

Navigating Interoperability in Diverse IoT Ecosystems: A Study of Current Research and Emerging Challenges

Manju Sadasivan¹, Dr. Ashok Kumar T A²

¹Research Scholar, CMR University, Bengaluru, India

²Professor and Director, CMR University, Bengaluru, India

Abstract— Internet of Things technology is embodied in a wide spectrum of networked products, systems, and sensors, which exploit phenomenal progress made in computing power, electronics miniaturization, and network interconnections, providing capabilities that could previously not be possible. These devices are connected to the internet and do not require any kind of human intervention and are smart enough to collect and exchange data over the internet. Interoperability in heterogeneous IoT contexts is a key difficulty arising from the wide variety of devices, data formats and communication protocols utilized in the Internet of Things (IoT) ecosystem. To enable effective communication among the vast IoT devices, protocols, and technologies, an all-encompassing standardization of IoT needs to be established, as well as clearly defined protocols and interfaces, where solutions such as middleware, ontology, and semantic web technologies can be used. The use of the middleware solutions and the integration platforms supports smooth interactions and collaborations between different devices, systems, and applications, which in turn promote higher productivity, efficiency, and innovative capabilities. An ontology provides smart devices with the meaning of data coming from other smart devices, based on a common vocabulary and semantic relationships. The Semantic Web enables smooth communication, sharing of data, and collaboration with other IoT devices and systems using semantic annotations, data integration, context awareness, reasoning, and dynamic discovery. This paper summarizes the state of the art approaches and relevant aspects of Interoperability in Heterogeneous IoT systems.

Index Terms — Internet of Things, Interoperability, Middleware, Ontology, RDF, Semantic Web, Smart Gateway.

I. INTRODUCTION

IOT networks are massive networks that use millions and billions of various devices. In order for these many devices to be able to communicate with one another, some sort of coordination system must be enforced. These gadgets all have unique specifications built into their designs. Heterogeneous in every way, including at the level of physical

devices, protocols, and users. Therefore, a key issue to tackle within the realm of the internet of things is heterogeneous IoT devices and their subnets.

IoT devices come in a variety of unknown configurations. The different configuration modes for IoT devices come from unidentified owners, which, incidentally, adds a lot of complication. Managing semantic disparities is another complexity. Additionally, there could be contrasting semantics. Thus, different developers as well as user groups apply various processing logics to the same IoT network devices or applications.

In heterogeneous IoT, it is essential to have communication among all these units, devices, and protocols for data and service exchange. Agbaje et al. [1] refer interoperability among IoT devices, platforms, and systems despite differences in technology, protocols, and standards as "how they can work together coherently and exchange data and information effectively". IoT heterogeneous ecosystems make up a set of different devices from different manufacturers using different communication protocols and data formats. For the further realization and potential of IoT, it is very important to ensure interoperability which allows complex, integrated systems to exploit data from many sources and be exchanged. Interoperability is required for efficient data transfer, cooperation, and coordination among heterogeneous IoT devices and services [2]. Interoperability should be managed in a way that ensures users experience a seamless access to IoT system services. Users should not need to acquire knowledge about the inner workings of these implementations, the mechanics of translation, or other details. In this paper, the interoperability in heterogeneous IoT systems, achieving interoperability using various methods, open challenges, benefits and related work done in the field are discussed.

II. INTERNET OF THINGS

Nowadays, the internet of things is commonly used to connect objects to the internet so that they may exchange or share data. IoT services are essential in creating smart environments in homes, buildings, and cities. IoT includes distinctive characteristics including resource constraints, heterogeneity, and scalability. A vast volume of data is produced every moment by these connected things and objects. Numerous challenges, including management, aggregation, and storage for enormous created data, have been raised. The heterogeneity of numerous things is one of the most significant and difficult issues. Regarding devices, communication methods, data formats, protocols and meanings, the IoT exhibits significant diversity. Different sources produce different types of data, which are represented with various semantics. The disparity in semantics makes it difficult to provide smooth communication and services across different IoT platforms [3]. Semantic models facilitate meaningful information exchange between such disparate applications. In this study, the extant material on achieving interoperability using various methods are summarized.

