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The Internet of Things: A Review of Enabled Technologies and Future Challenges

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ABSTRACT The Internet of Things (IoT) is an emerging classical model, envisioned as a system of billions of small interconnected devices for posing the state-of-the-art findings to real-world glitches. Over the last decade, there has been an increasing research concentration in the IoT as an essential design of the constant convergence between human behaviors and their images on Information Technology. With the development of technologies, the IoT drives the deployment of across-the-board and self-organizing wireless networks. The IoT model is progressing toward the notion of a cyber-physical world, where things can be originated, driven, intermixed, and modernized to facilitate the emergence of any feasible association. This paper provides a summary of the existing IoT research that underlines enabling technologies, such as fog computing, wireless sensor networks, data mining, context awareness, real-time analytics, virtual reality, and cellular communications. Also, we present the lessons learned after acquiring a thorough representation of the subject. Thus, by identifying numerous open research challenges, it is presumed to drag more consideration into this novel paradigm.

INDEX TERMS Internet of Things, fog computing, wireless sensor networks, smart cities, cellular IoT, real-time analytics.

I. INTRODUCTION

The Internet technology has been experiencing considerable modifications since its early times and has turned out to be an imperative transmission framework aiming at everywhere and every time connectivity [1]. The Internet of Things (IoT) is a new concept permitting billions of tiny machines, for example, sensors, to be connected to the Internet [2], [3]. With the Internet growth, IoT has carried out an impressive effect to several fields and there have been numerous IoT applications employed for enhancing the network operation and users' quality of experience. These applications can be employed in the following areas: healthcare, industries, vehicular communications, wireless sensor networks (WSNs), cloud computing, fog computing, edge computing, software defined networking (SDN), data mining, cellular networks, and many more [4]–[13].

With the growing utilization of smart devices, networks' survivability and self-organization have become extremely challenging. However, some proposed self-organizing paradigms, as in [14]–[16], may increase the strength of networks. In IoT, the association of different heterogeneous devices reduces the capability of network resources, which pulls the attention of researchers towards this emerging field [17], [18].

TABLE 1. Analysis of presented surveys.

Survey	Reference	Scope
Smart Cities: IoT Enabling Technologies	[25]	Data traffic, virtual power plant, emergency system, health system
Heterogeneous IoT	[5]	Sensing layer, networking layer, cloud computing layer, application layer
Fog Computing for IoT	[19]	Cloud layer, fog layer, device layer
Data mining for IoT	[26]	Clustering, Classification, Frequent patterns, Association rules
WSN-based data centric IoT	[3]	Data aggregation mechanisms
IoT-based cellular communications	[1]	Long Term Evolution (LTE)
Context Awareness-based IoT	[27]	Applications and middleware solutions
Virtual object-based IoT	[28]	Historical evolution and current features
Real-Time analytics based IoT	[29]	Wireless, wired, and hybrid data centers

The development of IoT leads to a huge number of content creation, which acquires bulky processing units, content stores (caches), and bandwidth provision [19]. This is due to the fact that the number of Internet connected tiny nodes would reach 27 billion by 2021 [20], [21]. Some applications would need secure transmissions, while some others may need local storage for fast transmissions and low response time [22], [23]. This huge amount of content caching with local processing would require sophisticated techniques for local administration. With the improvement of IoT, several technologies have been introduced [24], which are the main focus of this paper and are discussed in the following sections in detail. Several good surveys have been published on IoT enabled technologies, such as IoT-based smart cities [25], heterogeneous IoT [5], fog computing for IoT [19], data mining for IoT [26], WSN-based data centric IoT [3], IoT-based cellular communications [1], context awareness-based IoT [27], virtual object-based IoT [28], and IoT-based real-time analytics [29]. This survey provides a detailed explanation of the mentioned papers in terms of their contributions and future directions for further research. To the best of our knowledge, we are the first to provide a survey of existing papers published on IoT enabled technologies. In reality, no survey has been able to provide a comprehensive classification of the IoT enabled technologies with respect to smart cities, mining, fog computing, WSN, and cellular communications among others in a single paper.

This survey is organized such that Section II presents the outcomes of [25] in terms of data traffic, virtual power plant, emergency systems, and health systems. Section III outlines the output of [5] with respect to four layers, i.e., sensing, networking, cloud computing, and application. Section IV describes fog computing for IoT [19] with reference to three layers, i.e., cloud layer, fog layer, and device layer. Section V draws a sketch of data mining for IoT [26] classified into four technologies, i.e., clustering, classification, frequent patterns, and association rules. Section VI reports the WSN-based data centric IoT [3] with regard to different data aggregation mechanisms. Section VII summarizes the IoT-based cellular communications [1] considering the long term evolution (LTE). Section VIII elaborates context awareness-based IoT [27] relating to a wide range of applications and middleware solutions. Section IX delineates Virtual object-based IoT [28] in connection with historical evolution and current features. Section X illustrates the real-time analytics based IoT [29] in conjunction with wireless, wired, and hybrid data centers. Section XI discusses the learned lessons, and Section XII characterizes the future research challenges faced by IoT. Finally, Section XIII concludes the survey. The overall structure of this survey is portrayed in a very simplified manner through Figure 1, whereas their scope is presented in Table 1. Table 2 catalogs the acronyms and their definitions used in this survey.

II. IoT-BASED SMART CITIES

A smart city consists of information gathering, processing, and forwarding technologies that inspire the invention of tools for improving life quality [30]. A smart city covers a range of entities, such as transportation, health, infotainment, food, energy, and education. A smart city contains a number of classifications of end-users, for example, inhabitants, administration, business associates, and so on. Though, a number of surveys are available on smart cities, such as [3] and [31]–[40] discussing different overviews and architectures of smart cities, this portion elaborates the most recent survey [25] on smart cities. The survey in [25] consists of four main phases, which are discussed in the following subsections. The authors have illustrated demonstrative steps from different perspectives, for instance, traffic management, health systems, emergency systems, and smart grids. In addition, they have discussed initial implementations of the proposed steps in a smart city and underlined their actions. Furthermore, they have presented numerous research opportunities related to information gathering, users' privacy, and enabling technologies in the promotion of a smart city. Their survey is useful for smart cities related research because it carefully aids a measure for information processing in a secure and straightforward style.

A. TRAFFIC MANAGEMENT

The basic objective of a smart city is to offer state-of-the-art transportation and traffic services [31], which is recognized through a smart traffic management system. Smart traffic management focuses on providing inhabitants of a smart city

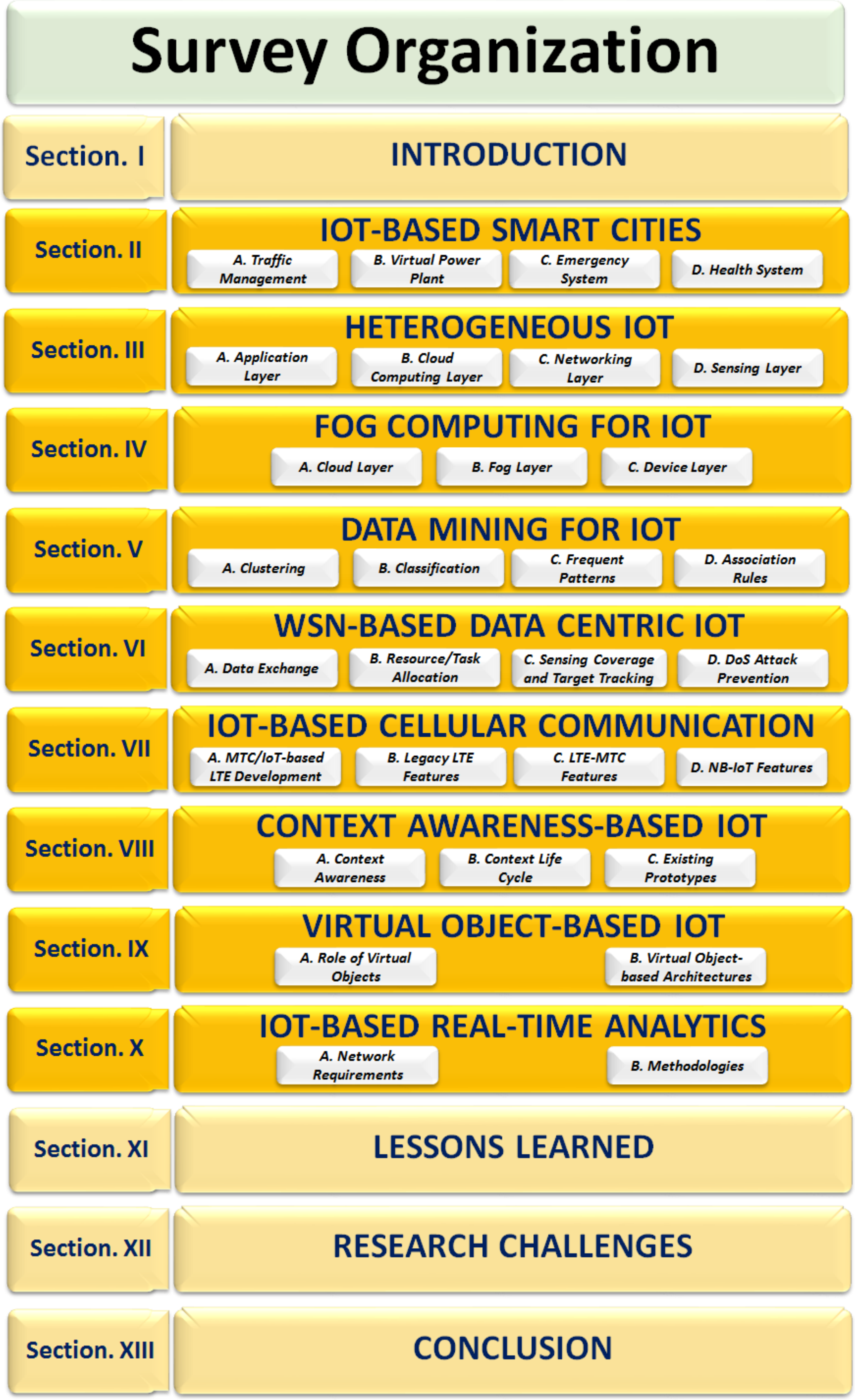


FIGURE 1. Structure of the Survey.

