitive IOT applications needs constant computation of data generated by edge devices which makes the cloud not suitable for such applications. Hence, the edge architecture is vital so as to satisfy the necessities of employing cloud related platforms close to the data source of the network. Critical infrastructure (CI) are facilities such as oil and gas pipeline, power plants, airports, water treatment plants and communication systems in physical or virtual form that are considered vital for the regular operations of an economy and the society as a whole.**

Based on the challenges observed with the cloud and IOT paradigms integration, an edge computing framework was proposed and experimental procedures was carried out using the IFOGSIM simulation tool. Parameters such as delay and network bandwidth utilization was analyzed in contrast to the cloud and edge based architecture. It was shown that the edge based architecture shows less delay and less network utilization rates.

Keywords— Critical Infrastructure, Edge Computing, Internet of Things and Delay Sensitive Applications

I. INTRODUCTION

As a prevailing paradigm, the internet of things (IOT) is increasing into various aspects of our lives with several applications ranging from smart cities, smart grid, smart homes and healthcare [1]. The IOT gadgets numbering in Billions are linked to the Internet constantly with projection of the devices reaching 500 billion by the year 2030. Produced data by the IOT gadgets are communicated regularly from sensors to the primary storage platform designated at the remote cloud server. Several delay sensitive IOT applications needs constant computation of data generated by edge devices which makes the cloud not suitable for such applications. Hence, the edge architecture is vital so as to satisfy the necessities of employing cloud related platforms close to the network data source [2].

Given the huge growth of connected devices and considering network ranges, it tend to go with the emergence of IOT technology. Sensor networks been vital element of IOT, rises to be pervasive and extensively utilized in diverse areas of usage [2] [3].

The Internet industry worldwide is growing rapidly and showing vital potential development and vitality as it is progressively suitable for supporting fiscal growth thereby surmounting disputes. With the adoption of technologies such as 5G, artificial intelligence and big data, the world is experiencing remarkable changes to better productivity especially for IOT related activities. Amid rising utilization of the internet, the world is experiencing a paradigm change consisting of human's Internetwork linkage to IOT links [4] [5].

IOT as an evolving technology enables an incredible amount of gadgets to get linked to Internet which include smart equipment, sensors, actuators, buildings, vehicles and beam pumping units. It connects ubiquitous devices thereby enabling things getting detected and controlled remotely. The IOT is envisioned to enhance effectiveness, precision and along with cost savings. It is presently influencing basic roles in several promising services which includes smart cities, smart grids and intelligent transportation systems[6].

More so, Cloud computing since inception has shown promising functions in increasing the visibility and abilities of computing, storage and networking structure of applications. It has been viewed as an architecture known to promote universal access of network resources and services to users as at when needed worldwide[7][8].

Years ago, the computation loads and volume of data in cloud servers keep rising whereby the computation outcomes and regulated information are constantly transferred to the centralize cloud storage. The cloud architecture given its advantages of faster processing still encounter issues of rising time delay [9][10]. The time delay has been on the rise due to the overhead triggered by inter cloud communications.

The Edge computing paradigm has become a vital resolution to tackle the issues of evolving technologies such as cloud and IOT by reducing data transmission rates, latency and pressure linked with cloud data computation. The generated data by the edge devices in an edge computing architecture are usually process at the edge of the network instead of been transferred to the distant cloud storage where they are computed by the edge devices with only information containing unusual patterns been transmitted to the distant cloud [11][12].

Critical infrastructure (CI) are those vital assets which includes oil and gas pipeline, power plants, airports, water treatment plants, public health, transportation systems, agriculture, security service, power grids and communication systems in physical or virtual form that are considered vital for the regular operations of an economy and the society as a whole [13] [14].

The connection of CI and edge technologies in the form of embedded systems, mobile technologies, smart devices,

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wireless technologies and the extensive growth of the Internet are easing the deployment of robust and dependable results where the failure of a particular system often results to major catastrophe [15][16][17]. This has led to issues that have influenced the IOT systems service delivery time significantly. The study seeks to review the current state of Edge computing and architectures, its role in critical infrastructure delay sensitive applications, Architectural issues of Cloud and IOT integration, proposed an Edge computing framework for delay sensitive critical infrastructure and also the simulation of the proposed framework.

The core input carried out by this research includes:

i. Outlined the challenges associated with IOT and Cloud based systems
ii. Review the role of edge computing in Critical infrastructure IOT based systems.
iii. Highlight the various Edge Computing Architectures
iv. Present an Edge computing framework for delay sensitive critical infrastructure
v. The simulation of the proposed framework

The study consist of eight sections that begins with introduction, architectural issues of IOT and cloud based systems, edge computing role in critical infrastructure IOT systems, edge computing deployment architectures, Edge computing framework for delay sensitive critical infrastructure, Experimentation ,Results discussions and lastly conclusion and further studies.

II. Architectural ISSUES of IOT and Cloud based Systems

With the IOT disruption leading to connection of mobile and static gadgets in billions offering real time applications, the cloud architecture technology tend to encounter major issues in the form of high latency, extreme bandwidth request and facilities of mobility [18]. Over the years, several of the computing jobs earlier linked with cloud based architecture are been relocated to the edge network [1] with the data been computed as distributed jobs [19].

The importance of cloud architecture and IOT paradigm integration is aimed at evolving improving results in the form of universal and protected technique. This qualities often make process of merging quite simple, but the challenges that arises as a result of the integration includes big data, privacy concerns, safety, homogeneity and lawful features.