III. INTEROPERABILITY

To share or exchange information, physical objects would need to interact with one another. Any gadget, anywhere, at any time, can communicate with any other device. We must address the interoperability issue if we are to have communication that is available whenever and wherever we need it. User interoperability pertains to the compatibility and interaction between a user and a device, while device interoperability relates to the compatibility and interaction between two distinct devices. The problems are so distinct between user and device and device and device. Difference in technology, data formats, structure and protocol, meaning and geographical locations all lead to the need for interoperability. Technical, Syntactic, Semantic and Organizational Interoperability are the different types of interoperability [4].

Technical interoperability is the ability of different systems, devices, or applications to seamlessly interact, communicate, and exchange data with each other, despite differences in their underlying technologies, architectures, or platforms [5]. The goal of Syntactic interoperability is to guarantee that devices can appropriately exchange data and messages based on a common understanding of the

structure and syntax of the data. The capacity of two or more computing systems to exchange information via a shared meaning that can be accurately and automatically understood is known as Semantic interoperability. In order to maintain the semantics of the original message, interoperability at the semantic level necessitates a shared understanding of the meaning of the content being transferred [6]. Organizational interoperability typically refers to the exchange of useful data among numerous organizations, regardless of their varied geographic locations, varying infrastructure, and utilization of distinct information systems [7].

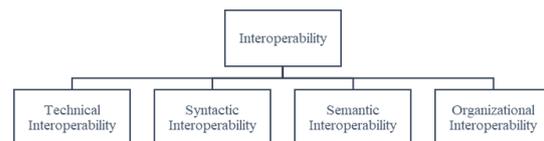


Fig. 1.Types of interoperability

Easy communication between diverse IoT devices, protocols, and technologies can be ensured through the utilization of ontology, middleware, and semantic web technologies.

A. *Ontology*

An ontology comprises a collection of ideas and categories related to a specific field or domain, illustrating their attributes and relationships. The use of an ontology can add semantic annotations to the raw sensory data, which allows knowledge and easy communication, as well as data integration and coordinated actions across varied devices and platforms. In this regard, ontology is very vital in achieving interoperability among heterogeneous IoT devices [8]. An ontology is a structured representation of knowledge: it establishes a common vocabulary, the relationships between different entities, and for that matter, within a specific domain. It defines a common vocabulary and semantic relationships such that devices understand data from other devices even when employing dissimilar protocols or data formats. This contextual understanding helps devices to interpret the data meaningfully, which in turn enables appropriate modifications in their behavior and more intelligent decisions [9].

A. *Middleware*

Middleware solutions and integration platforms offer dynamic capabilities that can fill the gap among heterogeneous devices to ensure interoperability.

Middleware acts as a bridge over various systems, applications, and devices and ensures smooth communication and data exchange across various systems [10].

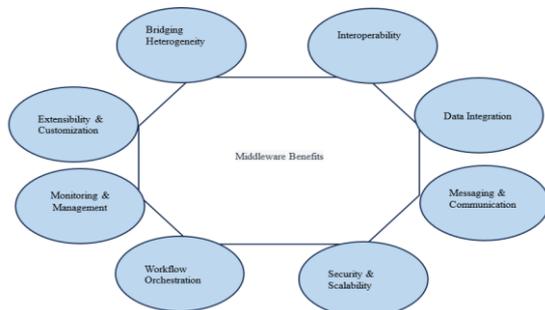


Fig. 2. Advantages of implementing Middleware technology

- a) *Heterogeneity Bridging*: Middleware Solution serves as a data translator and transformer between incompatible formats, protocols, and interfaces used by different devices
- b) *Interoperability*: Middleware solutions enhance interoperability through bridging of different devices.
- c) *Data Integration*: Middleware solutions also integrate many sources of data, whether sensor, databases, or applications. The middleware gathers data from multiple systems, transforms the format of the data to a standardized one, and presents that data to other systems and applications for processing, analysis, and decision-making.
- d) *Communication*: Middleware solutions provide reliable and scalable communications channels that ensure messages are delivered, buffered, and processed even when devices or systems are temporarily out of action or vary in availability.
- e) *Security and Scalability*: Security features can also be included to build such middleware solutions to ensure that the data exchanged between devices and systems should have confidentiality, integrity, and authenticity. In addition, Middleware may also include characteristics related to scalability to handle the growing volume of data that is exchanged, device connections that take place, and system demands also rise.
- f) *Workflow Orchestration*: Integration platforms usually feature workflow orchestration capabilities so that users will be allowed to build and automate complicated business processes involving a lot of systems and applications. Here, these platforms provide visual tools or

programming interfaces to define the process, manage their dependencies, and monitor the execution.

