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Review Article

Challenges in Integration of Heterogeneous Internet of Things

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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 [8]. 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 [9]. According to [10], 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 [11]. 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 serves 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"	
ScienceDirect	("IoT" OR "Internet of Things") AND ("heterogenous") AND ("challenges")	IoT heterogeneity
ACM	("IoT") AND ("heterogenous") AND ("challenges")	
SpringerLink	("IoT") AND ("heterogeneity") AND ("challenges")	

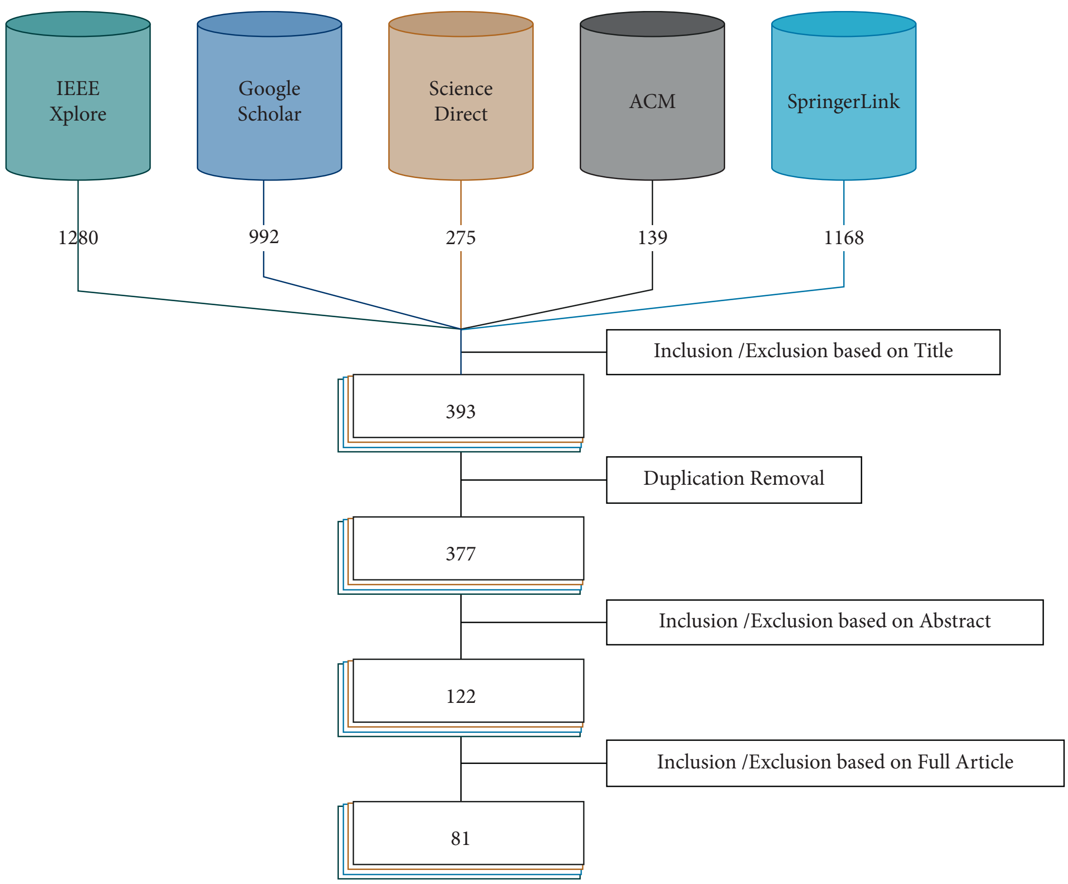

Figure 1: Selection of articles using the tollgate approach.

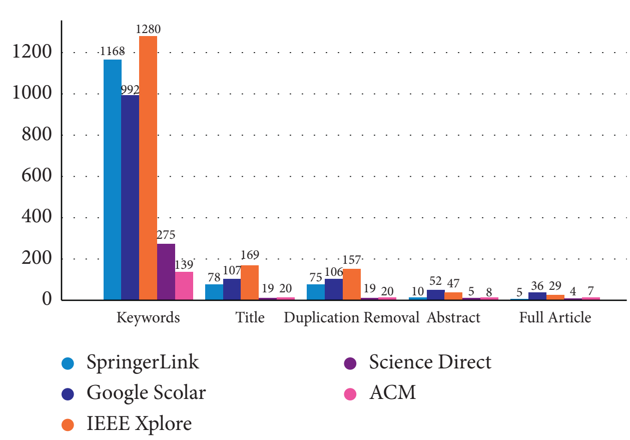

Figure 2: Paper selection based on digital libraries.