TABLE 2. Acronyms and their definitions.

Acronym	Definition	Acronym	Definition
BCCH	Broadcast Control Channel	OT	Operation Theater
BS	Base Station	PRACH	Physical Random Access Channel
CATM UE	MTC Category for User Equipment	PSNR	Peak-Signal-to-Noise-Ratio
CCTV	Closed-Circuit Television	PUCCH	Physical Uplink Control Channel
CLA	Context Lifecycle Approach	PUSCH	Uplink Shared Channel
C-RAN	Cloud-Radio Access Network	QoS	Quality-of-Service
CXaaS	Context-as-a-Service	RAN	Radio Access Network
DMRS	Demodulation Reference Signal	RFID	Radio-Frequency Identification
DoS	Denial of Service	RLC	Radio Link Control
ELA	Enterprise Lifecycle Approach	RSU	Road Side Unit
F-RAN	Fog-Radio Access Network	SDN	Software Defined Network
GPS	Global Positioning System	SRS	Sounding Reference Signal
H2H	Human-to-Human	SSE	Sum of Squared Errors
IOS	Internet Operating System	SVM	Support Vector Machine
IoT	Internet of Things	UII	Unique Item Identification
KDD	Knowledge Discovery in Databases	VANET	Vehicular Ad hoc Network
LAN	Local Area Network	VNI	Visual Networking Index
LSVM	Linear Support Vector Machine	VPP	Virtual Power Plant
LTE	Long Term Evolution	WSN	Wireless Sensor Network
MTC	Machine Type Communication	3GPP	3rd Generation Partnership Project
M2M	Machine-to-Machine	4G	Fourth Generation
NB	Narrowband	5G	Fifth Generation

with the information so as to be informed in a better way. This can cause selecting clever and harmless choices, and therefore benefiting from the transportation system. To better manage the transportation system, several skills can be exercised, such as vehicle navigation, regulating traffic signals, and motion circuits, which lead to combine real-time data that can be used for safe driving and parking guidance. A sketch of smart traffic management system is portrayed in Figure 2(a). With the help of moving vehicles or sensing tools, smart traffic management acquires transport related information. Moving vehicle information is obtained through several ways, such as smartphone-based monitoring and global positioning system (GPS).

Sensing devices-based system is the second way of obtaining traffic information. Sensing tools consist of inductive loop detectors, audio detectors, video detectors, or any other sensors. In the inductive loop detection method, a car is detected when it passes through the loop's magnetic area. The audio detection estimates traffic crowdedness through audio signals, which are produced by passing vehicles on the road. The video is detected through cameras fixed on poles near the motorways/highways. Presently, traffic data obtained via video detectors and inductive loops cannot be retrieved, publicized, and evaluated, as it is not fully developed and standardized. Thus, the standardization of this data requires a smart traffic management system so that it may then be analyzed and distributed for a safer drive.

B. VIRTUAL POWER PLANTS

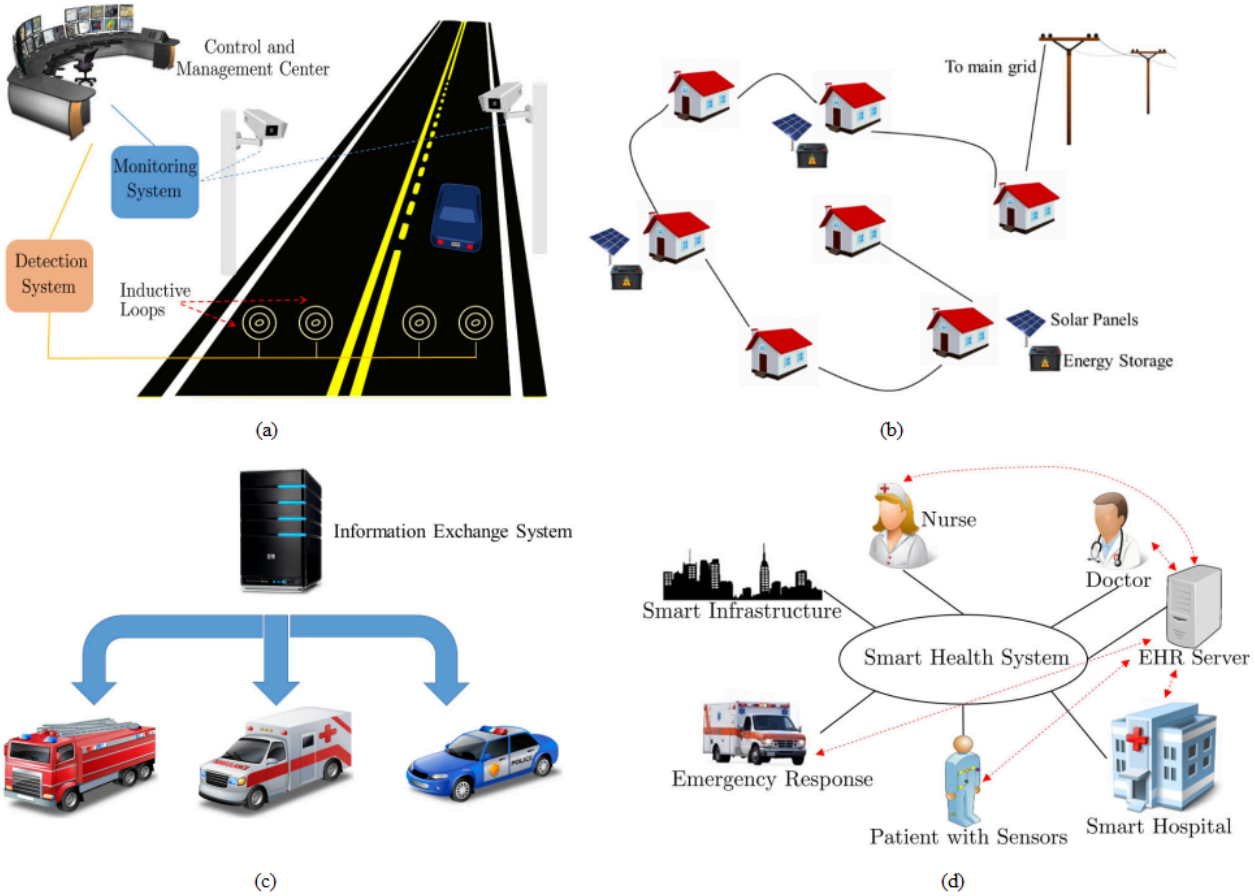
With the technological improvements and inventions of modern systems, for instance, smart meters and smart grids, over the last decade, have rationalized the maneuver of utility companies. To confront with the enforced regulations by the regulating agencies, for example, diminishing carbon emissions and supporting greater user mobility, utility companies need to form a balance among these regulations and deliver flexible facilities to the users at affordable cost [41]. virtual power plants (VPPs) [42], [43] are proposed to tackle challenges related to load reduction and pricing. A VPP is the combination of subscribers (domestic or commercial), demand response, and energy resources. The combination and categorization of subscribers allow the companies to predict and investigate the demands of subscribers in a better fashion and give way to the subscribers' profit that they contribute to the companies. The main goal of VPP in the smart city, i.e., resource gathering for load reduction, may be obtained by planting energy storage facilities to houses. Figure 2(b) depicts the operation of a smart VPP system.

Successful attempts in the development of VPPs familiarized VPP in Switzerland [44] and Germany [45].

C. EMERGENCY SYSTEMS

One of the objectives of a smart city is to provide security and protection to its citizens. To achieve this goal, a smart emergency system is needed which can be utilized for the implementation of law, detection of crime, and administration of accidents and natural calamities. For data aggregation, various tools have been developed such as traffic sensors and closed-circuit television (CCTV) cameras. This data, accompanied by analytical assessment, embraces the possibility of enhancing data quality used by hospitals, fire unit, and police department. The concentration of law implementation bodies is changing from recognizing individual offenders to organizing units on the basis of risk classes [46].