- g) *Monitoring and Management*: Middleware solutions can include monitoring and management functions that help control the health, performance, and availability of linked devices, systems, and applications. They can provide real-time insights, diagnostics, and reporting to support troubleshooting and performance optimization.
- h) *Extensibility and Customization*: Middleware solutions are extensible and highly configurable and therefore could support a very wide range of integration needs and scenarios. It often provides APIs, adapters, and connectors through which developers can integrate new devices, systems, or protocols while extending the functionalities that already exist in existing integrations.

A. Semantic Web

Semantic Web provides a robust set of technologies and standards that will definitely help overcome the interoperability challenges in heterogeneous IoT environments. Semantic Web allows data to be described along with its intended meaning using standardized ontologies and vocabularies. Through semantic annotations applied to them, information produced by IoT devices, sensors, and data streams becomes easier to understand and evaluate. Devices from different vendors or domains can therefore communicate data and understand each other's semantics for good data integration

The Semantic Web includes RDF and SPARQL which is an RDF query language. These supports flexible data integration and fusion. Data from multiple sources can be collected and fused by mapping and translating them into a common semantic representation, regardless of their native formats or protocols. IoT devices produce vast amounts of data. Contextual information, such as spatiality, time, and environmental condition, is very important in decision-making and automation. Semantic Web supports the systematic and machine-readable annotation of context information. Contextual data can be enriched by adding IoT data to achieve a more subtle understanding of the data. Semantic technologies support automated reasoning and inference that can bridge the interoperability gap by making IoT systems more understandable [11]. Publishing of metadata and capabilities using

semantic descriptions makes it clear and exposes what an IoT device or service can do. These will be discovered and merged dynamically depending on their functionalities and compatibility. In a nutshell, the Semantic Web allows for communication, data exchange, and cooperation among IoT devices and systems with semantic annotations, data integration, context awareness, reasoning, and dynamic discovery.

IV. SEMANTIC INTEROPERABILITY

Semantic interoperability is the ability of different information systems or software programs to communicate data and to correctly understand each other's meaning. Data exchange and interpretation across systems that differ by vendor, different data models, or operate in different environments are all part of this term. Semantic interoperability is critical in many fields where data transmission and integration are vital, including healthcare, e-commerce, finance, and government systems. It guarantees that data is accurately exchanged and understood, allowing for effective collaboration, information interchange, and decision-making across several platforms. Semantic web, ontologies, and semantic data models assist devices in interpreting data semantics, allowing for enhanced comprehension and interoperability across diverse IoT systems [12, 13].

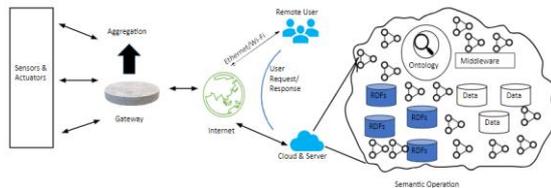


Fig 3. Semantic model working methodology [7]

Several critical components must be addressed in order to achieve semantic interoperability.

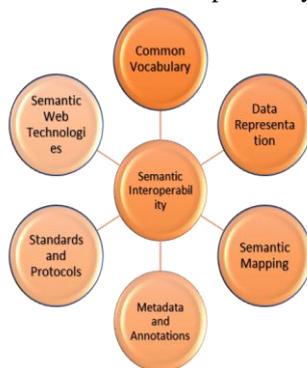


Fig. 4. Critical components to achieve semantic interoperability

- a) *Common Vocabulary*: Systems must then reuse a common and standardized vocabulary, such as industry standard data models, ontologies, or taxonomies. These vocabularies define the meaning of data representation terminology and concepts to ensure consistency in its interpretation and accuracy.
- b) *Data Representation*: Represent and encode the data in a standard form to enable interpretation and conception. The most widely-used of these are RDF (Resource Description Framework), JSON (JavaScript Object Notation), and XML (eXtensible Markup Language).
- c) *Semantic Mapping*: It is significant to map or align the semantics of the data elements when integrating multiple sources of data. All this implies creating links and correspondences between concepts used in different systems so that semantics or meaning can be interpreted properly and integrated.
- d) *Metadata and Annotations*: Metadata explains more about the data, including source, context, and meaning. Annotations, in terms of semantic tags or labels, are a way of adding additional semantic descriptions to data, allowing it to be more analysable and integrable.
- e) *Standards and Protocols*: Interoperability can be enhanced by using common standards and protocols. This can be done by setting clear guidelines for data sharing, communication, and system integration.
- f) *Semantic Web Technologies*: RDF, SPARQL (SPARQL Protocol and RDF Query Language), and OWL (Web Ontology Language) technologies enable rich semantic representation, querying, and reasoning over structured data.