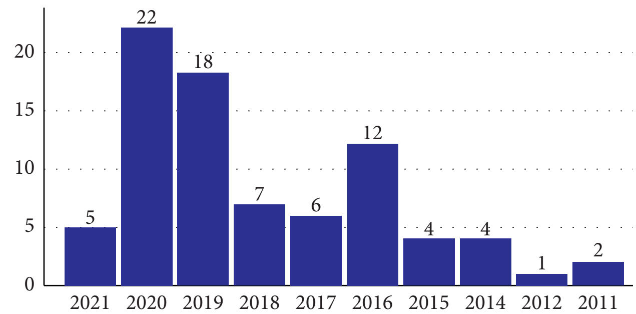

Figure 3: Paper selected on a yearly basis.

Table 3: Challenges identified through SLR.

S. No	Challenges	Frequency, 81	Percentage (%)	Papers ID
1	Fragmentation in connectivity, protocols	10	14	PiD4, PiD2, PiD4, PiD5, PiD36, PiD54, PiD60, PiD66, PiD74, PPiD78
2	Diversity in network technologies	9	13	PiD3, PiD6, PiD7, PiD8, PiD9, PiD10, PiD46, PiD54, PiD63
3	Management of networks	6	8	PiD8, PiD11, PiD13, PiD14, PiD15, PiD16
4	Heterogeneous communication issues	26	36	PiD3, PiD10, PiD11, PiD13, PiD15, PiD17, PiD20, PiD21, PiD26, PiD28, PiD29, PiD49, PiD57, PiD58, PiD61, PiD62, PiD64, PiD65, PiD68, PiD70, PiD72, PiD73, PiD75, PiD80, PiD81
5	Heterogeneity of devices issues	35	49	PiD2, PiD3, PiD8, PiD11, PiD12, PiD14, PiD16, PiD19, PiD20, PiD21, PiD22, PiD23, PiD24, PiD25, PiD26, PiD27, PiD28, PiD45, PiD46, PiD47, PiD50, PiD51, PiD56, PiD57, PiD58, PiD62, PiD63, PiD65, PiD68, PiD70, PiD71, PiD72, PiD77
6	Communication between heterogeneous devices	15	21	PiD3, PiD7, PiD10, PiD18, PiD28, PiD29, PiD30, PiD31, PiD32, PiD33, PiD47, PiD50, PiD53, PiD69, PiD71
7	Management and configuration of devices	13	18	PiD11, PiD14, PiD16, PiD30, PiD33, PiD34, PiD35, PiD36, PiD37, PiD54, PiD61, PiD62
8	Heterogeneous data/data formats	26	36	PiD1, PiD6, PiD10, PiD18, PiD25, PiD26, PiD27, PiD28, PiD32, PiD36, PiD38, PiD39, PiD40, PiD41, PiD42, PiD57, PiD58, PiD62, PiD64, PiD65, PiD68, PiD69, PiD70, PiD72, PiD79
9	Data security	12	17	PiD23, PiD31, PiD43, PiD44, PiD45, PiD46, PiD49, PiD52, PiD53, PiD76, PiD77
10	Communication security	16	22	PiD19, PiD23, PiD31, PiD32, PiD35, PiD43, PiD44, PiD47, PiD48, PiD49, PiD50, PiD51, PiD52, PiD53, PiD54, PiD55
11	Device security	14	20	PiD8, PiD19, PiD23, PiD24, PiD31, PiD43, PiD48, PiD49, PiD52, PiD53, PiD54, PiD55, PiD67
12	Heterogeneity in standards, platform	10	14	PiD1, PiD34, PiD36, PiD56, PiD57, PiD58, PiD59, PiD60, PiD66, PiD72
13	Integration of devices and data	14	20	PiD12, PiD18, PiD21, PiD23, PiD38, PiD41, PiD53, PiD56, PiD60, PiD61, PiD62, PiD63, PiD64, PiD65
14	Interoperability issue	16	22	PiD5, PiD9, PiD23, PiD27, PiD30, PiD37, PiD51, PiD59, PiD65, PiD66, PiD67, PiD68, PiD69, PiD70, PiD71, PiD72

(3) Heterogeneity in formats of data is critical in ScienceDirect, SpringerLink, and IEEE Xplore

(4) 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 communication is critical in Timeframe I from 2011 to 2016 as shown in Table 5.

(1) Heterogeneity of devices is critical in Timeframe I and Timeframe II

(2) Heterogeneity in formats of data 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	%	x^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	Proposed solutions			
	Ref	Year	Approach	Solution
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
Diversity in network technologies	[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
	[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

Table 6: Continued.

