Challenges in Integration of Heterogeneous Internet of Things

Muhammad Noaman, 1 Muhammad Sohail Khan 1, Muhammad Faisal Abrar 2, Sikandar Ali 3, Atif Alvi 4, and Muhammad Asif Saleem 5

1 Department of Computer Software Engineering, University of Engineering and Technology Mardan, Khyber Pakhtunkhwa, Mardan 23200, Pakistan
2 Department of Computer Science, University of Engineering and Technology Mardan, Mardan 23200, Khyber Pakhtunkhwa, Pakistan
3 Department of Information Technology, The University of Haripur, Haripur 22620, Khyber Pakhtunkhwa, Pakistan
4 Department of Computer Science, University of Management and Technology, Lahore, Pakistan
5 Department of Software Engineering, Lahore Garrison University, Lahore, Pakistan

Correspondence should be addressed to Sikandar Ali; sikandar@uoh.edu.pk

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Internet of Things (IoT) is considered the upcoming industrial and academic revolution in the technological world having billions of things and devices connected to the Internet. These connected devices are heterogeneous. They have different standards and technologies which communicate through different protocols. Therefore, the implementation of IoT on a large scale is difficult due to these heterogeneity challenges. This motivated us to overcome the scaling problem of IoT by identifying the challenges from the literature and providing solutions. This study is based on the identification of the heterogeneous challenges with solutions via a systematic literature review. A total of 81 primary sources were selected. After extracting and synthesizing the data, we identified 14 different IoT heterogeneity challenges. Some of the identified challenges are “heterogeneity of devices,” “heterogeneity in formats of data,” “heterogeneity in communication,” and “interoperability issue due to heterogeneity.” The identified challenges have been analyzed from digital libraries and timeframe perspectives. Furthermore, we have found a total of 81 solutions for those challenges, with at least 5 unique solutions for each challenge. In the future, we will categorize the challenges and prioritize the solutions by using a multi-criteria decision-making problem.

1. Motivation

IoT is the expansion of current Internet services to provide connectivity to each object of this world. IoT has become the most prominent technology across the globe. It is an emerging technology that is under development process where everyone is trying to interpret it according to their needs. The implementation and interpretation of IoT face some serious challenges like security, virtualization, and heterogeneity. Heterogeneity itself is a multifaceted challenge hindering the large-scale implementation of IoT vision. It is due to these challenges that so far only limited implementations of IoT systems have become a reality. This motivated us to perform a systematic literature review to identify those IoT heterogeneity challenges and their solutions. Another contribution of this study is conducting a depth analysis of those challenges using the chi-square test based on digital libraries and timeframe.

2. Introduction

In today’s technological world, IoT is considered an important advancement among the trending technologies. The term IoT can be simply defined as the devices that can be connected with sources of the Internet [1]. In past years, these devices have been constantly growing. Reference [2] reported that around 500 billion devices will be connected to the Internet by 2030. In the physical as well as in the virtual
world, these IoT devices will further interconnect with other devices in a large number, which will give new birth to the forms of interaction. This will enable us to connect all objects of our surroundings in every corner of the world in a single period. These objects can be sensors, smartphones, automobiles, industrial robots, refrigerators, thermostats, tablets, etc. The IoT is widespread in both academia and industry. It is producing business opportunities in multiple fields of industrial markets, in both public and private sectors in a very broad range. The industrial revolution of IoT will have billions of heterogeneous devices on the Internet of Things in the near future.

At the other extreme, the IoT vision of a large-scale implementation faces serious challenges across many dimensions. One of the main obstructions in IoT is its inclination toward heterogeneity, and the heterogeneous nature might be in form of protocols, device data format, communication capabilities of the devices, technologies, hardware, etc. [3,4]. It is due to these types of challenges that so far only limited implementations of IoT systems have become a reality. For IoT to evolve toward its vision of global implementation, these obstructions need to be reduced on different levels. To activate and provide the service, devices must be connected to the Internet. The identification of heterogeneity-based challenges that exist at different levels is needed, and the current solutions adopted and/or implemented by different studies for handling heterogeneity in IoT systems need to be highlighted. The objective of this study is to conduct a systematic literature review to identify those IoT heterogeneity challenges and find out the solutions implemented by different studies to handle IoT heterogeneity challenges. The significance of this study is that it will provide the identification and analysis of heterogeneity challenges in IoT systems and provide a summary of different studies that implemented various solutions to handle the heterogeneity of IoT systems. Another significant contribution is that it will provide a future direction to researchers to make a better stand-alone architecture aiming to tackle the heterogeneity challenges at different levels of IoT systems. As a result, IoT systems can be utilized and implemented in a wide range of industrial fields.