V. OPEN CHALLENGES

Interoperability will be a key to the general adoption and success of the Internet of Things. Further work in development towards common standards and open protocols will further facilitate the unfolding of a unified, interconnected IoT ecosystem that will both serve users and industries. However, some issues are presented by interoperability in IoT. Some of the significant challenges encountered in the interoperability of IoT devices include:

- *Data Formats and Semantics*: Various IoT devices generate volumes of data in different formats. It is difficult to ensure that data coming

from many types of devices will always be well-formatted or processed similarly. Standardization of data format and semantics is, therefore, essential for effective interoperability to be achieved.

- *Standards and Frameworks:* Another reason for interoperability problems is that there are no widely agreed standards and frameworks on how data should be exchanged and connected through IoT. Various suppliers have their proprietary protocols that apply to their respective devices, leading to the incompatibility of their devices with others.
- *Diverse Communication Protocols:* Different IoT devices use a variety of communication protocols: Wi-Fi, Bluetooth, Zigbee, Z-Wave, MQTT, CoAP; they are not necessarily interoperable with each other. Devices having different protocols require much more implementation effort and result in a split ecosystem.
- *Power and Resource Constraints:* Many IoT devices have limited power and processing resources. Ensuring compatibility can be a challenge without going down the drain, depleting resources, or potentially jeopardizing device performance.
- *Privacy Concerns:* Interoperability increases the transfer of data between the devices and platforms. So, there is a significant demand to maintain the user's data responsibly and according to the privacy standards.
- *Security Concerns:* In IoT, any communication between devices poses a vulnerability regarding a security breach. So, secure communication and data exchange between devices will be needed to avoid security breach and data breach [14, 6].

VI. INTEROPERABILITY BENEFITS

Interoperability helps in achieving scalability and flexibility in IoT solutions. It allows customers to integrate devices and services of different providers, thus encouraging healthy competition and innovation. In addition, it can help in realizing more extended and versatile IoT applications. The level of compatibility and integration here gives a number of key advantages for users and the IoT ecosystem altogether [15].

- *Enhanced User Experience:* Interoperable IoT products enable easy setting up, configuration, and management of smart devices. They can

integrate devices from any supplier in a way that eliminates compatibility problems, thus achieving a more natural and intuitive user experience.

- *Improved Analytics and Insights:* With interoperability, data from several devices can be gathered, aggregated, and analyzed much better.
- *Integration with Other Technologies:* IoT devices can now integrate along with new technologies like artificial intelligence, edge computing, and cloud services to be able to consider even more complex applications and services.
- *Industry Standards and Interoperability:* By promoting industry-wide interoperability standards, gadgets can communicate with each other, therefore driving a stronger and more reliable IoT.

Flexibility and Choice: Interoperability gives customers the freedom to choose from any vendor-agnostic IoT appliance. They are not restricted to the ecosystem of a single brand, allowing them to choose the best equipment for their unique needs and preferences. This flexibility also enables the users to replace inferior IoT nodes with better performing ones with minimal or no impact to the rest of the network and systems.

VII. RELATED WORK

Interoperability in heterogeneous IoT devices is a significant research area aimed at addressing the challenges associated with the seamless integration and communication of various IoT devices from various manufacturers, utilizing various communication protocols and standards. Few studies published real-time system models, while others provided conceptual frameworks for execution and a study of applications as well as bottlenecks. Some study on the approaches offered by different authors for implementing interoperability in heterogeneous IoT devices is presented in the table below. Table 1 includes the authors' names and references, as well as outlines their contributions and the approaches they employed.

VIII. CONCLUSION

The Internet of Things is constantly evolving, and new research, projects, and developments continue to emerge. Numerous efforts have been made to address interoperability challenges. Middleware, ontology, and semantic web technologies are frequently used to

enable seamless communication among various IoT applications spanning across heterogeneous hardware, connectivity and protocols. In this paper, the most recent research carried out on interoperability in various contexts have been examined and summarized. In order to build a better

understanding on the major bottlenecks to realize proper interoperability and collaboration across various IoT devices in a heterogeneous environment, this study makes an effort to throw light on some of the challenges and solutions proposed by the ongoing research.