Challenge addressed	Proposed solutions			
	Ref	Year	Approach	Solution
Heterogeneity in communication	[35]	2016	Algorithm	Hierarchal clustering algorithm for dynamic and heterogeneous IoT
	[36]	2016	Framework	Relying on a device and distributed SDN connectivity to overcome the issue of heterogeneous communication methods used in IoT
	[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
	[50]	2020	Mechanism	eWoT, a semantically interactive ecosystem of IoT devices that provides 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
	[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
	[55]	2019	Middleware	PICO, REST web service-based data-centric middleware for real-time communication and storage of data
	[56]	2018	Architecture	A fully decentralized IoT access control system, based on blockchain technology architecture
Management and configuration of devices	[32]	2019	Platform	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

Table 6: Continued.

Challenge addressed	Proposed solutions			
	Ref	Year	Approach	Solution
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
Data security	[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
	[69]	2020	Proposed system	PEIoT, a data streaming system with enhanced privacy (i) Providing users with the ability to subscribe to/unsubscribe from data (ii) Enabling data controllers to invoke various privacy-enhancing technologies
	[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 JN5148
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

Table 6: Continued.

Challenge addressed	Proposed solutions			
	Ref	Year	Approach	Solution
Integration of devices and data	[86]	2019	Proposed system	SensPnP, a novel plug-and-play solution which combines hardware with firmware
	[87]	2020	Architecture	Blockchain-based architecture to improve integration and reduce computation overhead and energy consumption
	[88]	2015	Proposed system	A solution based on management distribution of devices among gateways and making use of web service delegation
	[89]	2016	Architecture	Architecture for data integration from heterogeneous data sources like government agencies and unreliable sources
	[90]	2020	Model	Point-to-point integration model in IoT applications, with three layers: hardware, communication, and integration
Interoperability issue	[91]	2019	Model	Three internetworking models based on the status of the city
	[92]	2020	Framework	AFaaS, authorization framework as a services to support interoperability challenge
	[93]	2018	Framework	SHIOT, an SDN-based framework which is based on ontology and applies SDN controller
	[94] [95]	2018	Platform	New design of decentralized IoT platform having capabilities of edge computing, fog computing, and cloud computing
	[96] [90] [91] [92] [93]	2014 2022 2022 2022 2019	Framework	A lightweight, middleware-independent development framework for interoperability monitoring
	[97]	2021	Framework	Trust-based middleware framework for managing interoperability challenges in heterogeneous IoT
	[98]	2016 2020 2021 2022	Method	Model-based engineering methods to ensure those complex software systems are interoperable with each other

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.

References

[1] I. Within and C. Farook, “IoT generic frameworks: what needs to improve,” in *Proceedings of the 2019 7th International Conference on Smart Computing & Communications (ICSCC)*, pp. 1–5, IEEE, Sarawak, Malaysia, June 2019.

[2] A. H. Mohd Aman, E. Yadegaridehkordi, Z. S. Attarbashi, R. Hassan, and Y.-J. Park, “A survey on trend and classification of internet of things reviews,” *IEEE Access*, vol. 8, pp. 111763–111782, 2020.

[3] D. C. Yacchirema Vargas and C. E. Palau Salvador, “Smart IoT gateway for heterogeneous devices interoperability,” *IEEE Latin America Transactions*, vol. 14, no. 8, pp. 3900–3906, 2016.

[4] N. Pazos, M. Müller, M. Aeberli, and N. Ouerhani, “ConnectOpen-automatic integration of IoT devices,” in *Proceedings of the 2015 IEEE 2nd World Forum on Internet of Things (WF-IoT)*, pp. 640–644, IEEE, Milan, Italy, December 2015.