The organization of this paper is as follows: Section 3 presents a literature review related to IoT history, challenges, and heterogeneity concerns. Section 4 explains the research methodology used to achieve the objectives of this research. Section 5 provides the result and discussion of IoT heterogeneity challenges and the solutions to those challenges found in this study. Section 6 concludes this review and suggests future work.

3. Literature Review

Because of the broad and complex nature of IoT, it has not yet got a single unique definition that is acceptable to the whole global community of users. Many researchers, practitioners, academicians, developers, and corporate people have defined IoT in their terms, but the credit must be attributed to Kevin Ashton, an expert on digital innovation who for the first time used and defined it. According to [5], IoT could be nicely defined as follows: a very comprehensive and accessible network of intelligent devices which can act and react in accord with situations; self-organize; share information, data, and resources; and be subject to change in the environment.

IoT is growing and maturing day by day. It is the latest, most fine, and excellent concept in information technology. It is a new paradigmatic shift in information technological advancement. The expression “Internet of Things,” concisely shortened to IoT, is comprised of two words, “Internet” and “Things.” Internet uses a standard set of Internet protocols (TCP/IP) to connect and serve a large number of users around the globe [6, 7]. It is a global system of interconnected computer networks. Internet is interconnected networks that includes a large number of local to regional commercial networks that may be private, government-owned, public, or academic networks. These networks are connected through a wide range of electronic, wireless, and optical network technologies. The Internet is generally defined as a global network that connects millions of computers. About 190 states of the world are linked through the Internet that constantly shares data, opinions, and news. According to [9], there is an estimated 5,080,388,142 Internet users around the world. This large sum of users indicates that about 40% of the world’s total population uses the Internet.

The word “Things” in the “Internet of Things” can be any object or person identifiable in the real world. Daily necessities include electronic devices that we come across as well as daily used advanced technological items like equipment and gadgets. In the near future, other certain everyday objects are expected to connect with the Internet, which will lead to a period of extreme expansion of the Internet known as the Internet of Things. IoT system is based on devices to sense, actuate, control, and monitor activities. IoT devices that are connected to other devices and applications can exchange data with each other, they may receive information from some other IoT devices. To process data, they may send the data either to centralized servers locally or it may send data for processing to cloud.

The National Intelligence Council (NIC) of the United Nations (UN) has considered IoT as one of the six “Disruptive Civil Technologies” [12]. In this respect, we can list many fields that are already benefiting from the services of different architectural forms of IoT like transportation, e-governance, smart city, smart health, life support, education, retail, logistics, agriculture, automation, manufacturing of industrial products, and management of businesses.

Ericsson [13] and Evans [14] have conducted surveys and estimated that the use of the Internet will further increase, grow, and be boosted tenfold in the coming days. According to their estimation, about 50 billion devices would have connected by 2020. This expected number of new Internet devices shall be supposedly called constricted devices [15]. These devices are small in size, are enclosed in nature, and have a low cost. They are specifically designed for the purpose of executing specific tasks like monitoring the physical environment. IoT devices are limited in terms of
communication capabilities, processing power, and energy consumption due to their low cost. That is why these constrained devices are very heterogeneous in terms of their essential communication protocols, device data formats, and technologies.

Due to the heterogeneity of IoT, devices on the market nowadays have diversity in communication protocols, methods of network connectivity, and resulting models of application. It is not feasible to support such kinds of diversities in IoT, because developers typically lack the proper resources required to have a grip on the specifics of the constrained devices and network [16]. The main objective is to decrease, hide, or eradicate such a broad range of diversity of the technologies, applications models, and protocols from the users of IoT [17]. Because of the heterogeneous nature of IoT, it is one of the newly emerging research areas which has robust potential to bring a paradigm shift in the understanding of fundamental computer science principles and standards of our future living [18]. The demand for constrained IoT devices is expected to increase; this problem is expected to get worse in the future. Therefore, there will be a need to improve the integration of a large number of constrained devices in IoT. In this study, we have performed SLR aiming to identify the heterogeneity challenges and provide a summary of the solutions adopted for those challenges.