TABLE 1: RELATED WORK IN THE IMPLEMENTATION OF INTEROPERABILITY IN HETEROGENEOUS IOT DEVICES.

Authors	Year	Approaches	Contribution
Farhan et. al [16]	2017	Semantic web	The authors have published a study that has brought forth the Semantic Interoperability Model for Big-data in IoT (SIMB-IoT) with an aim to provide semantic interoperability among heterogeneous IoT devices of the health care domain. With regard to this model, various symptoms collected from different IoT sensors, medication with side effects are proposed. Information between the physician and patient are semantically annotated and transferred in a meaningful way. The graphical databases are explored by employing SPARQL queries to find the hidden patterns. This paper does not take into account syntax interoperability and security issues.
Sigwele et al [17]	2018	Semantic web	The proposed framework is the healthcare collaboration framework based on IoT infrastructure with a focus on semantic concepts. In the proposed framework, the intelligent semantic gateway is introduced. The web application utilized by it features a restful Application Programming Interface (API) that enables the making of healthcare information from each system accessible for collaborative purposes.
Farahzadi et al [18]	2018	Middleware	Presents the key attributes and qualities of middleware, exploring diverse architectural styles and service domains. Additionally, it provides information about various middleware solutions suitable for CoT-based platforms and includes a compilation of existing challenges and concerns.
Kang et. al [19]	2020	Semantic IoT	The authors used the Resource Description Framework graph extension approach to develop the semantic IoT framework. They employed an aggregator based on the oneM2M standard platform. Data is represented in the form of an RDF graph and dynamically adapted by semantic queries. Performance evaluation is done by comparing the system with a real-world IoT system that supports ontology.
Cimmino et.al [20]	2020	Ontology	Proposed an innovative approach that employs a framework based on SPARQL queries to identify and access IoT devices that share diverse data. eWoT enables transparent interaction with an IoT ecosystem of Web-accessible IoT devices using SPARQL queries.
Joy Iong Zong et. al [21]	2020	Fog centered	In this paper, the authors developed a Fog centered semantic model for the improvement in interoperability of IOT devices. This has reduced energy consumption, delay in service, bandwidth usage, and

			cost. It contains an adequate offloading procedure that prevents most of the requests from being executed in the cloud.
Jameel et. al [22]	2021	Ontology	A mechanism rooted in ontology has been deployed to achieve semantic interoperability within IoT healthcare systems, specifically focusing on the cardio-vascular domain. This model successfully addresses the challenge of semantic interoperability arising from the diverse data of patients. Machine Learning based Prediction is not used for refinement of Diagnostics.
Ahmed Swar et. al [23]	2021	Ontology	Proposes a middleware layer that collects data from heterogeneous sources, such as sensors, cameras, and radio frequency identification devices (RFIDs). The smart traffic concept as interpreted by combining existing ontologies. A model which makes use of semantic web technologies and provides an integrated interface to the users to access heterogeneous data coming from different devices. It develops a data model based on semantic integration layer, aligning data in a normalized form. The continuous readings of a wide variety of sources are maintained through the MYSQL database.
Sihem et.al [24]	2022	Ontology	In this research paper, the authors introduced a unified cross-domain ontology known as CDOnto. This ontology is designed to be adaptable to several IoT domains and can be enhanced with specific ontologies for individual domains. The proposed ontological model adopts a contextual approach to arrange and differentiate the representations of various domains.
Albouq et al [25]	2022	–	This study provides a complete evaluation of the existing methods and approaches for dealing with interoperability issues. Furthermore, the article categorizes the available options for overcoming the lack of interoperability. This study highlighted the benefits and drawbacks of the available strategies for enabling interoperability.
Khatoon et al[26]	2023	Ontology	This paper introduces an ontology-building tool for dynamic agriculture that parses ontology files, extracts data, and updates them according to the needs of users. With angular libraries using OWL file parsing, the proposed framework supports user-defined ontologies as well, providing real-time update in such a file. Thus, semantic interoperability in agriculture IoT will be enhanced, providing data management with an effective, adaptive nature.
Lamnaour et al[27]	2024	Semantic web	This paper proposes a new middleware model using semantic web technologies and context-aware computing. This model employs low-level ontologies for automatic registration, classification, and identification of heterogeneous smart devices. It further contains a search engine for matching smart devices with requests at the user/application layer to realize real-time measurements. This way, efficient and adaptive management of IoT systems is achieved.