[5] S. Madakam, R. Ramaswamy, S. Tripathi, and V. Lake, "Internet of things (IoT): a literature review," *Journal of Computer and Communications*, vol. 03, no. 05, pp. 164–173, 2015.
[6] J. Huang, B. Lv, Y. Wu, Y. Chen, and X. Shen, "Dynamic admission control and resource allocation for mobile edge computing enabled small cell network," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 2, pp. 1964–1973, 2021.
[7] Y. Chen, F. Zhao, Y. Lu, and X. Chen, "Dynamic task offloading for mobile edge computing with hybrid energy supply," *Tsinghua Science and Technology*, vol. 10, 2021.
[8] G. Nunberg, *The Advent of the Internet, 12th April, Courses*, 2012.
[9] "Internet," 1996, V. Beal, https://www.webopedia.com/definitions/internet/.
[10] I. L. Stats, "Internet world Statistics," 2021, https://www.internetlivestats.com/.
[11] X. Zhang, H. Chen, Y. Zhao et al., "Improving cloud gaming experience through mobile edge computing," *IEEE Wireless Communications*, vol. 26, no. 4, pp. 178–183, 2019.
[12] P. P. Ray, "A survey on Internet of Things architectures," *Journal of King Saud University - Computer and Information Sciences*, vol. 30, no. 3, pp. 291–319, 2018.
[13] L. Ericsson, *More than 50 Billion Connected Devices—Taking Connected Devices to Mass Market and Profitability*, Technology report, 2011.
[14] D. Evans, "The internet of things: How the next evolution of the internet is changing everything 2011," 2015, http://www.cisco.com/web/about/ac79/docs/innov/IoTIBSG0411FINAL.pdf.
[15] F. Van den Abeele, J. Hoebeke, I. Moerman, and P. Demeester, "Integration of heterogeneous devices and communication models via the cloud in the constrained internet of things," *International Journal of Distributed Sensor Networks*, vol. 2015, no. 10, pp. 1–16, 2015.
[16] J. Huang, C. Zhang, and J. Zhang, "A multi-queue approach of energy efficient task Scheduling for sensor Hubs," *Chinese Journal of Electronics*, vol. 29, no. 2, pp. 242–247, 2020.
[17] X. Zhang, Z. Qi, G. Min, W. Miao, Q. Fan, and Z. Ma, "Cooperative edge Caching based on Temporal Convolutional networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 33, no. 9, pp. 2093–2105, 2022.
[18] T. Qiu, N. Chen, K. Li, M. Atiquzzaman, and W. Zhao, "How can heterogeneous internet of things build our future: a survey," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 3, pp. 2011–2027, 2018.
[19] M.-M. Moazzami, G. Xing, D. Mashima, W.-P. Chen, and U. Herberg, "SPOT: a smartphone-based platform to tackle heterogeneity in smart-home IoT systems," in *Proceedings of the 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT)*, pp. 514–519, IEEE, Reston, VA, USA, December 2016.
[20] R. Herrero, "6LoWPAN fragmentation in the context of IoT based media real time communication," *Internet Technology Letters*, vol. 3, no. 2, p. e144, 2020.
[21] W. Wang, X. Liu, Y. Yao, Y. Pan, Z. Chi, and T. Zhu, "Crf: Coexistent routing and flooding using wifi packets in heterogeneous iot networks," in *Proceedings of the IEEE INFOCOM 2019-IEEE conference on computer communications*, pp. 19–27, IEEE, Paris, France, May 2019.
[22] Z. An, Q. Lin, P. Li, and L. Yang, "General-purpose deep tracking platform across protocols for the internet of things," in *Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services*, pp. 94–106, ACM, 2020.
[23] E. M. Torroglosa-Garcia, J. M. A. Calero, J. B. Bernabe, and A. Skarmeta, "Enabling roaming across heterogeneous IoT wireless networks: LoRaWAN MEETS 5G," *IEEE Access*, vol. 8, pp. 103164–103180, 2020.
[24] H. Le, N. Achir, and K. Boussetta, "Fog computing architecture with heterogeneous Internet of Things technologies," in *Proceedings of the 2019 10th International Conference on Networks of the Future (NoF)*, pp. 130–133, IEEE, Rome, Italy, October 2019.
[25] E. De Poorter, I. Moerman, and P. Demeester, "Support for heterogeneous dynamic network environments through a reconfigurable network service platform," in *Proceedings of the 2011 1st International Symposium on Access Spaces (ISAS)*, pp. 174–179, IEEE, Yokohama, Japan, June 2011.
[26] K. Sood, K. K. Karmakar, S. Yu, V. Varadharajan, S. R. Pokhrel, and Y. Xiang, "Alleviating heterogeneity in SDN-IoT networks to Maintain QoS and Enhance security," *IEEE Internet of Things Journal*, vol. 7, no. 7, pp. 5964–5975, 2020.
[27] G. Aloi, G. Caliciuri, G. Fortino et al., "Enabling IoT interoperability through opportunistic smartphone-based mobile gateways," *Journal of Network and Computer Applications*, vol. 81, pp. 74–84, 2017.
[28] I. Al Ridhawi, M. Aloqaily, A. Boukerche, and Y. Jaraweh, "A blockchain-based decentralized composition solution for iot services," in *Proceedings of the Icc 2020-2020 ieee international conference on communications (icc)*, pp. 1–6, IEEE, Dublin, Ireland, June 2020.
[29] I. Bedhief, M. Kassar, and T. Aguili, "SDN-based architecture challenging the IoT heterogeneity," in *Proceedings of the 2016 3rd Smart Cloud Networks & Systems (SCNS)*, pp. 1–3, IEEE, Dubai, United Arab Emirates, December 2016.
[30] C. Pham, Y. Lim, and Y. Tan, "Management architecture for heterogeneous IoT devices in home network," in *Proceedings of the 2016 IEEE 5th Global Conference on Consumer Electronics*, pp. 1–5, IEEE, Kyoto, Japan, October 2016.
[31] B. Oniga, L. Denis, V. Dadarlat, and A. Munteanu, "Message-based communication for heterogeneous internet of things systems," *Sensors*, vol. 20, no. 3, p. 861, 2020.
[32] J. D. C. Silva, J. J. P. C. Rodrigues, K. Saleem, S. A. Kozlov, and R. A. L. Rabelo, "M4DN.IoT-A networks and devices management platform for internet of things," *IEEE Access*, vol. 7, pp. 53305–53313, 2019.
[33] Z. Qin, G. Denker, C. Giannelli, P. Bellavista, and N. Venkatasubramanian, "A software defined networking architecture for the internet-of-things," in *Proceedings of the 2014 IEEE network operations and management symposium (NOMS)*, pp. 1–9, IEEE, Krakow, Poland, May 2014.
[34] H. Huang, J. Zhu, and L. Zhang, "An SDN_based management framework for IoT devices," in *Proceedings of the 25th IET Irish Signals & Systems Conference 2014 and 2014 China-Ireland International Conference on Information and Communications Technologies (ISSC 2014/CIICT 2014)*, pp. 175–179, IET, Limerick, June 2014.
[35] J. S. Kumar and M. A. Zaveri, "Hierarchical clustering for dynamic and heterogeneous internet of things," *Procedia Computer Science*, vol. 93, pp. 276–282, 2016.
[36] A. Desai, K. Nagegowda, and T. Ninikrishna, "A framework for integrating IoT and SDN using proposed OF-enabled management device," in *Proceedings of the 2016 International Conference on Circuit, Power and Computing Technologies (ICCPCT)*, pp. 1–4, IEEE, Nagercoil, India, March 2016.
[37] J. Bernal Bernabe, J. L. Hernandez Ramos, and A. F. Skarmeta Gomez, "TACIoT: multidimensional trust-aware access control system for the Internet of Things," *Soft Computing*, vol. 20, no. 5, pp. 1763–1779, 2016.