4. Research Methodology

A systematic literature review (SLR) methodology is adopted to identify the heterogeneity challenges in IoT systems, hindering a global IoT vision, and to find solutions to the identified heterogeneity challenges.

4.1. Research Questions. The first step of a systematic literature review is to define research questions. The research questions of this study are mentioned in Table 1.

4.2. Search String. The second phase of a systematic literature review is to find relevant studies on the research topic. We identified digital libraries in which primary search was carried out: IEEE Xplore, SpringerLink, Google Scholar, ScienceDirect, and ACM. We then defined a set of keywords related to our research topic: “Internet of Things,” “IoT,” “heterogeneity,” “heterogeneous,” and “challenges.” Finally, search strings were defined and used to collect published articles related to the research topic. Search strings are provided in Table 2.

4.3. Study Selection. The research selection process is to perform search in digital libraries based on the tollgate approach considering the search strings. Figure 1 shows a selection of articles using the tollgate approach.

In snowballing process, we selected 9 papers from journals (IEEE TMC, TPDS, JSAC, ToN, TWC) and conferences (SIGCOMM, MobiCom, MobiSys, INFOCOM), the content of which is analyzed and discussed in Section.

Initially, 3854 papers were selected by applying search protocol to the selected digital libraries. A selection process has been applied based on keywords, titles, duplication removal, abstracts, and full text of selected papers. We excluded the papers of the following types:

1. Studies published in sources other than conferences, journals, patents, and technical reports
2. Research papers not published in the English language
3. Studies published before 2010
4. Studies that are not related to the defined search strings

To evaluate the quality of the included research papers, we assessed the following aspects:

1. The study provides information about any challenge related to IoT heterogeneity
2. The study represents a clear solution to the identified challenge of heterogeneity
3. The published study is from a stable and recognized publication source

Figure 2 shows a summary of paper selection based on digital libraries, and Figure 3 shows the paper selection on a yearly basis.

5. Analysis and Discussion

In this section, we have discussed the results relevant to our RQs. For the analysis, we used the linear chi-square test of association. For categorical values of predictor and outcome variables, the chi-square test is counted as more significant than other statistical tests. To answer RQ1, identified challenges/critical issues through the SLR are presented in Table 3. We have found a significant difference in heterogeneity challenges.

We set an occurrence percentage threshold of 30%. Accordingly, “Heterogeneity of devices,” “heterogeneity in formats of data,” and “heterogeneity in communication” are the most critical identified challenges.

5.1. Comparison of Challenges Based on Digital Libraries. Table 4 shows the analysis of the identified challenges based on digital libraries. We have Google Scholar, IEEE Xplore, SpringerLink, ScienceDirect, and ACM as digital libraries. From the analysis, we have found the following:

1. Heterogeneity in communication is critical in Google Scholar and SpringerLink
2. Heterogeneity of devices is critical in Google Scholar, IEEE Xplore, and SpringerLink
Table 1: Research questions.

| No. | Research questions                                                                 |
|-----|------------------------------------------------------------------------------------|
| RQ1 | What are the challenges in heterogeneous IoT in the literature?                    |
| RQ2 | What are the solutions to these challenges in heterogeneous IoT in the literature?|

Table 2: Search strings.

| Sources       | Search string                                                                 | Context       |
|---------------|-------------------------------------------------------------------------------|---------------|
| Google Scholar| (“Heterogeneous Internet of Things”) AND (“issues OR challenges”)             |               |
| IEEE Explore  | "Heterogeneous" AND ("IoT" OR "Internet of Things") AND "challenges"         | IoT heterogeneity |
| ScienceDirect | ("IoT" OR "Internet of Things") AND ("heterogenous") AND ("challenges")       |               |
| ACM           | ("IoT") AND ("heterogenous") AND ("challenges")                              |               |
| SpringerLink  | ("IoT") AND ("heterogeneity") AND ("challenges")                             |               |

**Figure 1:** Selection of articles using the tollgate approach.

**Figure 2:** Paper selection based on digital libraries.
Heterogeneity in formats of data is critical in ScienceDirect, SpringerLink, and IEEE Xplore.

Interoperability issue is critical in ACM and SpringerLink.

5.2. Comparison of Challenges Based on Timeframe.
Table 5 shows the analysis of the identified challenges based on timeframe. We have divided the duration into two timeframes: Timeframe I from 2011 to 2016 and Timeframe II from 2017 to 2021. From the analysis, we have found the following:

- Heterogeneity in formats of data is critical in Timeframe I from 2011 to 2016.
- Interoperability issue is critical in Timeframe I and Timeframe II.