Generally, mass surveillance in a smart city gives rise to a number of advantages with respect to security and well-being. These advantages are gained by means of information collection through sensing devices and CCTVs [47]. Nevertheless, the persisting surveillance gives birth to privacy



(a) (b)

(c) (d)

FIGURE 2. A smart city that includes (a) traffic management scenario, which consists of sensing technologies for collecting vehicles' information; (b) virtual power plant scenario, which allows the utility companies for estimating and scrutinizing the subscribers' demands and create the value that the subscribers provide to the companies; (c) smart emergency system, which is used for the implementation of laws, detection of crimes, and prevention of accidents and natural calamities; and (d) smart health system, which includes different objects and technologies, such as wearable devices and sensors [25].

concerns due to the assessment of gathered information by one particular company. The combination of data exchange, big data analytics, and sensing tools are indispensable to institutionalize a smart emergency system. For the masses life safety in case of any natural calamity or accident, combining precise data and execution of this data swiftly in an accurate way and providing the appropriate company are mandatory. Thus, the establishment of a smart emergency system for the exchange of information among different organizations is of a great importance so that to allow quick responses and issue operation directives. Currently, Bhubaneswar city of India has deployed a smart emergency system, which consists of 114 CCTV cameras at 28 different locations [48]. Figure 2(c) exemplifies the implementation of a smart emergency system.

D. HEALTH SYSTEMS

To provide low-cost services in an efficient way, current healthcare systems experience considerable challenges. These challenges are more intensified by the growing aged citizens, which turn into a huge number of continuing diseases and more demand for a better healthcare provisioning [49]. Furthermore, due to limited resources in some cities, it is difficult to obtain a proper healthcare system. Therefore, existing healthcare systems require changes to transform into a smart healthcare system. Several tools and mechanisms, for instance, sensors and wearable devices, together make smart healthcare systems [50]. A smart healthcare system is presented in Figure 2(d).

Additional elements of a smart healthcare system include smart emergency systems and smart hospitals. Smart hospitals consist of tools that are used in operations, such as smartphones and cloud computing. The existing model for a smart health system includes sensor nodes which are installed near the body of the patient [51]–[53], or adjacent to it [54], [55]. Body sensors that are installed in the clothes, homes, etc., detect diseases, such as heart beat rate and blood pressure. With the aim of improving the healthcare system, different technologies require to be merged with sensor networks, for example, anomaly detection [56], [57], decision support [58], [59], behavioral pattern discovery [60], [61], and activity recognition [62], [63].

In Saensuk city of Thailand, a smart healthcare system was launched in January, 2016 with the collaboration of Intel and Dell. They started with the aim of providing health facilities to citizens [64]. In the first phase, old citizens were targeted in this project, which is almost 15% of the city population. The patients wear smart Bluetooth-enabled devices which collect and investigate the data related to sleeping, walking, and movements. The collected data is then sent to the city central cloud system, where medical practitioners prepare an appropriate report and thereby an essential action is performed on urgent basis.

The initial phase in the development of a smart city is the collection of data in the whole city through different tools. The most important aspects that are indispensable for fulfilling the citizens' needs are the quality of collected data and its usage. Different types of sensor devices are used in a sensor network for data collection, such as sensors for traffic management [65], sensors for VPPs [66], sensors for smart emergency [67], and sensors for smart health systems [68].

III. HETEROGENEOUS IoT

Heterogeneous IoT is a potential growing area of research [69], [70], which can change the life style of individuals. Heterogeneous IoT has been implemented in different fields, for example, VANETs, security systems, environmental monitoring, smart cities, smart homes, and manufacturing. Thus, depending on numerous application fields, heterogeneous IoT offers a number of promising amenities to our lives [71]. It consists of mixed network architectures, such as mobile network (i.e., 3G/4G/5G), wireless sensor networks (WSNs), VANETs, and WiFi. Due to the combination of these architectures, the absolute information can be achieved anywhere, anytime [72]. These architectures may further be connected to cloud servers through satellites or Internet, and passively send crucial information in no time to a distant server for processing [73]. The main server executes and investigates a huge set of information for getting the smart control of entities.

IoT is a complicated paradigm with various heterogeneous systems [74]. In the survey [5], the authors have proposed a heterogeneous IoT with four layers, i.e., sensing, networking, cloud computing, and application. In these four layers, everyone has a scalable and self-governing role. The collected information from different nodes are cached at cloud servers via well-organized heterogeneous network entities. These entities incorporate miscellaneous network models. Because of cutting-edge sensing devices and enhanced system architectures, heterogeneous IoT is applied in every field of life. The above mentioned four-layered architecture is presented in Figure 3 and explained in the following subsections.

A. APPLICATION LAYER

The application layer of the heterogeneous IoT consists of a number of applications, for instance, VANETs, WSNs, WiFi, and cellular networks. Mobile subscribers communicate freely with one another using mobile handsets via different applications, for example, WhatsApp, Skype, Line, WeChat, Facebook messenger, Yahoo messenger, etc. VANETs are employed in smart transportation for observing emergency traffic incidents. Humans, cars, and mobile handsets are connected and VANETs can make decisions on the collected traffic-related information. WiFi supports different protocols and is commonly deployed in smart cities, smart homes, and healthcare systems.

WSNs may observe environmental factors, such as sound, humidity, temperature, smoke, light, gas, etc. WSNs are employed in debris flow forecast and forest fire direction. Heterogeneous applications are utilized in everyday life and thereby require to allow simple and easy-to-use interfaces for the use of applications.

B. CLOUD COMPUTING LAYER

In heterogeneous IoT, the cloud computing layer is responsible for the retrieval and execution of information gained from other layers [75]. Cloud computing in the wide-ranging heterogeneous IoT can instantly handle the vast amount of information in an accurate manner. This is possible because cloud servers have controlling systematic computing capability. Besides storage capacity, cloud servers also have the ability to make decisions on the basis of obtained information. In addition, in certain critical heterogeneous IoT applications, cloud servers can take actions rapidly on the basis of emergency event-aware mechanisms. With the growing intensity of data heterogeneity, pungent decision making via active cloud computing is time consuming. Due to prevailing systematic computing capabilities, cloud computing has improved heterogeneity power in comparison to middleware. Middleware can defend the differentiations of distinct operating systems and different network protocols for providing high quality service for various applications.

Nevertheless, the majority of the common middleware services use an exclusive scheme, which is hard for obtaining the interoperability. Similarly, the middleware services have memory overhead and time delay constraints due to mismatched schemes of the subsystems. Cloud server as an abstract layer which gathers communication information for heterogeneous networks in a specific style.

C. NETWORKING LAYER

Heterogeneous IoT in the networking layer is utilized for drawing a professional network structure to forward data between the sender and the receiver. Thus, topologies such as tree, star, scale-free, and hybrid, are introduced to offer room for higher data transfers. Likewise, these network structures can transfer data to the cloud server(s) via super nodes, sink nodes, and other communication entities. Network topologies can also supervise the nodes through resourceful network strategies.

Various protocols have been designed for routing data in heterogeneous IoT. Therefore, network topologies have a number of challenges such as data throughput, energy