[38] R. Xu, W. Jin, and D. H. Kim, "Knowledge-based edge computing framework based on CoAP and HTTP for enabling heterogeneous connectivity," *Personal and Ubiquitous Computing*, vol. 26, no. 2, pp. 329–344, 2020.

[39] S. Xia, Z. Yao, Y. Li, and S. Mao, "Online distributed offloading and computing resource management with energy harvesting for heterogeneous MEC-enabled IoT," *IEEE Transactions on Wireless Communications*, vol. 20, no. 10, pp. 6743–6757, 2021.

[40] J. Yang, C. Ma, B. Jiang, G. Ding, G. Zheng, and H. Wang, "Joint optimization in cached-enabled heterogeneous network for efficient industrial IoT," *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 5, pp. 831–844, 2020.

[41] H. Jiang, Z. Xiao, Z. Li, J. Xu, F. Zeng, and D. Wang, "An energy-efficient framework for internet of things underlaying heterogeneous small cell networks," *IEEE Transactions on Mobile Computing*, vol. 21, no. 1, pp. 31–43, 2022.

[42] T. Theodorou, G. Violettas, P. Valsamas, S. Petridou, and L. Mamatas, "A multi-protocol software-defined networking solution for the Internet of Things," *IEEE Communications Magazine*, vol. 57, no. 10, pp. 42–48, 2019.

[43] J. Gascon-Samson, M. Rafiuzzaman, and K. Pattabiraman, "Thingsjs: towards a flexible and self-adaptable middleware for dynamic and heterogeneous iot environments," in *Proceedings of the 4th Workshop on Middleware and Applications for the Internet of Things*, pp. 11–16, December 2017.

[44] C. Sarkar, A. U. Nambi, R. V. Prasad, A. Rahim, R. Neisse, and G. Baldini, "DIAT: a scalable distributed architecture for IoT," *IEEE Internet of Things Journal*, vol. 2, no. 3, pp. 230–239, 2015.

[45] N. Gyory and M. Chuah, "IoTOne: Integrated platform for heterogeneous IoT devices," in *Proceedings of the 2017 International Conference on Computing, Networking and Communications (ICNC)*, pp. 783–787, IEEE, Silicon Valley, CA, USA, January 2017.

[46] A. Pamboris, C. Kozis, and H. Herodotou, "Cuttlefish: a flexible and lightweight middleware for combining heterogeneous IoT devices," in *Proceedings of the 2020 IEEE 17th Annual Consumer Communications & Networking Conference (CCNC)*, pp. 1–6, IEEE, Las Vegas, NV, USA, January 2020.

[47] Y. Mesmoudi, M. Lamnaour, Y. El Khamlichi, A. Tahiri, A. Touhafi, and A. Braeken, "A middleware based on service oriented architecture for heterogeneity issues within the internet of things (MSOAH-IoT)," *Journal of King Saud University - Computer and Information Sciences*, vol. 32, no. 10, pp. 1108–1116, 2020.