REFERENCES

- [1] P. Agbaje, A. Anjum, A. Mitra, E. Oseghale, G. Bloom and H. Olufowobi, "Survey of

- Interoperability Challenges in the Internet of Vehicles," in *IEEE Transactions on Intelligent Transportation Systems*, vol. 23, no. 12, pp. 22838-22861, Dec. 2022, doi: 10.1109/TITS.2022.3194413.
- [2] Muhammad Noaman, Muhammad Sohail Khan, Muhammad Faisal Abrar, Sikandar Ali, Atif Alvi, Muhammad Asif Saleem, "Challenges in Integration of Heterogeneous Internet of Things", *Scientific Programming*, vol. 2022, Article ID 8626882, 14 pages, 2022. <https://doi.org/10.1155/2022/8626882>
- [3] Ganzha, M., Paprzycki, M., Pawłowski, W., Szymeja, P., Wasielewska, K. (2018). Towards Semantic Interoperability Between Internet of Things Platforms. In: Gravina, R., Palau, C., Manso, M., Liotta, A., Fortino, G. (eds) *Integration, Interconnection, and Interoperability of IoT Systems*. Internet of Things. Springer, Cham. https://doi.org/10.1007/978-3-319-61300-0_6
- [4] Sigwele T, Hu YF, Ali M et al (2018) An intelligent edge computing based semantic gateway for healthcare systems interoperability and collaboration. In: 2018 IEEE 6th International Conference on Future Internet of Things and Cloud (FiCloud). 6-8 Aug 2018.Barcelona, Spain.
- [5] Torab-Miandoab, A., Samad-Soltani, T., Jodati, A. et al. Interoperability of heterogeneous health information systems: a systematic literature review. *BMC Med Inform Decis Mak* 23, 18 (2023). <https://doi.org/10.1186/s12911-023-02115-5>
- [6] Noura, M., Atiquzzaman, M. & Gaedke, M. Interoperability in Internet of Things: Taxonomies and Open Challenges. *Mobile Netw Appl* 24, 796–809 (2019). <https://doi.org/10.1007/s11036-018-1089>
- [7] Hafizur Rahman and Md. Iftexhar Hussain. 2020. A comprehensive survey on semantic interoperability for Internet of Things: State-of-the-art and research challenges. *Trans. Emerg. Telecommun. Technol.* 31, 12 (December 2020). <https://doi.org/10.1002/ett.3902>
- [8] P. Rathee and S. K. Malik, "IWD towards Semantic similarity measure in ontology," *J. Inf. Optim. Sci.*, vol. 41, no. 7, pp. 1561–1577, 2020, [Online]. Available: <https://www.tandfonline.com/doi/abs/10.1080/002522667.2020.1802129>.
- [9] S. U. Mageswari, C. Mala, A. Santhanavijayan, and D. Gerard, "A non-collaborative approach for modeling ontologies for a generic IoT lab architecture," *J. Inf. Optim. Sci.*, vol. 41, no. 2, pp. 395–402, 2020.
- [10] <https://www.yenlo.com/blogs/what-is-middleware-and-how-does-it-work/>
- [11] Venceslau, A.; Andrade, Rossana Maria; Vidal, V.; Nogueira, T. and Pequeno, V. (2019). IoT Semantic Interoperability: A Systematic Mapping Study. In *Proceedings of the 21st International Conference on Enterprise Information Systems - Volume 1: ICEIS*, ISBN 978-989-758-372-8, pages 535-544. DOI: 10.5220/0007732605350544.
- [12] Bernasconi, A., Guizzardi, G., Pastor, O. et al. Semantic interoperability: ontological unpacking of a viral conceptual model. *BMC Bioinformatics* 23 (Suppl 11), 491 (2022). <https://doi.org/10.1186/s12859-022-05022-0>
- [13] Venceslau, A.; Andrade, Rossana Maria; Vidal, V.; Nogueira, T. and Pequeno, V. (2019). IoT Semantic Interoperability: A Systematic Mapping Study. In *Proceedings of the 21st International Conference on Enterprise Information Systems - Volume 1: ICEIS*, ISBN 978-989-758-372-8, pages 535-544. DOI: 10.5220/0007732605350544.
- [14] S. S. Albouq, A. A. A. Sen, N. Almashf, M. Yamin, A. Alshantiti and N. M. Bahbouh, "A Survey of Interoperability Challenges and Solutions for Dealing With Them in IoT Environment," in *IEEE Access*, vol. 10, pp. 36416-36428, 2022, doi: 10.1109/ACCESS.2022.3162219.
- [15] <https://www.ringcentral.com/gb/en/blog/definitions/interoperability/>
- [16] Farhan Ullah, Muhammad Asif Habib, Muhammad Farhan, Shehzad Khalid, Mehr Yahya Durrani, Sohail Jabbar, *Semantic interoperability for big-data in heterogeneous IoT infrastructure for healthcare, Sustainable Cities and Society*, Volume 34, 2017, Pages 90-96, ISSN 2210-6707, <https://doi.org/10.1016/j.scs.2017.06.010>.
- [17] (m11)Sigwele T, Hu YF, Ali M et al (2018) An intelligent edge computing based semantic gateway for healthcare systems interoperability and collaboration. In: 2018 IEEE 6th International Conference on Future