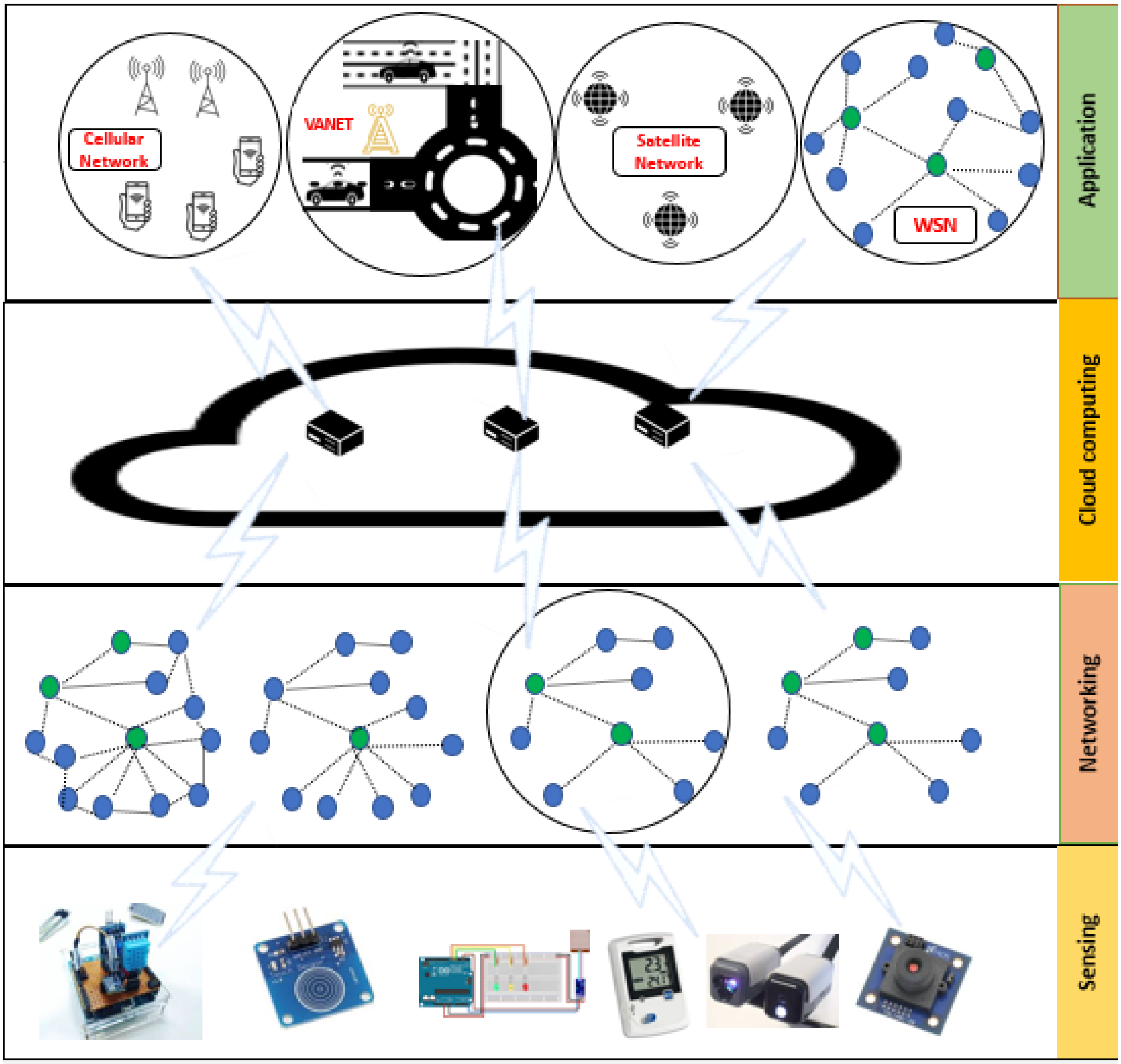


FIGURE 3. A heterogeneous IoT, which comprises four layers, i.e., sensing layer, networking layer, cloud computing layer, and application layer. The sensing layer includes cameras, flame sensors, gas sensors, sound sensors, environmental sensors, motion sensors, and color sensors; The networking layer consists of various topologies, such as tree topology, star topology, scale-free topology, and hybrid topology; The cloud computing layer consists of powerful servers, which receives data from other layers for processing; The application layer includes WSN, WiFi, VANET, and mobile network (Adapted from [5]).

consumption, and malicious attacks. Some protocols are self-structured, which help enhance the strength of network topologies in case of node failure. For forwarding a huge number of information to cloud servers, heterogeneous IoT requires higher capabilities of data transfers. In some places in heterogeneous IoT, such as hazardous locations, energy saving protocols are deployed for lengthening the network lifetime.

D. SENSING LAYER

Various sensors in the sensing layer of IoT collect data from different nodes and then it is provided to the cloud servers for decision making. A large number of sensors is deployed in a specific location and a topology is formed for the transmission of this data. A conventional network consists of sink nodes, sensor nodes, and management nodes. A sink node takes data from the sensor nodes and converts it into a multi-hop communication style. A network operator administers the sensor network and delivers observing activities via management nodes. Because of energy exhaustions and environmental effects, some of the nodes can die/disappear quickly and therefore alter the network structure. To guarantee network connectivity and provide an effective network model for data transfer, the redundant (wireless) communication links are subtracted by selecting the backbone node and power management.

To strengthen the network, several algorithms and mechanisms have been proposed [76]–[78]. Moreover, various sensors in the heterogeneous IoT model exist, which deal with the challenge of handling malicious nodes. One of the major weak points is privacy of the device location information. Therefore, smart sensors are deployed to enhance the privacy of heterogeneous IoT devices.

Since 1999, IoT has been penetrating in a fast speed into various manufacturing areas, for example, industry, agriculture, smart homes, transportation, healthcare, etc. Different IoT nodes are used in industrial productions, such as, in supply chain management, the applications of heterogeneous IoT are applied to the purchase of materials, stocks, and auctions. In agriculture, IoT devices are used to sense the temperature of greenhouse, conditions of soil, humidity, and other environmental factors. In smart homes, IoT devices are used to improve home safety and provide a congenial living environment [79]. Intelligent transportation is the need for the future vehicular communications, which simplifies data gathering, its execution, distribution, and exploration for travelers. In healthcare, the use of IoT devices plays an important role, ranging from the primary investigation of patients [80] to the operation theater (OT) [81], [82]. Heterogeneous IoT has stimulated the improvement of wearable smart devices [83] and revealed a new trend of mobile health.

IV. FOG COMPUTING FOR IoT

Cloud computing, a commonly used architecture, faces connectivity issues between the cloud servers and the edge nodes [84]. These issues are fixed at the Internet, however, for latency-sensitive applications this fixation does not seem suitable [85]. In the IoT paradigm, billions of devices can be connected for sharing information about home automation, environmental monitoring, and industrial administration. However, IoT confronts several challenges in information dissemination for some analytical applications, such as traffic management [86], home smart meter monitoring [87], and augmented reality [88]. For supporting these topographies, fog computing is incorporated into IoT to enhance computing resources and caching capacities.

Fog computing empowers processing at the network's edge, near the subscribers. It also endorses virtualization but, as fog does not function independently, this is linked with a cloud [84]. Fog computing incorporates astonishing attributes for a range of applications, which have been revealed in a number of papers [89]–[91] in terms of smart grids, connected vehicles, cyber-physical systems, and smart buildings. Pertaining to caching resources and computational capacities, fog and cloud systems are quite heterogeneous. Fog nodes may have restricted resources in contrast to cloud nodes. In addition, fog nodes might also have considerable variances in one particular fog domain. Therefore, it is extremely challenging for a fog system to tackle this heterogeneity. It is indispensable to take this heterogeneity into consideration at the architecture level as well as at the time of designing a specific mechanism for the deployment of application components [84]. Furthermore, the alliance of cloud and fog is inevitable to tackle the issue of heterogeneity, which has been reported in [92].

Fog systems are expected, in the foreseeable future, to cover millions of IoT nodes and thereby need adaptable scalability. This scalability can be ensured by alteration in the architectural modules. A number of fog computing architectures have been proposed for academia as well as industry. For example, Cisco has proposed a framework, called IOx, which merges IoT applications within a fog system and Cisco IOS for realizing fast and secure services. The IOx system provides reliable service hosting and information processing in Cisco switches, routers, and processing units. The OpenFog consortium was founded to build a fog computing-based open architecture, testbeds and working models, classify and improve technology via an open fog environment. Furthermore, a combined paradigm of radio access network (RAN) and fog computing, known as F-RAN [93], has been proposed for minimizing the provision latency with the utilization of local computing and signal processing, cooperative service administration, and distributed caching facilities near the subscribers [94]. A software defined network (SDN)-based architecture, called cloud-radio access network (C-RAN), was proposed in [95], which implements fog on top of the cloud to validate the interoperation of fog and cloud for 5G network. Due to these architectures, fog computing has been measured to provision different IoT networks and applications, such as energy management [96], healthcare [97], and augmented reality [98].

The architecture of fog computing consists of three layers, i.e., cloud layer, fog layer, and device layer, as shown in Figure 4. These layers are discussed in the following subsections [19].

A. CLOUD LAYER

The cloud layer in the fog architecture is a combination of caching and processing model that offers different IoT applications from a global viewpoint. The cloud has noteworthy processing capabilities and caching resources, and can be accessed anywhere, anytime by subscribers if they are connected to the Internet. The cloud uses virtualization technology for obtaining the segregation of IoT applications and information of different subscribers. These applications can freely provide various facilities to different subscribers at the same time. The cloud gets the precise information from different fog devices and employs global evaluation on the information submitted by these devices. It also executes information from other informants for advancing business perception in IoT applications [99], for example, optimization of network resources [100], smart healthcare system [89], and smart power distribution [101]. Moreover, the cloud provides guidelines to the underlying layer, i.e., fog layer, for enhancing the quality of delay-sensitive applications provided by fog devices.