5.3. Proposed Solutions. To answer RQ2, solutions to the identified challenges are presented in Table 6. We have found a total of 81 solutions for those challenges, with at least 5 unique solutions for each challenge.
Table 4: Summary of challenges based on digital libraries.

| Challenges                                      | Google Scholar, n=36 | IEEE Xplore, n=29 | ScienceDirect, n=4 | ACM, n=7 | SpringerLink, n=5 | Chi-square test, $\alpha=0.05$ |
|------------------------------------------------|----------------------|-------------------|-------------------|----------|------------------|-----------------------------|
|                                                | $f$ | % | $f$ | % | $f$ | % | $f$ | % | $f$ | % | $x^2$ | $p$ |
| Fragmentation in connectivity, protocols       | 5   | 14 | 3   | 10 | 0   | 0  | 2   | 29 | 0   | 0  | 4.1393 | 0.0419 |
| Diversity in network technologies              | 4   | 11 | 3   | 10 | 1   | 25 | 0   | 0  | 1   | 20 | 1.6701 | 0.1962 |
| Management of networks                         | 3   | 8  | 3   | 10 | 0   | 0  | 0   | 0  | 0   | 0  | 1.6683 | 0.1965 |
| Heterogeneity in communication                 | 12  | 33 | 7   | 24 | 1   | 25 | 1   | 14 | 2   | 40 | 0.3876 | 0.5336 |
| Heterogeneity of devices                       | 16  | 44 | 10  | 34 | 1   | 25 | 2   | 29 | 5   | 100| 1.6342 | 0.2011 |
| Communication between heterogeneous devices    | 7   | 19 | 6   | 21 | 1   | 25 | 0   | 0  | 1   | 20 | 1.4601 | 0.2269 |
| Management and configuration of devices        | 8   | 22 | 3   | 10 | 0   | 0  | 1   | 14 | 0   | 0  | 2.9163 | 0.0877 |
| Heterogeneity in formats of data               | 9   | 25 | 10  | 34 | 3   | 75 | 2   | 29 | 2   | 40 | 4.4138 | 0.0357 |
| Data security                                  | 4   | 11 | 5   | 17 | 0   | 0  | 0   | 0  | 1   | 20 | 1.9809 | 0.1593 |
| Communication security                         | 8   | 22 | 5   | 17 | 1   | 25 | 1   | 14 | 1   | 20 | 0.5067 | 0.4766 |
| Device security                                | 5   | 14 | 6   | 21 | 0   | 0  | 1   | 14 | 1   | 20 | 1.3884 | 0.2387 |
| Heterogeneity in standards, platform           | 7   | 19 | 1   | 2  | 0   | 0  | 1   | 14 | 1   | 20 | 3.4381 | 0.0637 |
| Integration of devices and data                | 6   | 17 | 6   | 21 | 0   | 0  | 1   | 14 | 1   | 20 | 1.0421 | 0.3073 |
| Interoperability issue                         | 6   | 17 | 4   | 14 | 1   | 25 | 2   | 29 | 3   | 60 | 3.4303 | 0.0640 |
### Table 5: Summary of challenges based on timeframe.

| Challenges                                         | Timeframe I (2011–2016), \(n = 23\) | Timeframe II (2017–2021), \(n = 58\) | Chi-square test, \(\alpha = 0.05\) |
|----------------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
|                                                     | \(f\)  | %   | \(f\)  | %   | \(\chi^2\) | \(p\)   |
| Fragmentation in connectivity, protocols            | 2      | 9   | 8      | 14  | 0.4918     | 0.4831  |
| Diversity in network technologies                   | 5      | 22  | 4      | 7   | 2.7502     | 0.0972  |
| Management of networks                              | 3      | 13  | 3      | 5   | 1.1185     | 0.2902  |
| Heterogeneity in communication                      | 8      | 35  | 18     | 31  | 0.0042     | 0.9478  |
| Heterogeneity of devices                            | 13     | 57  | 22     | 38  | 0.8052     | 0.3695  |
| Communication between heterogeneous devices         | 4      | 17  | 11     | 19  | 0.0878     | 0.7669  |
| Management and configuration of devices             | 3      | 13  | 10     | 17  | 0.3112     | 0.5769  |
| Heterogeneity in formats of data                    | 8      | 35  | 18     | 31  | 0.0042     | 0.9478  |
| Data security                                       | 2      | 9   | 10     | 17  | 1.0399     | 0.3078  |
| Communication security                              | 3      | 13  | 13     | 22  | 0.9920     | 0.3192  |
| Device security                                     | 2      | 9   | 12     | 20  | 1.6784     | 0.1951  |
| Heterogeneity in standards, platform                | 3      | 13  | 7      | 12  | 0.0001     | 0.9901  |
| Integration of devices and data                     | 6      | 26  | 8      | 14  | 1.0677     | 0.3015  |
| Interoperability issue                              | 5      | 22  | 11     | 19  | 0.0086     | 0.9257  |