- Internet of Things and Cloud (FiCloud). 6-8 Aug 2018. Barcelona, Spain.
- [18] Farahzadi A, Shams P, Rezazadeh J, Farahbakhsh R, Middleware technologies for cloud of things: a survey, *Digital Communications and Networks*, Volume 4, Issue 3, 2018, Pages 176-188, ISSN 2352-8648, <https://doi.org/10.1016/j.dcan.2017.04.005>. <https://www.sciencedirect.com/science/article/pii/S2352864817301268>.
- [19] S. Kang, K. Chung, "IoT Framework for Interoperability in the oneM2M Architecture," *Advances in Electrical and Computer Engineering*, vol.20, no.2, pp.11-18, 2020, doi:10.4316/AECE.2020.02002.
- [20] Cimmino, Andrea, María Poveda-Villalón, and Raúl García-Castro . 2020. "eWoT: A Semantic Interoperability Approach for Heterogeneous IoT Ecosystems Based on the Web of Things" *Sensors* 20, no. 3: 822. <https://doi.org/10.3390/s20030822>.
- [21] Dr. Joy Iong Zong Chen & Dr. S. Smys (2020), Interoperability Improvement in Internet of Things Using Fog Assisted Semantic Frame Work, *Journal of trends in Computer Science and Smart technology (TCSST)*, Vol.02/ No. 01, Pages: 56- 68, <https://www.irojournals.com/tcsst/> DOI: <https://doi.org/10.36548/jtcsst.2020.1.006>.
- [22] Jameel Ahamed & Mohammad Ahsan Chishti (2021): Ontology based semantic interoperability approach in the Internet of Things for healthcare domain, *Journal of Discrete Mathematical Sciences and Cryptography*, DOI: 10.1080/09720529.2021.1873255.
- [23] Ahmed Swar, Ghada Khoriba, Mohamed Belal , (2021), A unified ontology-based data integration approach for the internet of things, *International Journal of Electrical and Computer Engineering (IJECE)* Vol. 12, No. 2, April 2022, pp. 2097~2107 ISSN: 2088-8708, DOI: 10.11591/ijece.v12i2.pp2097-2107.
- [24] Sihem, Benkhaled & Hemam, Mounir & Djeddar, Meriem & Maimour, Moufida. (2022). An Ontology – based Contextual Approach for Cross-domain Applications in the Internet of Things. *Informatica*. 46. 10.31449/inf.v46i5.3627.
- [25] S. S. Albouq, A. A. A. Sen, N. Almashf, M. Yamin, A. Alshantqi and N. M. Bahbouh, "A Survey of Interoperability Challenges and Solutions for Dealing With Them in IoT Environment," in *IEEE Access*, vol. 10, pp. 36416-36428, 2022, doi: 10.1109/ACCESS.2022.3162219.
- [26] Khatoun, P & Ahmed, Muqem. (2023). Design and development of dynamic Agri-ontology for IoT interoperability. *International Journal of Communication Systems*. 36. 10.1002/dac.5516.
- [27] Lamnaour, Mohammed & Raiss, Moundir & Mesmoudi, Y. & Khamlichi, Yasser & Tahiri, Abderrahim & Touhafi, Abdellah. (2024). A Semantic-Based Middleware for Supporting Heterogeneity and Context-Awareness Within IoT Applications. *Journal of Communications*. 19-27. 10.12720/jcm.19.1.19-27.