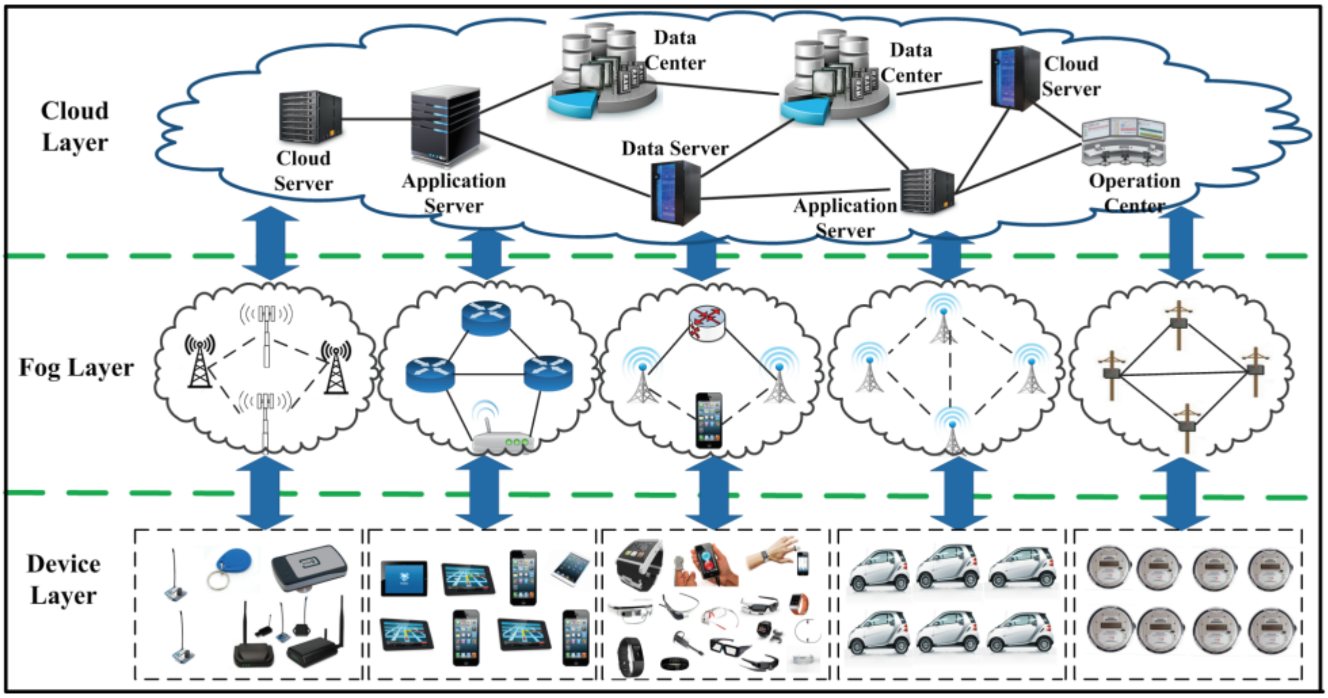


FIGURE 4. Fog computing for IoT applications consisting three layers: (i) Cloud layer, (ii) Fog layer, and (iii) Device layer. (i) The cloud layer consists of different servers, i.e., cloud server, application server, data server; and data centers and operation centers. (ii) The fog layer comprises various technologies ranging from Bluetooth to satellite links. (iii) The device layer includes mobile devices such as cellphones, watches, vehicles, etc.; and fixed devices, such as desktop computers, routers, and switches [19].

B. FOG LAYER

The fog layer includes network tools, for instance, switches, routers, base stations (BS), and gateways, equipped with processing capabilities. It also consists of fog devices, such as video cameras, mobile phones, industrial controllers, and embedded servers, which may be placed anywhere with network connections, i.e., on a road side unit (RSU), in a cellphone, in a car, or on the top of a power tower. These devices can be deployed in two ways, i.e., either in a hierarchical fashion between the cloud servers and the IoT nodes, or above the IoT nodes. The fog layer inclines to stretch the cloud computing facilities to the edge of the network. It has particular caching resources and processing capabilities to minimize computational overhead on resource-restricted IoT nodes.

Besides traditional routing and packet forwarding, delay-sensitive and real time applications may be transferred from cloud servers to fog devices. Because the applications are stored on fog devices only one or two hops far from the subscriber devices, they hold local knowledge about the devices and subscribers, such as subscribers' mobility pattern and overall information regarding the location. In addition, the fog devices provide different services without involving cloud servers, for example, smart traffic lights [102], vehicular navigation [103], and content dissemination [104]. The fog devices also provide temporary caching and real-time evaluation on the information gathered by IoT nodes. It sends reviews of data to the cloud via the forwarding of fog devices deployed at a higher level in the network order.

C. DEVICE LAYER

The device layer includes two kinds of IoT devices, i.e., fixed and mobile. The fixed devices are deployed in particular locations or in specific fields, such as radio-frequency identification (RFID) tags and sensors, to accomplish classified jobs, for example, air quality monitoring, forest fire detection, and goods finding. On the other hand, mobile IoT devices are carried by users, for instance, wearable cameras, sports watches, smart glasses, smart clothes, fitness shoes, smartphones, and vehicles [105]. A range of devices owned by one user can make a cluster and connect to each other via wireless ad hoc networks. Generally, these devices have restricted processing and caching capacities, and limited bandwidth [106] and thereby unable to answer to evolving events. The main goal of these devices is to gather information and provide it to the upper layer, i.e., fog layer. For establishing a smart city, different IoT devices (both mobile and fixed) are deployed throughout the city and required to be connected for gathering information and distributing among users when needed.

Fog computing allows IoT applications at the network edge by governing the edge resources. The primary advantage of fog computing is to deal with the IoT information by exploiting the fog devices located near the subscribers to result in the expediency of content caching, processing, distribution, and administration. Fog computing has the following five eminent advantages over the cloud computing [102]:

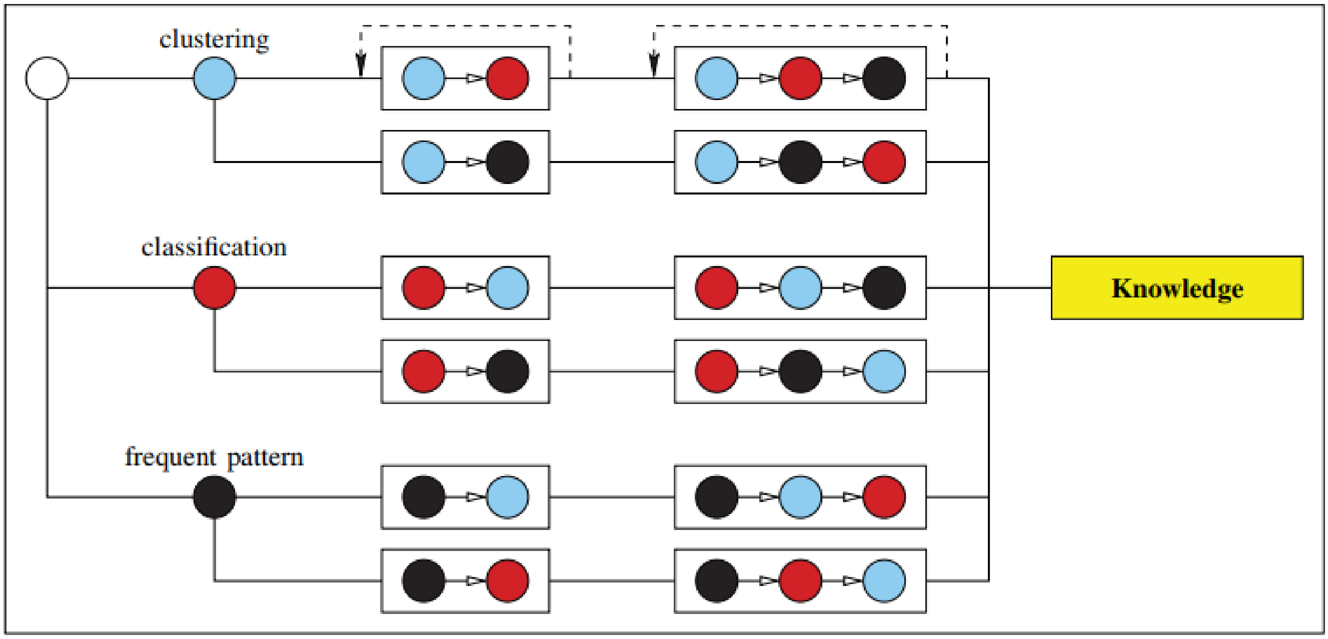


FIGURE 5. An example of combining different mining technologies, i.e., clustering, classification, frequent pattern, and association rules into a single system. The combination of these technologies is in such a way that clustering comes first, then classification, and then again returns to clustering and then classification; or it can be an iterative system of clustering, classification, and frequent pattern, where association rules mining is used for defining a particular pattern in the system [26].

- Location Awareness: where the location of fog devices may be traced to provide users with conveniences at the edge network.
- Geographic Distribution: where the nodes are placed at specified locations to ensure that the fog devices can receive good quality stream from the IoT nodes.
- Content Retrieval Delay: due to local caching and information processing, a content retrieval delay is much lower than the cloud.
- decentralization: no centralized server is required for administering computing resources [107].
- Application Support: large-scale IoT applications are supported, e.g., environmental monitoring and health management [89].

Furthermore, fog computing also provides real-time services, such as smart traffic lights [108], healthcare systems [109], car navigation [103]; temporary storage, e.g., content caching at the edge [100], software updating [110], management of shopping carts [111]; information distribution, i.e., gathering energy consumption [109], malware defense [110], local information dissemination [104]; and decentralized computation, for instance, computation offloading [112], [113].

Besides several features, fog computing is prone to attacks due to centralized content caching and processing systems. An attacker can instigate various attacks to interpose fog computing [114], such as spam, tampering, denial-of-service (DoS), Eavesdropping, and Impersonation.

V. DATA MINING FOR IoT

Data mining is a way of evaluating and clenching data into effective information. It encompasses inventing state-of-the-art and applicable models from a huge stack of information and utilizing different approaches to excavate secret data [115]. Data mining can be expressed via several terms, such as information extraction from raw data, knowledge discovery in databases (KDD), and pattern analysis and information harvesting [116]. In view of the fact that IoT signifies a new model for the Internet, it confronts several challenges, such as data gathering and processing [117]. To surmount these challenges, various data mining approaches have been proposed, as presented in [118]–[121]. The relationship between data mining and big data has been proposed in different papers, such as the idea of clustering data stream is presented in [122], and a distributed grid clustering technique for sensor data is presented in [123].