### Table 6: Summary of solutions for identified challenges.

| Challenge addressed                                | Ref | Year | Approach          | Proposed solutions                                                                 |
|----------------------------------------------------|-----|------|-------------------|-------------------------------------------------------------------------------------|
| Fragmentation in connectivity, data formats, and protocols | [4] | 2015 | Framework         | ConnectOpen, providing a flexible communication agent deployed at the gateway         |
|                                                    | [19] | 2016 | Platform          | SPOT, a smartphone-based platform that makes use of open device driver models using XML |
|                                                    | [15] | 2015 | Platform          | Cloud-based platform to integrate the services with communication models and constrained devices |
|                                                    | [20] | 2020 | Architecture      | The recursive Inter-network architecture-based approach that reduces the protocol complexity and improves standardization |
|                                                    | [21] | 2019 | Protocol          | Coexistent routing and flooding (CRF) using unique features of the physical layer technology-to-physical communication method for concurrent routing |
|                                                    | [22] | 2020 | Platform          | iArk, a universal tracking platform for all types of IoT devices operating in the very high-frequency band |
|                                                    | [23] | 2020 | Mechanism         | New roaming mechanism for LoRaWAN (low bandwidth wide area network) protocol based on reliable 5G network |
|                                                    | [24] | 2019 | Architecture      | Fog computing-based, multi-technology service architecture for IoT devices |
|                                                    | [25] | 2011 | Framework         | IDRA, reconfigurable network framework to directly connect the devices that are correlated to each other |
| Diversity in network technologies                  | [26] | 2019 | Framework         | SDN-IoT, a framework that provides the functionality of converting \(m\) heterogeneous controllers to \(n\) homogeneous controllers |
|                                                    | [27] | 2017 | Middleware        | A smartphone-based mobile gateway that provides an interface between devices and the Internet, being flexible and transparent |
|                                                    | [28] | 2020 | Proposed system   | A decentralized, blockchain-based cloud solution for creating complex services of the network at the edge using IoT devices |
| Management of networks                              | [29] | 2016 | Architecture      | A solution based on the utilization of dockers implemented on devices |
|                                                    | [30] | 2016 | Architecture      | Combining both direct and indirect current management approaches |
|                                                    | [31] | 2020 | Model             | Message-based communication model consists of a dictionary of services for devices and servers to interact |
|                                                    | [32] | 2019 | Platform          | M4DN.IoT, a platform for the management of IoT networks with a user-friendly interface |
|                                                    | [33] | 2014 | Architecture      | Extending the multi-network information architecture (MINA) middleware with SDN multilayer IoT controller |
|                                                    | [34] | 2014 | Framework         | Framework for managing and configuring the network dynamically based on SDN |
| Challenge addressed                                           | Ref. | Year | Approach          | Proposed solutions                                                                                                                                                                                                 |
|--------------------------------------------------------------|------|------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Heterogeneity in communication                               | [35] | 2016 | Algorithm         | Hierarchal clustering algorithm for dynamic and heterogeneous IoT systems                                                                                                                                            |
|                                                              | [36] | 2016 | Framework         | Relying on a device and distributed SDN connectivity to overcome the issue of heterogeneous communication methods used in IoT systems                                                                                 |
|                                                              | [37] | 2016 | Proposed system   | TACIoT, a flexible and reliable IoT access control system                                                                                                                                                             |
|                                                              | [38] | 2020 | Framework         | Knowledge-based framework using edge computing for heterogeneous connectivity in the Internet of Things networks                                                                                                   |
|                                                              | [39] | 2021 | Algorithm         | Distributed online optimization algorithm based on game theory and optimization theory. The algorithm works online and jointly decides to offload heterogeneous tasks, allocate computing resources, and manage battery power |
|                                                              | [40] | 2020 | Model             | Optimal geographic distribution across heterogeneous networks with caching support. Extending optimization to heterogeneous networks using simulated user distributions                                                      |
|                                                              | [41] | 2020 | Framework         | Elastic zoom algorithm for cells based on the end-user quality of service and traffic load                                                                                                                           |
|                                                              | [42] | 2019 | Platform          | MINOS, multi-protocol software that defines a networking platform                                                                                                                                                |
| Heterogeneity of devices                                     | [43] | 2017 | Platform          | ThingsJS, a JavaScript-based middleware platform and runtime environment that bypasses system-specific complexities                                                                                             |