[48] A. Essameldin and K. A. Harras, "The hive: an edge-based middleware solution for resource sharing in the internet of things," in *Proceedings of the 3rd Workshop on Experiences with the Design and Implementation of Smart Objects*, pp. 13–18, ACM, October 2017.

[49] Z. Chi, Y. Li, H. Sun, Y. Yao, and T. Zhu, "Concurrent cross-technology communication among heterogeneous IoT devices," *IEEE/ACM Transactions on Networking*, vol. 27, no. 3, pp. 932–947, 2019.

[50] A. Cimmino, M. Poveda-Villalón, and R. García-Castro, "ewot: a semantic interoperability approach for heterogeneous iot ecosystems based on the web of things," *Sensors*, vol. 20, no. 3, p. 822, 2020.

[51] Y. Hong, "A resource-oriented middleware framework for heterogeneous internet of things," in *Proceedings of the 2012 international conference on cloud and service computing*, pp. 12–16, IEEE, Shanghai, China, November 2012.

[52] J. Famaey, R. Berkvens, G. Ergeerts et al., "Flexible multi-modal sub-gigahertz communication for heterogeneous internet of things applications," *IEEE Communications Magazine*, vol. 56, no. 7, pp. 146–153, 2018.

[53] S. Suman, T. Perumal, N. Mustapha, and R. Yaakob, "Device Verification and Compatibility for heterogeneous semantic IoT systems," in *Proceedings of the 2019 4th International Conference and Workshops on Recent Advances and Innovations in Engineering (ICRAIE)*, pp. 1–3, IEEE, Kedah, Malaysia, November 2019.

[54] X. Luo, L. Yin, C. Li et al., "A lightweight privacy-preserving communication protocol for heterogeneous IoT environment," *IEEE Access*, vol. 8, pp. 67192–67204, 2020.

[55] J. Chen, E. Cañete, D. Garrido, M. Díaz, and K. Piotrowski, "PICO: a platform independent communications middleware for heterogeneous devices in smart grids," *Computer Standards & Interfaces*, vol. 65, pp. 1–14, 2019.

[56] O. Novo, "Blockchain meets IoT: an architecture for scalable access management in IoT," *IEEE Internet of Things Journal*, vol. 5, no. 2, pp. 1184–1195, 2018.

[57] E. Dalipi, F. Van den Abeele, I. Ishaq, I. Moerman, and J. Hoebeke, "EC-IoT: an easy configuration framework for constrained IoT devices," in *Proceedings of the 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT)*, pp. 159–164, IEEE, Reston, VA, USA, December 2016.

[58] K. Košťál, P. Helebrandt, M. Belluš, M. Ries, and I. Kotuliak, "Management and monitoring of IoT devices using blockchain," *Sensors*, vol. 19, no. 4, p. 856, 2019.

[59] A. Javed, A. Malhi, T. Kinnunen, and K. Framling, "Scalable IoT platform for heterogeneous devices in smart environments," *IEEE Access*, vol. 8, pp. 211973–211985, 2020.

[60] X. Fan, Q. Chai, L. Xu, and D. Guo, "DIAM-IoT: a decentralized identity and access management framework for internet of things," in *Proceedings of the 2nd ACM International Symposium on Blockchain and Secure Critical Infrastructure*, pp. 186–191, ACM, October 2020.

[61] A. M. Nagib and H. S. Hamza, "SIGHTED: a framework for semantic integration of heterogeneous sensor data on the internet of things," *Procedia Computer Science*, vol. 83, pp. 529–536, 2016.

[62] E. S. Pramukantoro, W. Yahya, G. Arganata, A. Bhawiyuga, and A. Basuki, "Topic based IoT data storage framework for heterogeneous sensor data," in *Proceedings of the 2017 11th International Conference on Telecommunication Systems Services and Applications (TSSA)*, pp. 1–4, IEEE, Lombok, Indonesia, October 2017.

[63] Z. Ding, Q. Yang, and H. Wu, "Massive heterogeneous sensor data management in the Internet of Things," in *Proceedings of the 2011 International Conference on Internet of Things and 4th International Conference on Cyber, Physical and Social Computing*, pp. 100–108, IEEE, Dalian, China, October 2011.

[64] H. Ramadhan, F. I. Indikawati, J. Kwon, and B. Koo, "MusQ: a Multi-store query system for iot data using a datalog-like language," *IEEE Access*, vol. 8, pp. 58032–58056, 2020.