Data mining techniques are used for managing bulky data created by IoT devices [124]. In general, for a large-scale IoT system, the data mining technologies are supposed to be restructured, else, they can only be utilized for a small-scale IoT system that can merely generate a minute volume of data. In the last few years, several data mining models and algorithms have been designed [125]. For example, Zanin *et al.* [126] created a model for analyzing the aggregation of data mining and complicated network analysis [127], Chen *et a*l. [128] proposed an estimated algorithm for maintaining dynamic entities and attributes. The performance of data mining algorithms is largely affected by some operators, such as input, output, data scan, and rules creation and revision. The debate on different mining approaches is classified into the following four categories [26], as shown in Figure 5, so as to simplify the objectives of data mining for IoT. This categorization is either for improving the system performance or for offering better-quality services.

A. CLUSTERING

The issue of clustering [129] is commonly expressed as: Given a set of unlabeled patterns at a particular location, the output of an optimum cluster depends on a predefined value, for example, increasing the distance of inter-cluster and decreasing the distance of intra-cluster. The excellence of clustering result is computed on the basis of those applications for which a clustering algorithm is designed. For example, the peak-signal-to-noise-ratio (PSNR) and the sum of squared errors (SSE) are generally used for image clustering and data clustering, respectively [130].

One of the most popular algorithms for resolving hard clustering problems is the *k*-means [131]. To achieve better clustering results in the soft clustering problems, the *k*-means can also be combined with the fuzzy logic techniques. However, the design of new algorithms, for instance [132], has been slightly provoked by the *k*-means and its variants [133]. The *k*-means and its variants are utilized as local searching methods for finding clustering results. Unlike these algorithms, several heuristic methods have been proposed [134] that employ stochastic approaches to predict the clustering results. Heuristic algorithms, rather than local search methods, have a higher possibility to get better results in a large-scale and complex data set. The clustering results are not only measured on the basis of accuracy but also on two other aspects, i.e., appropriateness of the clustering for new situations and satisfaction of the problems' conditions. These surveillances bring about the formation of new clustering algorithms.

Clustering methods in the IoT environment use applications and services to decide a certain event, which raises another research issue of providing better-quality services. An appealing clustering application for smart home was proposed in [61], which focuses on digging the frequent patterns accompanied by identification of consumer behaviors

B. CLASSIFICATION

Classification [116], [135], [136], unlike clustering, requires some preceding information for guiding the practice of partitioning to develop a set of classifiers to characterize the patterns' distribution. In other words, comparing to clustering, which is an unverified learning practice, classification is an administered discovering process.

Classification algorithms are applied to design different classifiers, where the focus of classifiers is to demonstrate the dissemination of training patterns. Several algorithms, such as naive Bayesian classification [137], [138] and support vector machine (SVM) [139], have been proposed for the development of expedient classifiers [136]. The main goal of these classifiers is to increase the performance of the IoT system. Over the last decade, a number of applications and standards have proposed their own schemes for the IoT, which rises the issue of unique item identification (UII). For mitigating the UII issue, a tree-based classification scheme is proposed in [140], which abruptly identifies the type of an IoT node by checking only its few initial bits rather than checking the entire node's header.

The classification techniques can be divided into two groups (based on the region), i.e., indoor and outdoor. For the indoor IoT system, a number of applications have been industrialized, for example, a popular application was proposed in [141] for a smart home that identifies the human activities at home, and for smart healthcare, a technique for facial expression was proposed in [142] and a method for face recognition was suggested in [143]. On the other hand, the best outdoor example is the problem of traffic jam, which is commonly faced in big cities on daily basis. To avoid the issue of traffic jam, a drivers' guidance application was proposed in [144], which combines the driver's location information and vehicle's geographical information collected form the Internet for guessing the future traffic condition.

C. FREQUENT PATTERNS

The frequent pattern mining [116], [135], [145], [146] concentrates on two things, i.e., i) to expose the interested patterns from a huge amount of information, and ii) to keep the transactions in an order. Various researches have shown the potential and provided effective applications, such as intrusion detection [147], upholding privacy [148], and sequential data mining [149]. However, exploring and executing a huge amount of operations have grabbed the attention to a great extent in the last few years [150]. The most prominent research topic is how to handle billions of objects and RFID tags in an efficient manner to retrieve data from them in a smart IoT environment. Another noticeable topic is the spatial combination pattern mining [151]–[153] that is used to find the association between spatial combination patterns in the IoT system. To achieve this goal, amendment is required in the traditional association rule algorithms [152], [153], which include the features of spatial information.

A linear support vector machine (LSVM)-based system was proposed in [154] for enhancing the degree of precision of a system constructed for the prediction of behavior. Keeping in mind the operational cost of these systems with respect to response time, an algorithm was proposed in [155], which quickly responses in healthcare related issues, particularly for the aged citizens of the community. One more system was proposed in [156] to consider information obtained from the sensor networks for confirming the human conditions in an IoT network. A more significant system was developed in [157] that initially arranges the associations in a particular pattern and then these patterns are exploited for locating the services that the user may possibly need sooner or later.

D. ASSOCIATION RULES

Association rule is one of the famous methods for frequent pattern mining [116], [146], [158], which is typically employed for discovering the existing associations in a large database. The order of relations is a significant intricacy in the frequent pattern mining, which is known as sequential pattern [135], [145]. In contrast to sequential pattern, which aims at finding exciting patterns from a set of relations, association rule aims at determining exciting patterns from a particular relation [145]. Two survey papers, i.e., [158] and [145], elucidate the understanding of sequential patterns and association rules in a comprehensive form.

Corresponding to other methods for the association rules, considering the procurement entity invites the devotion of enterprises and researchers through the RFID or, more specifically, the IoT schemes. Schwenke *et al*. [159] developed a sophisticated scheme for defining the status of agents and the behavior of a consumer in a superstore. These behaviors include consumer's movement, action, and judgment. To determine the issue of consumers, i.e., unable to locate a particular product quickly they are in search for, certain consumer rules were combined with association rules and category-based rules into one specific purchase system in [160]. This system facilitates consumers to locate the products quickly in a superstore. Recent papers [161], [162] improve the performance of the *k*-means algorithm to categorize the actions to design a standard combinational architecture for every action prior to employ the association rules.

Deploying data mining techniques is a feasible approach to constitute a system think as a human or make it smart. However, this is still a complex task to make it function as presumed, which is the same as to attempt to constitute a computer think by itself. Before designing an appropriate, sophisticated, and flexible IoT system using data mining techniques, it is indispensable to identify the major problems it faces.

VI. WSN-BASED DATA CENTRIC IoT

A wireless sensor network (WSN) is the leading module of IoT that folds surrounding information and sends it to the main server for its execution. However, unlike traditional WSN, IoT-based WSN needs to be smarter [163]. Particularly, IoT-based WSN does not only execute ordinary tasks, for instance, collecting environmental data, but also perform important functions with least human involvement. Moreover, administering billions of IoT sensing devices leads to numerous challenges with respect to economical deployment and appropriate processing. Therefore, the deployment of smart algorithms is desirable so that to provide elasticity in the adaptation of dynamic IoT systems. The most widely deployed IoT algorithms, rather than optimization-based algorithms, are pricing and economic based approaches, which offer the following characteristics:

- Profit generation: Generating revenue is the most vital feature of the IoT economic approach, which should get the best out of the cost and revenue incurred.
- Entities interaction: The IoT elements, due to their different entity locations, have distinct goals and restrictions. Thus, to establish the best possible interactions among these realistic and self-centered entities, pricing approaches are familiarized.
- Payment strategies: Crowdsensing paradigm is deployed in the IoT for collecting information from moveable smart sensors. Therefore, flexible payment strategies must be employed to catch the attention of customers to provide their data so as to ensure the precision of sensing results.
- Pricing models: Exercising pricing models, such as auctions, or economic rules allow choosing sensing devices with maximum power and processing capabilities to execute sensing tasks and thereby ensure extending the network lifetime and minimizing the data redundancy as well as the computational overhead.

Various IoT paradigms have been proposed in the literature [164]–[167], which provide sufficient knowledge about the stated characteristics. The WSN-based data centric IoT survey [3] focuses on the following four issues: i) Data exchange, ii) Resource and task allocation, iii) Coverage and target tracking, and iv) Denial of service (DoS) attack prevention pertaining to economic models. These modules are discussed in the following subsections in detail.

Figure 6(a) shows a basic model of data collection in the WSN, which includes sensing nodes, a sink, and a mobile collector. The mobile collector is used to combine information from different sensing devices and send to the sink node through wireless links. Because of the capacity and energy restrictions of wireless channels and sensing devices, enhancing the network lifetime and energy efficiency are the utmost essential challenges [168]. Nevertheless, they also have to assume the basic quality-of-service (QoS) such as a high quality of data and low delay. Due to this conflict, the pricing and economic models have grasped the attention of the WSN research devotees. Figure 6(b) shows mobile users to send their information to the buyers through the platforms (servers). Using this model, the server broadcasts the collected information to all users (sellers), and then the interested users perform the sensing process. As the sensing process is completed, the sensed data along with the related prices are sent to the server. Finally, the server selects a group of users with the lowest requested prices and makes the payments.