|                                                              | [44] | 2014 | Architecture      | Architecture, combined with cognitive capabilities, that supports intelligent decision-making and automates service creation                                                                                       |
|                                                              | [45] | 2017 | Platform          | IoTOne, software platform to support heterogeneous Internet of Things devices and allow robust control of devices                                                                                                  |
|                                                              | [46] | 2020 | Middleware        | Cuttlefish, lightweight and flexible middleware having unified APIs for application development for heterogeneous device utilization                                                                            |
|                                                              | [47] | 2020 | Middleware        | MSOAH-IoT is based on a service-oriented architecture that handles various networking interfaces and collects data using REST API                                                                                |
|                                                              | [48] | 2017 | Architecture      | A middleware architecture and edge-based protocol that enables heterogeneous edge devices to dynamically exchange data and resources to improve application performance and privacy                                       |
|                                                              | [49] | 2019 | Framework         | A novel communication framework that enables simultaneous N-Way communication between Wi-Fi and Bluetooth low energy (BLE) devices eWoT, a semantically interactive ecosystem of IoT devices that provides |
|                                                              | [50] | 2020 | Mechanism         | SPARQL query-based mechanism for transparent discovery and access to IoT devices                                                                                                                                   |
| Communication between heterogeneous devices                   | [51] | 2012 | Framework         | Resource-oriented middleware framework using blockchain technology for dynamic and heterogeneous IoT systems                                                                                                    |
|                                                              | [52] | 2018 | Architecture      | Use of a multimodal d employing a variety of heterogeneous wireless networks                                                                                                                                       |
|                                                              | [53] | 2019 | Model             | Ontology-based device semantic web rule language between multiple devices in a heterogeneous system                                                                                                               |
|                                                              | [54] | 2020 | Protocol          | A device-to-device lightweight security protocol based on a symmetric key scheme to ensure secure communication between devices PICO, REST web service-based data-centric middleware for real-time communication and storage of data |
|                                                              | [55] | 2019 | Middleware        | A fully decentralized IoT access control system, based on blockchain technology architecture                                                                                                                        |
| Management and configuration of devices                      | [56] | 2018 | Architecture      | M4DN.IoT, a platform for the management of IoT networks with a user-friendly interface                                                                                                                          |
|                                                              | [57] | 2016 | Framework         | EC-IoT, making use of an open standard upon IoT communication protocol (COAP)                                                                                                                                     |
|                                                              | [58] | 2019 | Architecture      | An improved architecture for managing, monitoring, and configuring IoT devices, based on private blockchain                                                                                                        |
|                                                              | [59] | 2020 | Platform          | An open and scalable IoT platform having edge computing characteristics                                                                                                                                            |
|                                                              | [60] | 2020 | Framework         | DIAM-IoT, a framework for IoT device decentralized identification and access management                                                                                                                            |
| Challenge addressed                                      | Ref   | Year | Approach          | Proposed solutions                                                                                                                                 |
|---------------------------------------------------------|-------|------|-------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Heterogeneity in formats of data                        | [61]  | 2016 | Framework         | SIGHTED, a framework based on the semantic web and connected data principles                                                                       |
|                                                          | [62]  | 2017 | Framework         | A solution consisting of Internet gateway device functions, NoSQL database, web services, and IoT application                                      |
|                                                          | [63]  | 2011 | Framework         | SeaCloudDM, a novel sea-cloud-based heterogeneous data management framework                                                                       |
|                                                          | [64]  | 2020 | Proposed system   | MusQ, a solution that provides a multi-storing query system for IoT data using a formal unified query language (MQL)                                    |
|                                                          | [68]  | 2020 | Mechanism         | Ethereum blockchain consisting of generic and constrained devices that connect to the blockchain via a wired and wireless heterogeneous network        |
|                                                          | [65]  | 2020 | Architecture      | Software architecture for processing and analyzing data from heterogeneous sources with different structures in IoT scopes                          |