[65] D. Corral-Plaza, I. Medina-Bulo, G. Ortiz, J. Boubeta-Puig, and User Group, "A stream processing architecture for heterogeneous data sources in the Internet of Things," *Computer Standards & Interfaces*, vol. 70, p. 103426, 2020.

[66] Y. D. Al-Otaibi, "Distributed multi-party security computation framework for heterogeneous internet of things (IoT) devices," *Soft Computing*, vol. 25, no. 18, pp. 12131–12144, 2021.

[67] C. Dukkipati, Y. Zhang, and L. C. Cheng, "Decentralized, blockchain based access control framework for the

heterogeneous internet of things," in *Proceedings of the Third ACM Workshop on Attribute-Based Access Control*, pp. 61–69, ACM, March 2018.

[68] S. Misra, A. Mukherjee, A. Roy, N. Saurabh, Y. Rahulamathavan, and M. Rajarajan, "Blockchain at the edge: Performance of resource-constrained IoT networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 32, no. 1, pp. 174–183, 2021.

[69] S. Ghayyur, P. Pappachan, G. Wang, S. Mehrotra, and N. Venkatasubramanian, "Designing privacy preserving data sharing middleware for internet of things," in *Proceedings of the Third Workshop on Data: Acquisition To Analysis*, pp. 1–6, ACM, November 2020.

[70] M. S. Islam, H. Verma, L. Khan, and M. Kantarcioglu, "Secure real-time heterogeneous iot data management system," in *Proceedings of the 2019 First IEEE International Conference on Trust, Privacy and Security in Intelligent Systems and Applications (TPS-ISA)*, pp. 228–235, IEEE, Los Angeles, CA, USA, December 2019.

[71] S. Sicari, C. Cappiello, F. De Pellegrini, D. Miorandi, and A. Coen-Porisini, "A security-and quality-aware system architecture for Internet of Things," *Information Systems Frontiers*, vol. 18, no. 4, pp. 665–677, 2016.

[72] M. A. Kandi, H. Lakhlef, A. Bouabdallah, and Y. Challal, "An efficient multi-Group Key management protocol for heterogeneous IoT devices," in *Proceedings of the 2019 IEEE Wireless Communications and Networking Conference (WCNC)*, pp. 1–6, IEEE, Marrakesh, Morocco, April 2019.

[73] S. Yu, X. Zhang, P. Huang, and L. Guo, "Secure authentication in cross-technology communication for heterogeneous IoT," in *Proceedings of the 2019 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, pp. 1-2, IEEE, Newark, NJ, USA, November 2019.

[74] H. Xiong, Y. Wu, C. Jin, and S. Kumari, "Efficient and privacy-preserving authentication protocol for heterogeneous systems in IIoT," *IEEE Internet of Things Journal*, vol. 7, no. 12, pp. 11713–11724, 2020.

[75] Y. Zhang, Y. Han, and J. Wen, "SMER: a secure method of exchanging resources in heterogeneous internet of things," *Frontiers of Computer Science*, vol. 13, no. 6, pp. 1198–1209, 2019.

[76] L. Marin, M. P. Pawlowski, and A. Jara, "Optimized ECC implementation for secure communication between heterogeneous IoT devices," *Sensors*, vol. 15, no. 9, pp. 21478–21499, 2015.

[77] J. Liu, A. Ren, L. Zhang, R. Sun, X. Du, and M. Guizani, "A novel secure authentication scheme for heterogeneous internet of things," in *Proceedings of the ICC 2019-2019 IEEE International Conference on Communications (ICC)*, pp. 1–6, IEEE, Shanghai, China, May 2019.

[78] S. Sasirekha, S. Swamynathan, and S. Suganya, "An ECC-based algorithm to handle secure communication between heterogeneous IoT devices," in *Advances in Electronics, Communication and Computing*, pp. 351–362, Springer, Singapore, 2018.

[79] N.-N. Dao, T. V. Phan, U. Sa'ad et al., "Securing heterogeneous iot with intelligent ddos attack behavior learning," *IEEE Systems Journal*, vol. 16, no. 2, pp. 1974–1983, 2022.

[80] A. Mostafa, "Blockchain-based distributed authentication Mechanism for internet-of-things devices," in *Proceedings of the 2020 9th International Conference on Software and Information Engineering (ICSIE)*, pp. 159–164, November 2020.

[81] A. Kazmi, M. Serrano, and A. Lenis, "Smart governance of heterogeneous internet of things for smart cities," in *Proceedings of the 2018 12th International Conference on Sensing Technology (ICST)*, pp. 58–64, IEEE, Limerick, Ireland, December 2018.

[82] D. Conzon, M. R. A. Rashid, X. Tao, A. Soriano, R. Nicholson, and E. Ferrera, "BRAIN-IoT: model-based framework for dependable sensing and actuation in intelligent decentralized IoT Systems," in *Proceedings of the 2019 4th International Conference on Computing, Communications and Security (ICCCS)*, pp. 1–8, IEEE, Rome, Italy, October 2019.