Figure 6(c) shows a basic sealed-bid reverse auction model, whereas Figure 6(d) demonstrates the data aggregation model. The buyer (platform) splits the budget and the task deadline into various small-scale budgets and periods. The sellers (mobile users) find their particular appropriate periods and send their information to the buyer. Corresponding to the sellers' contributions, the buyer specifies the number of winners (using auction) and the price limit for the upcoming period. Later, the seller matches its cost with the price limit, if the price limit is higher than the cost then the data sensing task is accepted.

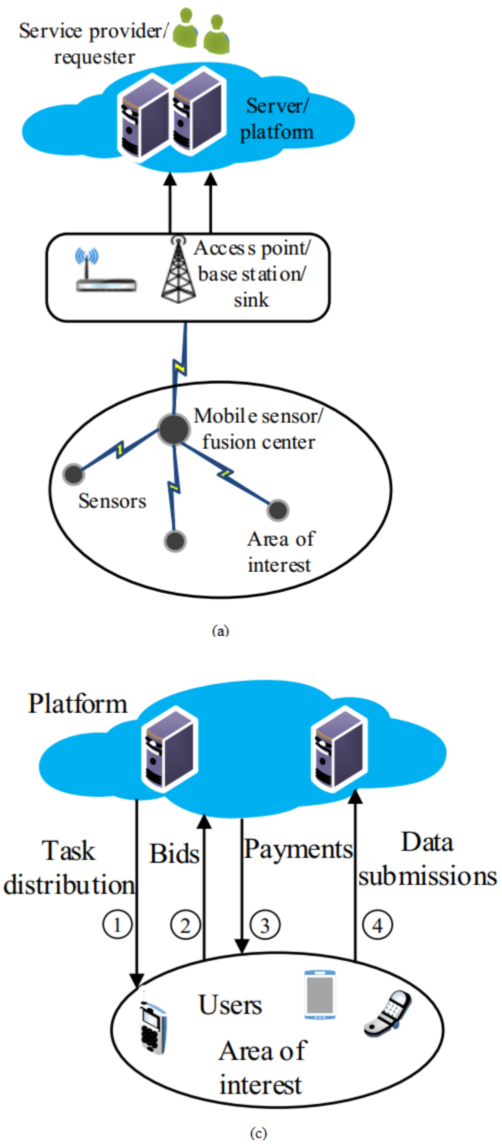


FIGURE 6. Data collection in (a) WSN, which consists of one access point at the requester's side for pricing. The data selling price is divided into two phases at the access point and sink. The price about the quality of data and its durability is set by the sink on the basis of requesters' expectancies. (b) Data collection in crowdsensing network, where users' sensing data is provided to the service provider through their cellphones. (c) Data collection in a sealed-bid reverse auction. (d) Data collection, where the service provider splits the budget and the targeted work into various small budgets and periods [3].

A. DATA EXCHANGE

WSNs usually contain a huge number of sensors for performing different tasks in a particular filed. The coordination of these sensors establishes a hierarchical or homogeneous network. The primary job of sensors is to collect information, process it, and then send it to the main controller, i.e., a sink node or a base station. A node in the WSN can forward its information to the sink node either directly or through other nodes. However, the routing paths or network structure may change occasionally, i.e., when a new node enters the network or an existing node dies then the position of nodes changes, which is known as topology formation. Therefore, for data collection and topology formation, several algorithms have been proposed in the literature, for instance, compressed sensing [169], location estimation [170], and distance vector [171] algorithms. These algorithms focus on data aggregation, topology formation, and efficient energy consumption with respect to pricing and economic models.

In the pricing and economic models, most of the collected information is sent to the server via cellular networks [172], i.e., a single-hop 3G or 4G [173]. Nonetheless, because of the cellular network cost or its bandwidth limit, it is not convincingly economical [174]. Thus, to realize the minimum transmission cost and maximum energy efficiency, opportunistic networking is feasible. Such mechanisms have been proposed in [175] and [176], which are designed to minimize the global system cost. The proposed model in [175] urges the sellers to send their data to nearest nodes by following the shortest communication paths. Likewise, [176] implements the cost-based pricing for calculating the cost of packet delivery between the sender and the sink node. The proposed model integrates courier nodes and wireless relay nodes and hereby saves resources by forwarding critical data with respect to packets' price.

B. RESOURCE AND TASK ALLOCATION

Computational resources in WSN, such as node caching size, processing power, and battery life, are very limited, therefore, resource optimization has become a yet-to-resolve issue. Conventional resource allocation schemes usually deduce that the existing network resources, for instance, bandwidth, cannot be replaced. Quite the reverse, the total existing system resources and transmission paths in the WSN are continuously changing. To provide solution to this problem, pricing strategies are employed with the flexibility of resource budget. Pricing strategies are best suitable for enhancing the communication power level of sensing devices.

On the other hand, task allocation is used to allocate sensing tasks to particular network nodes to perform certain operations. The two main objectives of the task allocation strategies are to reach a reasonable energy level among the devices and minimize the transmission time. Price formulation is the elementary remedy to the mentioned problems as it can constantly adapt to changes concerning the available resources.

Conventional resource management strategies are used to assign resources to the sensing devices in a static fashion. However, as the requirement and allocation of resources are typically not the same, conventional strategies do not satisfy the users' requirements [177]. To address this problem, market-enabled pricing mechanisms can be used by establishing an artificial market so that the sensors may exchange their resources dynamically. To determine the market balance, demand and supply models are deployed [169]. The allocation balance can only be achieved with a single iteration by instituting a delay buffer, as various iterations of the demand and price messages are exchanged between the provider and the sensor nodes. To provide users with information of a higher bandwidth cost, the smart data pricing is applied to manage the flow control and the data transmission rate [178]. Furthermore, the resource balance among sensing devices can only be obtained if the existing resources, e.g., energy, are taken into consideration in the price function.

In contrast, task allocation strategies focus on distributing tasks in particular sensing devices for execution. Static task allocation strategies may not fulfill the goal because network elements lack interactions in the WSN environment. Thus, dynamic task allocation strategies are the best solution for node interactions in the network, which also aim at the optimization of task assignment and utilization of resources. The first-price sealed-bid reverse auction [179] is one of the widely used task allocation schemes, which includes sellers and a buyer for executing a specific task.

C. SENSING COVERAGE AND TARGET TRACKING

In various WSNs, sensing coverage is a vital module which determines that how good a sensor observes the physical occurrence in a network. Several approaches have been designed for maximizing the sensing coverage, as in [180]–[183]. There are three basic types of sensing coverage, i.e., i) area coverage, ii) barrier coverage, and iii) target coverage [180].

The area coverage quantifies the vicinity of a covered sensing filed. In this module, static sensors are deployed and the uncovered area is rectified by choosing suitable mobile sensors through economic models. The barrier coverage is concerned with discovering an ingress route in the WSN with the goal to detect any intruders that try to enter the field. The target coverage is used to cover a group of distinct targets so that to extend the range of sensors for covering attracted targets. The target coverage focuses on covering all targets by adjusting the sensing area of each device. However, if the sensing range of a sensor increases, several restrictions can be faced, for example, sensing overlap and energy consumption [184].

The object tracking is a significant unit of the WSN in supervising applications. The central object categorization and recognition practice may be cost-effectively executed by controlled machine learning procedures [185]. To enhance the chances of object recognition, economical models are utilized to envision the future sites of the targeted items and to arrange the sensing devices in a resourceful mode while ensuring the tracking property.

D. DoS ATTACK PREVENTION AND PRIVACY MATTERS

Due to the nature of node deployment, WSN is prone to security threats. Different security algorithms for WSNs are categorized and assessed [186]. However, conventional algorithms lack communication between the WSN owners and attackers [187]. Because of this reality, economical models are proposed to concentrate on the privacy and security issues in the WSN with the following methods: DoS attack prevention and privacy concerns. A DoS attack is a pre-planned action of different devices with the purpose to intrude or disturb the WSN services. For this reason, pricing schemes are used to identify and quarantine the attackers. Privacy includes problems concerning delicate data of mobile users in the data collection [188]. In reality, the aggregated information can have the position statistics that may expose private information [189]. Therefore, pricing models are the suitable options for the protection of users' privacy.

A secure WSN routing algorithm is proposed in [190], which is based on the first-price sealed-bid auction to separate malicious nodes. The deployment of crowdsensing is a challenge in the WSN as it can expose the private data of a user, for instance, home address. Therefore, economic models and pricing schemes are useful to control the privacy of users. Privacy-preserving schemes are used to ensure that the information of users is not linked with their identities [191]. Considering the problem of privacy protection, a seal-bid second-price reverse auction is proposed in [192], which requires users to submit only their requested prices with unclear positions. A second scheme is proposed in [193], where user requests (prior to submission) are encrypted though a cryptographic scheme.