Even though the cloud architecture emergence have led to computation and data keeping limitations getting removed, the computing tasks and volumes of information are rising thereby leading to frequent increase in data traffic [8][20][21] and bandwidth issues[22]. The cloud and IOT devices connection interaction is as shown in Fig. 1

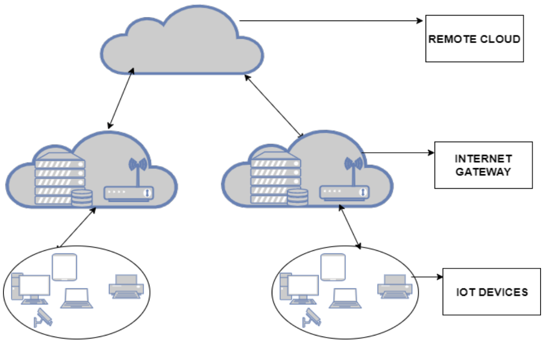


Fig. 1. Cloud and IOT Architecture [22]

III. Edge Computing Role in Critical Infrastructure IOT systems

Current cloud architecture lacks efficiency in processing the huge information within short time with the aim of satisfying the client's conditions especially for delay sensitive applications. More so, the long time it takes to process the huge information often influence the service delivery and the general working condition of the network.

In surmounting the limitations of the cloud paradigm, the edge computing paradigm was introduce which is an architecture that offers a decentralized solution involving computation of data at the network edge. Additionally, the edge architecture aids the IOT systems requiring less computation time thereby improving the energy utilization rate and use of resources [8][23][24][25].

Examining IOT applications in critical infrastructure such as oil pipeline, bridges, farmhouses, connected vehicles, power grids, smart homes, telecommunication systems, smart port and smart airports, it primarily needs constant functioning of the IOT gadgets at the deployed environment with some been severe in some cases [8][26].

In situations where there is sudden emergency such as procedure or device breakdown, measures need to be engaged instantly exclusive of requiring commands by the distant cloud storage [27][28]. With this conditions occurring, it is critical to take instant action against the occurrence by putting off the defective device in the case of an oil pipeline infrastructure network once the fault is detected [1][8][30].

The Edge architecture can thus be comprehended as a paradigm involving the generation, computation and investigation of the data usually by a device like an IOT gateway or customize gadgets having acceptable processing ability. The deployed edge procedures allows instant investigation for the collected vast amount of information produced by the sensor devices [31] [32] [33].

IV. Edge Computing Deployment Architectures

This section examines the different edge technologies.

A. Fog Computing

Given the issues linked with cloud computing, research has led to the idea of fog computing (FC) in resolving some of the challenges. This is aimed at making the cloud services closer to the data source which usually consists of sensors, embedded systems, mobile phones and autonomous cars [34][29][35].

The term Fog computing (FC) is a network architecture that uses the end user edge devices to obtain huge amount of storage, computing and communication resources utilized to carryout measurement, control, processing, configuration, and tasks [37]. FC which is a term coined by Cisco[36], refers to a distributed layer of a network environment linked alongside cloud architecture and IOT where the FC is acting in place of the central cloud thereby offering the opportunity for those data that needs instant processing [38][39]. The fog layer essentially consists of the centralized cloud, fog nodes that act as the mini clouds and the IOT devices level which is as shown in Fig. 2.

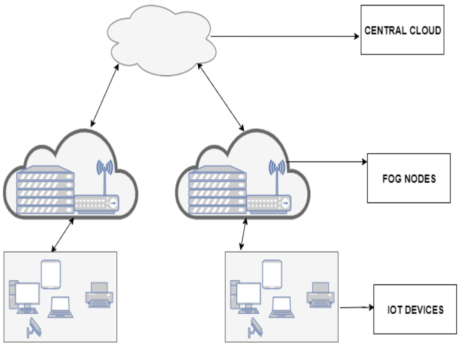


Fig. 2. FC Architecture [26][36]

B. *Cloudlet*

The Cloudlet is an edge based architecture that comprises of a mini datacentre situated at the network edge with the aim of bringing cloud computing capabilities nearer to the users. Cloudlet been specific to a geographical location, is primarily use for mobile devices where it is linked to a location as it traverses to and fro the network. The cloudlet main idea is the aid it offers to several time consuming systems through utilisation of effective computational mechanisms that proffers lesser delay[23][40]. The cloudlet interaction architecture is as shown in Fig. 3.

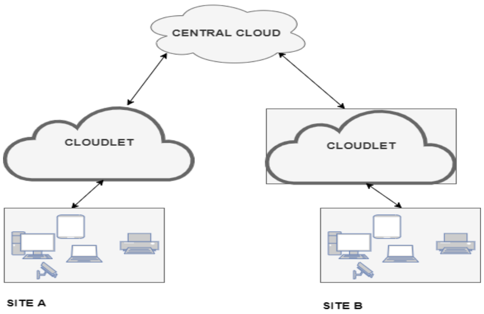


Fig. 3. Cloudlet Architecture [45]

D. Mobile Edge Computing

As an edge design, mobile edge computing (MEC) offers cloud architecture capabilities at the edge of network. While the primary cloud computing functions on remote cloud storage tend to be situated distance away from clients and gadgets, MEC allows tasks to be carried out at the base stations (BS)[7][41]. Mobile Edge Computing is intended for lower latency, location aware and higher bandwidth that actually positions computing functionalities and service environment at the cellular network edge[36][42]. The deployment of the edge servers on cellular BS enables the users to employ latest applications and services easily and rapidly[43][44]. As described by the European

Telecommunication Standard Institute (ETSI), MEC is also referred to as Multi Access Edge Computing with the aim of possessing different wireless communication technologies [45] [46]. The general architecture of the MEC is as shown in Fig. 4.