|                                                          | [66]  | 2021 | Framework         | Distributed multiparty secure computing framework for data authentication of devices                                                               |
|                                                          | [67]  | 2018 | Framework         | Framework for access control in IoT using block chain technology PEIoT, a data streaming system with enhanced privacy                               |
|                                                          | [69]  | 2020 | Proposed system   | (i) Providing users with the ability to subscribe to/unsubscribe from data                                                                       |
|                                                          |       |      |                   | (ii) Enabling data controllers to invoke various privacy-enhancing technologies                                                                  |
| Data security                                            | [70]  | 2019 | Model             | Two modules:                                                                                                                                      |
|                                                          |       |      |                   | (i) Secure data processing system to maintain IoT data security and integrity                                                                   |
|                                                          |       |      |                   | (ii) Drone-based data analytic system using edge computing and on-device computing                                                               |
|                                                          | [71]  | 2016 | Architecture      | A novel architecture consisting of a distributed interface having e-nodes—inexpensive, simple, and embedded nodes                                    |
| Communication security                                   | [72]  | 2019 | Protocol          | Multigroup key management protocol to ensure upstream and downstream secrecy, recovery from collision attacks, and network security               |
|                                                          | [73]  | 2019 | Mechanism         | A physical layer security mechanism to validate the single source for heterogeneous IoT                                                           |
|                                                          | [74]  | 2020 | Protocol          | Using proxy re-signature, a privacy-preserving authentication protocol for heterogeneous system                                                     |
|                                                          | [75]  | 2019 | Method            | SMER, a method for exchanging resources between heterogeneous devices securely                                                                    |
|                                                          | [76]  | 2015 | Algorithms        | Optimized elliptic curve cryptography (ECC) algorithms for the devices based on NXP/Jennic JNS148                                                   |
| Device security                                          | [77]  | 2019 | Proposed system   | Novel and lightweight authentication and key agreement scheme for heterogeneous IoT devices                                                      |
|                                                          | [78]  | 2018 | Algorithm         | ECC-based algorithm to authenticate and authorize new devices in a network                                                                     |
|                                                          | [79]  | 2021 | Framework         | MECshield, a DDoS prevention framework, based on mobile edge computing (MEC)                                                                     |
|                                                          | [80]  | 2020 | Proposed system   | Novel decentralized authentication mechanism based on blockchain technology                                                                     |
| Heterogeneity in standards, platform                     | [81]  | 2018 | Method            | Smart governance approach for heterogeneous IoT system management                                                                           |
|                                                          | [82]  | 2019 | Framework         | BRAIN-IoT, a framework and methodology for interconnecting heterogeneous platforms and automation                                                 |
|                                                          | [83]  | 2016 | Model             | The data model used in the VITAL project (open source IoT system of systems) for rapid development of IoT-based systems                             |
|                                                          | [84]  | 2021 | Platform          | Data Spine, federated platform for bridging interoperability gaps between heterogeneous IoT platforms                                               |
|                                                          | [85]  | 2017 | Model             | A concept of generic driver injection for developing mobile applications that can be deployed in a variety of environments using different middleware |
6. Conclusion and Future Work

This research is a systematic literature review that reviews the literature in the domain of IoT heterogeneity. The review has been implemented using a systematic methodology to select different studies addressing the challenges faced by heterogeneous IoT. To conduct this study, a total of 81 research papers that are published in different digital libraries from 2011 to 2021 were selected. For analysis purposes, we divided this duration into two timeframes. One is from 2011 to 2016, and the other is from 2017 to 2021. In this SLR, we have identified 14 different heterogeneity challenges that need to be addressed to implement IoT on a large scale. Challenges with occurrence percentage of more than 30% are defined as the most critical ones. In this study, we analyze the occurrence of those challenges based on digital libraries as well as timeframe. In this analysis, we found out that some challenges were more critical in the earlier timeframe than in the recent timeframe.

We also found out that some challenges are still critical in both timeframes. After identifying those challenges, we found at least 5 solutions for each identified challenge. The summary of those solutions is given in Table 6. In future work, we want to categorize the challenges and prioritize the solutions by using a multi-criteria decision-making problem.

### Data Availability

The data collected during the data collection phase will be provided by the corresponding author upon request.

### Conflicts of Interest

The authors declare that there are no conflicts of interest.

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