[83] A. Kazmi, Z. Jan, A. Zappa, and M. Serrano, "Overcoming the heterogeneity in the internet of things for smart cities," in *International Workshop on Interoperability and Open-Source Solutions*, pp. 20–35, Springer, Cham, 2016.

[84] R. A. Deshmukh, D. Jayakody, A. Schneider, and V. Damjanovic-Behrendt, "Data spine: a federated interoperability enabler for heterogeneous IoT platform ecosystems," *Sensors*, vol. 21, no. 12, p. 4010, 2021.

[85] K. Saatkamp, U. Breitenbücher, F. Leymann, and M. Wurster, "Generic driver injection for automated IoT application deployments," in *Proceedings of the 19th International Conference on Information Integration and Web-based Applications & Services*, pp. 320–329, ACM, Salzburg, Austria, December 2017.

[86] S. K. Roy, S. Misra, and N. S. Raghuwanshi, "SensPnP: Seamless integration of heterogeneous sensors with IoT devices," *IEEE Transactions on Consumer Electronics*, vol. 65, no. 2, pp. 205–214, 2019.

[87] L. Tseng, L. Wong, S. Otoum, M. Aloqaily, and J. B. Othman, "Blockchain for managing heterogeneous internet of things: a perspective architecture," *IEEE network*, vol. 34, no. 1, pp. 16–23, 2020.

[88] A. C. Olivieri and G. Rizzo, "Scalable approaches to integration in heterogeneous IoT and M2M scenarios," in *Proceedings of the 2015 9th International Conference on Innovative Mobile and Internet Services in Ubiquitous Computing*, pp. 358–363, IEEE, Santa Catarina, Brazil, July 2015.

[89] F. Montori, L. Bedogni, and L. Bononi, "On the integration of heterogeneous data sources for the collaborative Internet of Things," in *Proceedings of the 2016 IEEE 2nd International Forum on Research and Technologies for Society and Industry Leveraging a better tomorrow (RTSI)*, pp. 1–6, IEEE, Bologna, Italy, September 2016.

[90] D. Alulema, J. Criado, L. Iribarne, A. J. Fernández-García, and R. Ayala, "A model-driven engineering approach for the service integration of IoT systems," *Cluster Computing*, vol. 23, no. 3, pp. 1937–1954, 2020.

[91] J. Hwang, J. An, A. Aziz, J. Kim, S. Jeong, and J. Song, "Interworking models of smart city with heterogeneous internet of things standards," *IEEE Communications Magazine*, vol. 57, no. 6, pp. 74–79, 2019.

[92] S.-R. Oh and Y.-G. Kim, "AFaaS: Authorization framework as a service for Internet of Things based on interoperable OAuth," *International Journal of Distributed Sensor Networks*, vol. 16, no. 2, Article ID 155014772090638, 2020.

[93] H. A. Tran, D. Tran, L. G. Nguyen, Q. T. Ha, V. Tong, and A. Mellouk, "SHIOT: a novel SDN-based framework for the heterogeneous internet of things," *Informatica*, vol. 42, no. 3, 2018.

[94] B. Skrbic, D. Radovanovic, S. Tomovic, L. Lazovic, Z. Zecevic, and I. Radusinovic, "A decentralized platform for heterogeneous IoT networks management," in *Proceedings of the 2018 23rd International Scientific-Professional Conference on Information Technology (IT)*, pp. 1–4, IEEE, Zabljak, Montenegro, February 2018.

[95] J. Huang, B. Lv, Y. Wu, Y. Chen, and X. Shen, “Dynamic admission control and resource allocation for mobile edge computing enabled small cell network,” *IEEE Transactions on Vehicular Technology*, vol. 71, no. 2, pp. 1964–1973, 2022.
[96] P. Grace, J. Barbosa, B. Pickering, and M. Surridge, “Taming the interoperability challenges of complex iot systems,” in *Proceedings of the 1st ACM Workshop on Middleware for Context-Aware Applications in the IoT*, pp. 1–6, ACM, Bordeaux, France, December 2014.
[97] M. A. Abbasi, Z. A. Memon, N. M. Durrani, W. Haider, K. Laeeq, and G. A. Mallah, “A multi-layer trust-based middleware framework for handling interoperability issues in heterogeneous IoTs,” *Cluster Computing*, vol. 24, no. 3, pp. 2133–2160, 2021.
[98] P. Grace, B. Pickering, and M. Surridge, “Model-driven interoperability: engineering heterogeneous IoT systems,” *Annals of telecommunications*, vol. 71, no. 3-4, pp. 141–150, 2016.