Fig. 4. MEC Architecture [7] [41]

C. Dew Computing

As an edge paradigm, dew computing offers extra layer amidst the end users devices which consists of smart sensors that transform physical quantities into digital information. It allows effective management among Cloud, Edge and Fog layers thereby encouraging independence alongside cooperation between linked devices [47].

Dew computing as a model, links the main notion of cloud computing with the abilities of end devices. It fulfils diverse variations exhibited by cloud computing. Variations are often formed by halting the cloud services while the internet is not available thereby making the user loose connection to the cloud and cannot utilize the services. As such, Dew computing offers transitory service so as to handle and enable the user to proceed with the critical services as desired [48].

The Dew Computing paradigm additionally increases the dissemination of resources as observed with Fog Computing and stand at the lowest level of the architecture as seen in fig. 6. Dew computing is centered on the idea of micro-services which are offered by end-user devices which includes mobile devices, laptops and smart devices which are independent of the central nodes. In the Dew Computing architecture, some features and data are moved on the end devices, thus recognizing the abilities of distributed devices and services of the cloud [49]**.** The general architecture of dew computing paradigm is as shown in Fig.5.

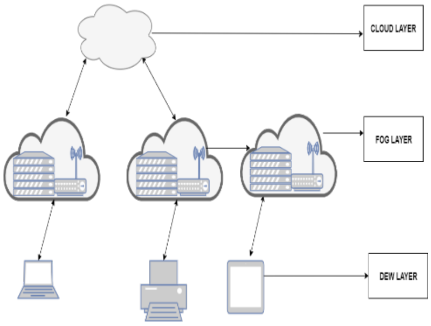
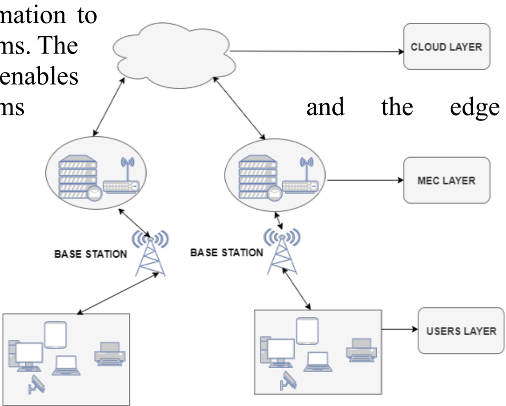


Fig. 5. Dew Computing Architecture [47]

E. *Mist Computing*

Mist computing as an edge computing architecture broadens the computational methods of IOT alongside the main cloud and the edge of the network. The cloud offers extreme processing facilities alongside huge range information to IOT systems. The mist level enables systems and the edge level



characterized with fog architecture to append processing layers amongst cloud and sensor mechanisms. The least level which comprises the limited computational IOT gadgets are regarded the mist level. The mist level architecture is aimed at minimizing large size information transmission weight of the network, likewise offering capabilities of actual time near the clients [50].

Considering processing and transmission abilities, the mist platform relies on collection of homogenous group of limited gadgets thereby allowing the sharing of facilities in a more active ecosystem of the IOT [50][51]. The general architecture of the mist computing is as presented in Fig. 6.

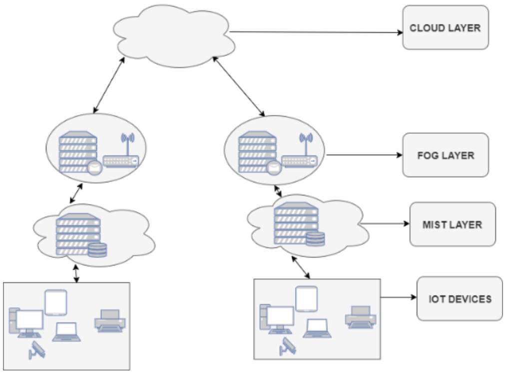


Fig. 6. Mist Computing Architecture

V. RELATED WORK

Given the impact and relevancy of critical infrastructure and edge computing in several domains of human endeavor, numerous research has been conducted in that regard. In [52], the authors studied fog computing and WSN for pipeline leakage detection. The study considered only energy as metric for analysis.

In [53], the authors considered the idea of federated edge for remote oil field disaster management where they examined the various task arrival and assignment rates. The study did not however evaluate metrics such as network utilization rate and its influence between cloud and edge scenarios.

In [54], the authors presented a proposal based on Bayesian Network model of Quality of Service (QoS) related parameters for the estimation of VM availability in Edge infrastructure. The study did not consider a particular area of application an[illegible]alysis of network [illegible]ation as an edge architectur[illegible] performance measurement.

The aut[illegible]] studied edge and cloud computing applications in smart grid. While the study examines ext[illegible]arious ed[illegible]oud paradigm applications an[illegible]ures, the[illegible] experi[illegible]arried out to eva[illegible]resented [illegible]s.

The authors in [56] utilized the approach of sliding window for critical systems response time enhancement. However, the application domain is in the automotive domain with[illegible]eva[illegible]n o[illegible]syst[illegible]etw[illegible]e in terms of bandwidth consumption between the edge and cloud architectures.

The authors in [57] reviewed the security threats, analysis and challenges of edge computing utilization in critical infrastructure. There was however no empirical backings given for the edge role in critical infrastructures.

The authors in [58] carried out a study on the use of edge computing and blockchain technology for securing critical infrastructure thereby making it more scalable. The study did not show any empirical backing to achieve the stated objectives.

The study in [59] shows the practical use case of edge and fog architectures in civil infrastructure structural health monitoring. The techniques seems promising to monitor critical infrastructures but no clear evaluation was made regarding the devices network bandwidth and energy consumption in comparison amongst the cloud and edge applications scenarios.

The management of resources in edge computing is often regarded as a difficult activity as it involves substantial volume of resource constraint devices so as to satisfy the IOT dispersed nature. Due to the high cost involved with the real time deployment of edge computing systems, the use of simulation is often popular among researchers nowadays. The Simulation tools apart from offering structures for designing personalized experimentation, it also helps in reproducible estimation [60].

Several simulators such as Edgecloudsim [61], iFogSim [62] and SimpleIoTSimulator [63] are in use currently for edge architecture scenarios modelling and experimentation. This research used the iFogSim simulator due to its simplicity, robustness and the fact that it proffers choices of simulating personalized edge architecture situations amid huge number of IOT and edge devices.

VI. EDGE COMPUTING FRAMEWORK FOR DELAY SENSITIVE CRITICAL INFRASTRUCTURE

The proposed edge architecture framework for as shown in Fig. 7 consist of an oil pipeline segment incorporated with IOT devices, edge analytics layer and the central cloud. The IOT device layer measure parameters such as flow rate, pressure and temperature. In the incidence of leakage as a result of the significant drop in any of the measured parameters, the system will be able to respond appropriate within short time period for immediate response to prevent loses and environmental damages that might occur. The edge mechanism is critical in this regard since decision will be taken at the edge instead of waiting for response from central cloud storage that might delay the action.

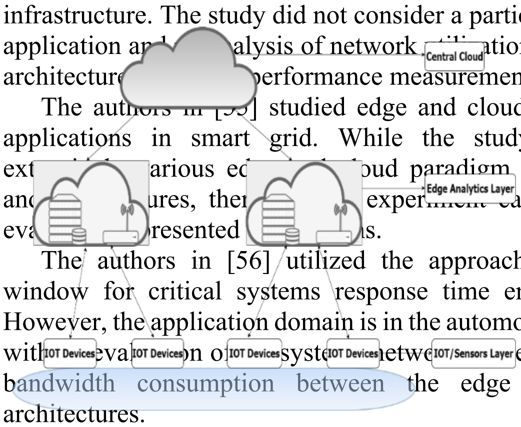


Fig. 7. Proposed Edge Architecture with an oil pipeline segment

VII. EXPERIMENT SETUP AND RESULTS DISCUSSION

The simulation was carried out using IfogSim imported into the Eclipse IDE. The terminal use was a Core i5 CPU with speed of 2.60GHz, 8GB of RAM and 64bit operating system based processor. Preceding the simulation was the network topology created for both cloud and edge architecture as seen in figs. 8 and 9 respectively. Fig.8 consists of 6 sensors which are connected to the cloud via the gateway server.

Similarly, Fig. 9 consist of two edge nodes named as edge node1 and edge node 2 having 3 individual sensors named 1 to 6 connected to them and linked to the cloud via the gateway server. The sensors in the context of the oil pipeline critical infrastructure are assumed to read the pressure, flowrate and temperature of the surrounding pipeline segment.

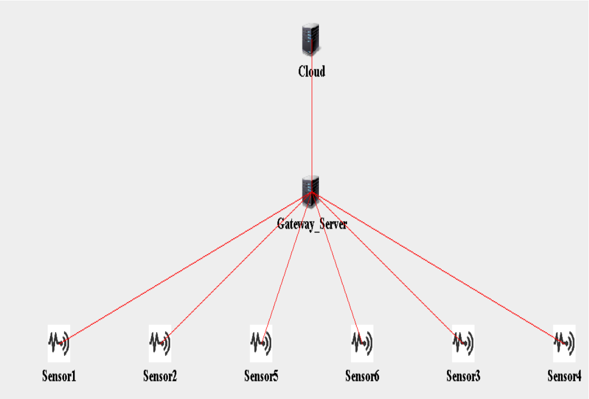


Fig.8 Cloud Topology with Sensors

The parameters used for both the cloud and edge topology for Figs. 9 and 10 is given in table 1 and 2 respectively

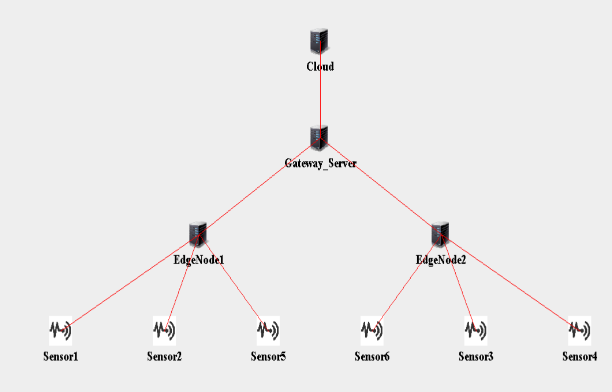


Fig.9 Edge Topology with Sensors, Gateway Server and Cloud

TABLE I. Cloud connected with Sensors and Gateway Serve

S/N	Parameters	Cloud	Gateway
1.	Rate/ MIPS	0.02	0.1
2.	Level	0	1
3.	Downlink Bandwidth (MB)	2000	1500
4.	Uplink Bandwidth (MB)	1500	1000
5.	RAM(MB)	30000	3500
6.	MIPS (CPU)	35600	2600

TABLE II. Cloud connected with Edge nodes, Gateway and Sensors

S/N	Parameters	Cloud	Gateway	Edge
1.	Rate/ MIPS	0.02	0.1	0.1
2.	Level	0	1	2
3.	Downlink Bandwidth (MB)	2000	1500	500
4.	Uplink Bandwidth (MB)	1500	1000	500
5.	RAM(MB)	30000	3500	3000
6.	MIPS(CPU)	35600	2600	2000

Considering delay and network utilization as the metrics, the observed performance of both the cloud and edge topology scenarios is as shown in Table 3 and 4 respectively.

TABLE III. Edge and Cloud Delay Analysis

Number of Sensors	Edge Delay	Cloud Delay
6	14.283	15.323
9	15.32	16.82
12	15.67	18.12
15	16.2	416.23
18	17.12	977.29
21	17.72	1931.5

TABLE IV. Edge and Cloud Network Utilization

Number of Sensors	Edge Network Utilization	Cloud Network Utilization
6	25645.94	572629.76
9	69567.88	1157725.52
12	112637.8	1776361.28
15	142691.8	2043585.04
18	169577.7	2056008.8
21	176134.7	2097096.92

Furthermore, the simulation outcomes also shows the contrast between the cloud and edge scenarios in terms of the delay and network utilization as depicted in Fig. 10 and 11 respectively.

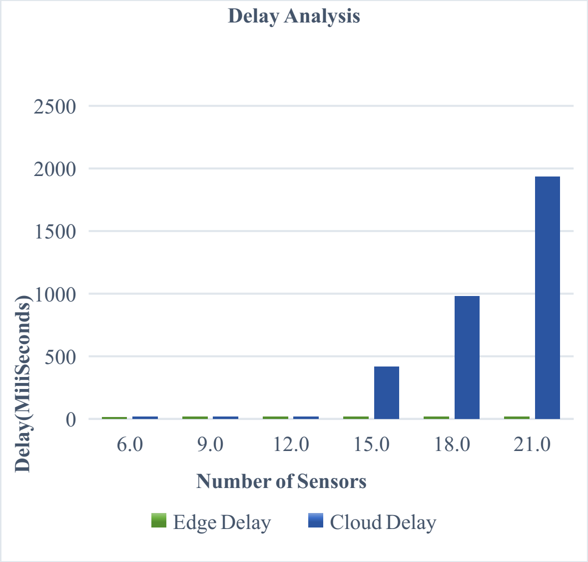


Fig. 10 Contrast between Edge and Cloud Delay

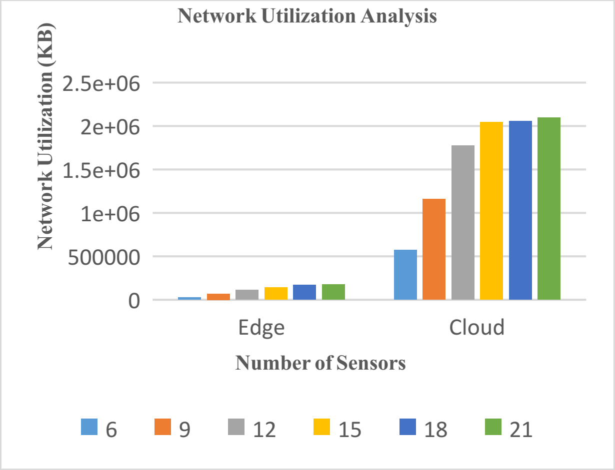


Fig. 11 Contrast between Edge and Cloud Network Utilization

From Figs. 10 and 11, it is evident that with the increase in the number of sensors the delay is seen to be high for the cloud scenario and also the network utilization is seen to be high in the cloud architecture in contrast with the edge architecture.

VIII. CONCLUSION AND FURTHER STUDIES

IOT allows interaction amongst gadgets, entities and any computational facility capable of sending and accepting information within network environment with no need for human intervention. The key feature of an IOT system is the huge amount of generated data by the sensor gadgets that requires computation within less time period on the remote cloud.

The existing cloud architecture however is not effective in meeting the demands of delay sensitive applications given the huge data to be process instantly to meet the users' requirement.

The Edge computing paradigm has become a vital resolution to tackle the issues of evolving technologies such as cloud and IOT by reducing data transmission rates, latency and pressure linked with cloud data computation.

In this study, an edge computing framework for an oil pipeline critical infrastructure was proposed and simulated. Parameters such as delay and network bandwidth utilization was analyzed in contrast to the cloud and edge based architecture. It was shown that the edge based architecture shows less delay and less network utilization rates. Further studies will involve developing a framework based on deep reinforcement learning for critical infrastructure continuous monitoring.

REFERENCES

[1] J. Ren, D. Zhang, S. He, Y. Zhang, and T. Li, “A survey on End-Edge-Cloud Orchestrated Network Computing Paradigms: Transparent Computing, Mobile Edge Computing, Fog ComputinG, and Cloudlet,” *ACM Comput. Surv.*, vol. 52, no. 6, 2019.

[2] Y. He, G. Han, M. Xu and M. Martínez-García, "A Pseudo-Packet Scheduling Algorithm for Protecting Source Location Privacy in the Internet of Things," in *IEEE Internet of Things Journal*, 2021, doi: 10.1109/JIOT.2021.3117957.

[3] Divya Gupta; Shalli Rani; Syed Hassan Ahmed Shah, "ICN-Fog Computing for IOT-Based Healthcare," in *IOT-enabled Smart Healthcare Systems, Services and Applications* , Wiley, 2022, pp.19-37, doi: 10.1002/9781119816829.ch2.

[4] C. Zhang, "Intelligent Internet of things service based on Artificial Intelligence Technology," *2021 IEEE 2nd International Conference on Big Data, Artificial Intelligence and Internet of Things Engineering (ICBAIE)*, 2021, pp. 731-734, doi: 10.1109/ICBAIE52039.2021.9390061.

[5] A. K. Sandhu, "Big data with Cloud Computing: Discussions and challenges," in *Big Data Mining and Analytics*, vol. 5, no. 1, pp. 32-40, March 2022.

[6] C. Song, S. Liu, G. Han, P. Zeng, H. Yu and Q. Zheng, "Edge Intelligence Based Condition Monitoring of Beam Pumping Units under Heavy Noise in the Industrial Internet of Things for Industry 4.0," in *IEEE Internet of Things Journal*, 2022, doi: 10.1109/JIOT.2022.3141382.

[7] M. Muniswamaiah, T. Agerwala and C. C. Tappert, "A Survey on Cloudlets, Mobile Edge, and Fog Computing," *2021 8th IEEE International Conference on Cyber Security and Cloud Computing (CSCloud)/2021 7th IEEE International Conference on Edge Computing and Scalable Cloud (EdgeCom)*, 2021, pp. 139-142, doi: 10.1109/CSCloud-EdgeCom52276.2021.00034.

[8] G. Carvalho, B. Cabral, V. Pereira, and J. Bernardino, “Engineering Applications of Artificial Intelligence Computation Offloading in Edge Computing Environments using Artificial Intelligence Techniques ☆,” *Eng. Appl. Artif. Intell.*, 95, pp. 103840, (2020).

[9] F. Guim *et al.*, "Autonomous Lifecycle Management for Resource-Efficient Workload Orchestration for Green Edge Computing," in *IEEE Transactions on Green Communications and Networking*, vol. 6, no. 1, pp. 571-582, March 2022, doi: 10.1109/TGCN.2021.3127531.

[10] M. Capra, R. Peloso, G. Masera, M. Ruo Roch, M. Martina, Edge Computing: “Edge computing: A survey on the Hardware Requirements in the Internet of Things world,” *Futur. Internet*, vol. 11, no. 4, pp. 1–25, 2019.

[11] W. Y. B. Lim *et al.*, “Federated Learning in Mobile Edge Networks: A Comprehensive Survey,” *IEEE Commun. Surv. Tutorials*, vol. 22, no. 3, pp. 2031–2063, 2020.

[12] L. Wang, J. Zhang, J. Chuan, R. Ma, and A. Fei, “Edge Intelligence for Mission Cognitive Wireless Emergency Networks,” *IEEE Wirel. Commun.*, vol. 27, no. 4, pp. 103–109, 2020.

[13] T. Wang, M. Z. A. Bhuiyan, G. Wang, M. A. Rahman, J. Wu, and J. Cao (2018). “Big data reduction for a Smart City’s Critical Infrastructural Health Monitoring,” IEEE *Communications Magazine*, Vol. 56, no 3, pp. 128–133.

[14] M. Chen *et al.*, (2020). “Living with I-Fabric: Smart Living Powered by Intelligent Fabric and Deep Analytics,” *IEEE Network.*, Vol. 34, no 5, pp. 156–163.

[15] P. Tedeschi and S. Sciancalepore (2019). “Edge and Fog Computing in Critical Infrastructures: Analysis, Security Threats, And Research Challenges,” *Proc. - 4th IEEE Eur. Symp. Secur. Priv. Work. EUROS PW 2019*, pp. 1–10.

[16] J. Farooq; Q. Zhu, "Internet of Things-Enabled Systems and Infrastructure," in *Resource Management for On-Demand Mission-Critical Internet of Things Applications* , IEEE, 2021, pp.1-8, doi: 10.1002/9781119716112.ch1.

[17] A. R. Dar and D. Ravindran, “Fog Computing Resource Optimization: A review on current scenarios and Resource Management,” *Baghdad Sci. J.*, vol. 16, no. 2, pp. 419–427, 2019.

[18] Y. Mansouri, M. Ali Babar, A review of edge Computing: Features and Resource Virtualization, *Journal of Parallel and Distributed Computing*, Vol. 150,2021, PP 155-183, https://doi.org/10.1016/j.jpdc.2020.12.015.

[19] T. Goethals, B. Volckaert and F. D. Turck, "Enabling and Leveraging AI in the Intelligent Edge: A Review of Current Trends and Future Directions," in *IEEE Open Journal of the Communications Society*, vol. 2, pp. 2311-2341, 2021, doi: 10.1109/OJCOMS.2021.3116437.

[20] T. Adegbija, R. Lysecky, and V. V. Kumar, “Right-provisioned IOT edge computing: An overview,” in *Proceedings of the ACM Great Lakes Symposium on VLSI, GLSVLSI*, 2019, pp. 531–536.

[21] E. Grande and M. Beltrán, “Edge-centric delegation of authorization for constrained devices in the Internet of Things,” *Comput. Commun.*, 160, pp. 464–474, 2020.

[22] C. H. Hong and B. Varghese, “Resource Management in Fog/Edge Computing: A survey on Architectures, Infrastructure, and Algorithms,” *ACM Comput. Surv.*, vol. 52, no. 5, (2019).

[23] F. Guim *et al.*, "Autonomous Lifecycle Management for Resource-Efficient Workload Orchestration for Green Edge Computing," in *IEEE Transactions on Green Communications and Networking*, vol. 6, no. 1, pp. 571-582, March 2022, doi: 10.1109/TGCN.2021.3127531.

[24] L. Li, L. Xiaofei, J. Hai, and L. Peng, “Computation Offloading Toward Edge Computing,” vol. 107, no. 8, (2019).

[25] L. U. Khan, I. Yaqoob, N. H. Tran, S. M. A. Kazmi, T. N. Dang, and C. S. Hong, “Edge Computing Enabled Smart Cities: A Comprehensive Survey,” *IEEE Internet Things J.*, 4662, pp. 1–1, 2020.

[26] P. Tedeschi and S. Sciancalepore, “Edge and fog computing in critical infrastructures: Analysis, security threats, and research challenges,” *Proc. - 4th IEEE Eur. Symp. Secur. Priv. Work. EUROS PW 2019*, pp. 1–10, (2019).

[27] Z. Zou, Y. Jin, P. Nevalainen, Y. Huan, J. Heikkonen, and T. Westerlund, “Edge and Fog Computing Enabled AI for IOT -An Overview,” *2019 IEEE Int. Conf. Artif. Intell. Circuits Syst.*, pp. 51–56, 2019.

[28] A. Santoyo-González *et al.*, “Latency-aware Virtualized Network Function provisioning for distributed edge clouds,” *J. Parallel Distrib. Comput.*, vol. 127, no. 2019, pp. 29–37, 2019.

[29] K. Wang, “Migration strategy of cloud collaborative computing for delay-sensitive industrial IOT applications in the context of intelligent manufacturing,” *Comput. Commun.*, vol. 150, no. October 2019, pp. 413–420, 2020.

[30] A. Chen and H. Dong, "A Pipeline On-line Detection and Control System Based on the IOT," *2021 IEEE 4th International Conference on Electronics Technology (ICET)*, 2021, pp. 1095-1098, doi: 10.1109/ICET51757.2021.9450968.

[31] F. A. Salaht, F. Desprez, A. Lebre, and A. Farah, “An overview of service placement problem in Fog and Edge Computing ACM Computing Surveys, Association for Computing Machinery, 2020, 53 (3), pp.1 - 39, 2020.

[32] M. Goudarzi, H. Wu, M. Palaniswami and R. Buyya, "An Application Placement Technique for Concurrent IoT Applications in Edge and Fog Computing Environments," in *IEEE Transactions on Mobile Computing*, vol. 20, no. 4, pp. 1298-1311, 1 April 2021, doi: 10.1109/TMC.2020.2967041.

[33] J. Wang, Z. Lu, and E. Al-Masri, “Edgify: Resource Allocation Optimization for Edge Clouds Using Stable Matching,” pp. 128–130, (2020).

[34] X. Wang, S. Member, Y. Han, S. Member, and V. C. M. Leung, “Convergence of Edge Computing and Deep Learning : A Comprehensive Survey,” pp. 1–36, 2020.

[35] Z. A. Mann, "Decentralized application placement in fog computing," in *IEEE Transactions on Parallel and Distributed Systems*, 2022, doi: 10.1109/TPDS.2022.3148985.

[36] H. Zahmatkesh and F. Al-turjman, “Fog computing for sustainable smart cities in the IOT era : Caching techniques and enabling technologies - an overview,” *Sustain. Cities Soc.*, vol. 59, no. March, p. 102139, 2020.

[37] S. M. Mohsin, S. Aslam, S. M. A. Akber, A. Iqbal, A. Waheed, and A. Ikram, “Empowering Cloud of Things with Edge Computing: A Comparative Analysis,” *ICISCT 2020 - 2nd Int. Conf. Inf. Sci. Commun. Technol.*, (2020).

[38] M. Yahuza *et al.*, "Systematic Review on Security and Privacy Requirements in Edge Computing: State of the Art and Future Research Opportunities," in *IEEE Access*, 8, pp. 76541-76567, (2020).

[39] M. Yahuza *et al.*, "Systematic Review on Security and Privacy Requirements in Edge Computing: State of the Art and Future Research Opportunities," in *IEEE Access*, 8, pp. 76541-76567, (2020).

[40] M. Babar, M. S. Khan, F. Ali, M. Imran and M. Shoaib, "Cloudlet Computing: Recent Advances, Taxonomy, and Challenges," in *IEEE Access*, vol. 9, pp. 29609-29622, 2021, doi: 10.1109/ACCESS.2021.3059072.

[41] P. Habibi, S. Member, M. Farhoudi, A. Leon-garcia, and L. Fellow, “Fog Computing : A Comprehensive Architectural Survey,” *IEEE Access*,8, pp. 69105–69133, 2020.

[42] S. Tuli, N. Basumatary, S. Singh, and M. Kahani, “HealthFog : An ensemble deep learning based Smart Healthcare System for Automatic Diagnosis of Heart Diseases in integrated IOT and fog computing environments,” *Futur. Gener. Comput. Syst.*, 104, pp. 187–200, (2020).

[43] M. Gheisari, G. Wang, and S. Chen, “An Edge Computing-enhanced Internet of Things Framework for Privacy-preserving in Smart City R,” 81, 1 – 10 (2020).

[44] D. Sun, X. Li, L. Zhao, Y. Wang, X. Cao, and J. Yang, “Study of Demand-Side Resources Collaborative Optimization System Based on the Cloud Edge Computing,” *2020 IEEE 5th Int. Conf. Cloud Comput. Big Data Anal. ICCCBDA 2020*, pp. 80–84, (2020).

[45] K. Ray and A. Banerjee, "Prioritized Fault Recovery Strategies for Multi-Access Edge Computing Using Probabilistic Model Checking," in *IEEE Transactions on Dependable and Secure Computing*, 2022, doi: 10.1109/TDSC.2022.3143877.

[46] A. Antony Franklin and S. D. Tambe, “Multi-access edge computing in cellular networks,” *CSI Trans. ICT*, vol. 8, no. 1, pp. 85–92, 2020.

[47] M. Gushev, “Dew Computing Architecture for Cyber-Physical Systems and IoT,” *Internet of Things*, vol. 11, p. 100186, 2020.

[48] P. Suwansrikham, S. Kun, S. Hayat, and J. Jackson, “Dew computing and asymmetric security framework for big data file sharing,” *Inf.*, vol. 11, no. 6, pp. 1–28, 2020.

[49] Kishore Medhi, Nurzaman Ahmed, Md. Iftekhar Hussain (2021). Dew-based offline computing architecture for healthcare IOT, *ICT Express*, 2021, https://doi.org/10.1016/j.icte.2021.09.005.

[50] A. Sattari, R. Ehsani, T. Leppanen, S. Pirttikangas, and J. Riekki, “Edge -supported Microservice-based Resource Discovery for Mist Computing,” *Proc. - IEEE 18th Int. Conf. Dependable, Auton. Secur. Comput. IEEE 18th Int. Conf. Pervasive Intell. Comput. IEEE 6th Int. Conf. Cloud Big Data Comput. IEEE 5th Cyber Sci. Technol. Congr. DASC/PiCom/CBDCom/CyberSciTech 2020*, no. August, pp. 462–468, 2020.

[51] P. Galambos, "Cloud, Fog, and Mist Computing: Advanced Robot Applications," in *IEEE Systems, Man, and Cybernetics Magazine*, vol. 6, no. 1, pp. 41-45, Jan. 2020, doi: 10.1109/MSMC.2018.2881233.

[52] H. Gupta, A. Dastjerdi, S. Ghosh, and R. Buyya. iFogSim: A toolkit for modelling and simulation of resource management techniques in internet of things, edge and fog computing environments. *Software: Practice and Experience (SPE)*, 47(9): 1275–1296, 2017.

[53] R. F. Hussain, M. A. Salehi, A. Kovalenko, Y. Feng and O. Semiari, "Federated Edge Computing for Disaster Management in Remote Smart Oil Fields," *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)*, 2019, pp. 929-936, doi: 10.1109/HPCC/SmartCity/DSS.2019.00134.

[54] A. Aral and I. Brandic, "Quality of Service Channelling for Latency Sensitive Edge Applications," *2017 IEEE International Conference on Edge Computing (EDGE)*, 2017, pp. 166-173, doi: 10.1109/IEEE.EDGE.2017.30.

[55] J. Li, C. Gu, Y. Xiang and F. Li, "Edge-Cloud Computing Systems for Smart Grid: State-of-the-Art, Architecture and Applications," in *Journal of Modern Power Systems and Clean Energy*, 2022, doi: 10.35833/MPCE.2021.000161.

[56] J. Burbano, A. Sakr and R. Schuster, "Sliding-Window Approach for Improving Response Time of Mission-Critical Applications," *2020 IEEE 5th International Symposium on Smart and Wireless Systems within the Conferences on Intelligent Data Acquisition and Advanced Computing Systems (IDAACS-SWS)*, 2020, pp. 1-7, doi: 10.1109/IDAACS-SWS50031.2020.9297078.

[57] P. Tedeschi and S. Sciancalepore, "Edge and Fog Computing in Critical Infrastructures: Analysis, Security Threats, and Research Challenges," *2019 IEEE European Symposium on Security and Privacy Workshops (EuroS&PW)*, 2019, pp. 1-10, doi: 10.1109/EuroSPW.2019.00007.

[58] Y. Wu, H. -N. Dai and H. Wang, "Convergence of Blockchain and Edge Computing for Secure and Scalable IIoT Critical Infrastructures in Industry 4.0," in *IEEE Internet of Things Journal*, vol. 8, no. 4, pp. 2300

-2317, 15 Feb.15, 2021, doi: 10.1109/JIOT.2020.3025916.

[59] C. Martín, D. Garrido, L. Llopis, B. Rubio, and M. Díaz, “Facilitating the monitoring and management of structural health in civil infrastructures with an Edge/Fog/Cloud architecture,” *Comput. Stand. Interfaces*, vol. 81, no. November 2020, 2022.

[60] R. Buyya; S. Narayana Srirama, "Modeling and Simulation of Fog and Edge Computing Environments Using iFogSim Toolkit," in *Fog and Edge Computing: Principles and Paradigms*, Wiley, 2019, pp.433-465, doi: 10.1002/9781119525080.ch17.

[61] C. Sonmez, A. Ozgovde, and C. Ersoy. Edgecloudsim. An environment for performance evaluation of edge computing systems. In *Proceedings of the Second International Conference on Fog and Mobile Edge Computing (FMEC’17)*, pp. 39–44, Valencia, Spain, May 8–11, 2017.

[62] S. Mohammed and F. M. Aliyu, "Fog Computing for Leak Detection in On-shore Transmission Pipelines," *2019 International Conference on Advances in the Emerging Computing Technologies (AECT)*, 2020, pp. 1-5, doi: 10.1109/AECT47998.2020.9194193.

[63] D. Perez Abreu, K. Velasquez, M. Curado, and E. Monteiro, “A comparative analysis of simulators for the Cloud to Fog continuum,” *Simul. Model. Pract. Theory*, vol. 101, no. July 2019, p. 102029, 2020.