VII. IoT-BASED CELLULAR COMMUNICATION

In the past, generally ''voice'' had been used as the source of interaction among humans, known as human-to-human (H2H) communication. Hence, the present network architecture and algorithms are designed for human-oriented transmission properties. Today, a totally changed communication architecture has been revealed with the exposition of ''machines'' in the infrastructure [194]. The transaction of information by any device is acknowledged as machine-to-machine (M2M) communication [195]. Accordingly, due to excessive Internet traffic, it is presumed that the Internet accessing devices are on the rise in the near future. This phenomenon is verified by the IoT structure being certified to approve a huge amount of devices for information exchange without the interaction of humans [106]. The network model should be sufficiently adaptable to cope with the network requirements as well as additional features.

A significant number of studies have considered the existing technologies in this respect, for example, WiFi (IEEE 802.11b), Bluetooth (IEEE 802.15.1), and ZigBee (IEEE 802.15.4) by combining machines in the shape of a huge heterogeneous network [196], [197]. Even though the mentioned technologies are widely deployed these days for particular applications as M2M communication, these technologies are very limited in covering the communication area [198], [199]. In addition to coverage area, process execution on unlicensed spectrum pushes these technologies to implement sensing procedures. Albeit these are not the reasons to discourage the technologies of local area networks (LANs) for enabling the IoT and machine type communication (MTC), it may enforce the coordination strategies to fulfill the requirements of IoT and M2M [200]. Due to offering flexible transmission rates and considerable coverage by cellular technologies, research attempts have motivated the optimization of current cellular systems taking into account the M2M requirements [201]. Among the feasible advancement, the well-known commercial paradigm, e.g., Sigfox [202], accompanied by the expansions of the existing cellular systems, for instance, the novel classifications of LTE, are considered. In the following subsections we discuss the LTE-IoT with respect to MTC and narrowband (NB) characteristics [1].

A. MTC/IoT-BASED LTE DEVELOPMENT

Despite the fact that data transmission in the cellular networks has been increasing for the last few years, cellular networks are generally used for H2H communication. Nevertheless, M2M traffic qualities are distinct from the human generated data in the cellular networks. For example, the downlink data rate in the M2M communication is lower than the uplink compared to human traffic [203]. Also, mobility in human devices is much higher than mobility in the M2M devices [204]. In consequence, special considerations are required for M2M devices in accessing the medium and therefore the access methods need to be revisited [205]. As IoT devices usually transmit a small amount of information and need broad coverage, a distinctive class namely NB-IoT, has been merged with the LTE for reinforcing the IoT characteristics [206]. The design goals for this particular class need minimum overhead, improved battery lifetime, and broad coverage. In addition, reiteration of the signal is deemed as the major element for offering performance improvement [207].

The 3rd generation partnership project (3GPP) standardization forum, from the physical layer view, has provisioned the accuracy of LTE to certify MTC communication over the LTE network. The main goal of this communication, as reported in several studies such as [208]–[210], is to provide broad coverage for MTC devices in demanding areas and also to extend the battery lifetime with consuming very little energy.

B. LEGACY LTE FEATURES

The most prominent goal of the LTE standard is to develop a flexible and modernized communication model. Several dedicated links quantified in the former 3GPP standards have been substituted by shared links and the overall amount of physical links has been considerably minimized. Logical channels signify the connections and transmission rate between the media access control (MAC) layer and the radio link control (RLC) layer. Two different kinds of logical channels are defined in the LTE, i.e., control channels and traffic channels. The control channels are used to send the important signaling for maintaining connectivity, while the traffic channels are utilized for sending users' data. The physical channels are handled at the physical layer, whereas the transport channels are used to connect physical layer to the MAC layer. The downlink and uplink shared channels are the most vital kinds of transport channels and are exploited for data transfer in the uplink and downlink. These physical channels are mapped to their corresponding transport channels. The uplink and downlink transmissions in the LTE are different with respect to physical channels, logical channels, and transport channels.

There are three uplink specifications for the LTE physical channel, i.e., physical random access channel (PRACH), physical uplink control channel (PUCCH), and physical uplink shared channel (PUSCH). The PRACH allows access to the network, the PUCCH carries the uplink information such as packet requests acknowledgements, and the PUSCH holds user information received from the user devices. In terms of uplink signals, the LTE clutches two standards, i.e., the sounding reference signal (SRS) and the demodulation reference signal (DMRS) [211]. The downlink channels in the LTE are divided into four categories, i.e., i) the dedicated control channel (DCCH), ii) the common control channel (CCCH), iii) the paging control channel (PCCH), and iv) the broadcast control channel (BCCH). All these channels, except the PCCH, are combined to develop a transport channel called the downlink shared channel (DSCH), which is used to provide data to the higher layers.

C. LTE-MTC FEATURES

The legacy LTE is different in performance from the MTC user devices, therefore, the MTC category for user equipment (CATM UE) class is recently tied for the MTC transmission. In order to improve low power consumption and enhance the coverage area, a number of approaches have been proposed [212]. Reduction in power consumption is also essential for the LTE-MTC UE to improve the battery lifetime. The most vital characteristic of the new category is to enhance the LTE coverage, which can be achieved by different proposed methods. To minimize the system cost and computational overhead, more restrictions are put on the MTC UE category. In this category, the bandwidth of a particular base station is distributed one time and is used during the entire operation. Hence, this is a better option to utilize a bandwidth element that may be a generic divisor of the existing bandwidth preferences in the legacy LTE.

Due to the usage of a single receiver procession and a little bandwidth provided to the MTC UE, the frequency diversity is removed. The concept of frequency hopping is appended to the LTE-MTC technology in order to recover some of the lost frequency range [213]. To explore it more, the MTC transmission jumps from one NB to the other to utilize different transmission channels and thus offers frequency ranges.

D. NB-IoT FEATURES

Because of the limited and inadequate resources, frequency ranges must be deployed in an economical fashion. For achieving frequency spectrum in an efficient way, the NB-IoT has been proposed with a variety of designed choices for the LTE spectrum [214]. The deployment scenarios can be divided into three categories, i.e., Stand-alone operation, In-band operation, and Guard-band operation. The first one is only envisioned to exchange the GSM (global system for mobile communication) carrier with an NB-IoT carrier. To transfer a certain amount of GSM data to the LTE network, some of the GSM carriers may be utilized to carry the IoT data. As the NB-IoT and the LTE are completely assimilated with regard to spectrum usage and system architecture, the LTE can be used for the in-band deployments without the IoT data. To support the entire elastic model, the in-band operation assumes that the NB-IoT carrier has similar cell IDs. The guard-band is applied in the LTE in order to avoid interference. The LTE guard-band in collaboration with the NB-IoT is taken into consideration during the physical layer design of the NB-IoT.

Two main modes of search spaces are classified for the NB-IoT, i.e., specific search space (SSS) and common search space (CSS). Same as the LTE-MTC with enabled reiterations, the NB-IoT offers the description of the search spaces. For the in-band backward compatibility of the NB-IoT operations, 15KHz subcarrier spacing is needed for the downlink transmission. Therefore, the NB-IoT sub-frame duration, slot duration, and downlink symbol duration are recycled from the legacy LTE. To uphold elasticity and compatibility in the definition of both 15KHz and 3.75KHz modes, the idea of resource unit (RU) is established for the NB-IoT so that to offer the necessary structure for resource mapping [215].

VIII. CONTEXT AWARENESS-BASED IoT

Context awareness is the basic property of pervasive and ubiquitous computing systems that has been in use for more than two decades. The emphasis on context-aware computing [216] moved forward from ubiquitous/pervasive computing, mobile computing, and desktop and web applications to the IoT since late 2000. Nevertheless, context-aware computing grew up into attraction with the publicity of ubiquitous computing [217], [218]. Since then, context-awareness related studies have been launched as renowned research topics in Information Technology. Numerous researchers have suggested descriptions and elucidations of various attributes of context-aware computing. The idea of context-awareness was proposed in 1999 by Abowd *et al.* [219], which has been unanimously acknowledged by the research community. In the last few years, a number of systems, models, and solutions have been proposed by different research forums corresponding to context-aware computing. The IoT foresees a time where billions of tiny devices would be connected to the Internet, which indicates the inconvenience to execute the aggregated data by those tiny nodes. Thus, context-awareness will perform a feasible role in determining the identification of data to be executed among other responsibilities, which are discussed in the following subsection in detail [27].

Figure 7 illustrates the taxonomy and various other qualities, which may offer significant importance in the IoT solutions. The proposed model [27] consists of the following modules: i) architecture that may be of various types such as component based, centralized or distributed, node or service based, ii) the level of context awareness would be either high (i.e., software level) or low (i.e., hardware level), iii) it must ensure the privacy as well as security, iv) the dynamic composition should be available without forcing the developer or customer to recognize particular devices or sensors, v) the communication is supposed to be managed in real time, such as event detection, context discovery, tracking, and annotation, vi) the functionalities of lookup facilities and registry maintenance should be present, vii) it must follow standard communication protocols, data structures, caching, and modeling techniques, viii) it should carefully manage resources such as energy, storage, and processing.

A. CONTEXT-AWARENESS

The word context has been delineated in several studies [218]–[227]. The definition provided in [218] is based

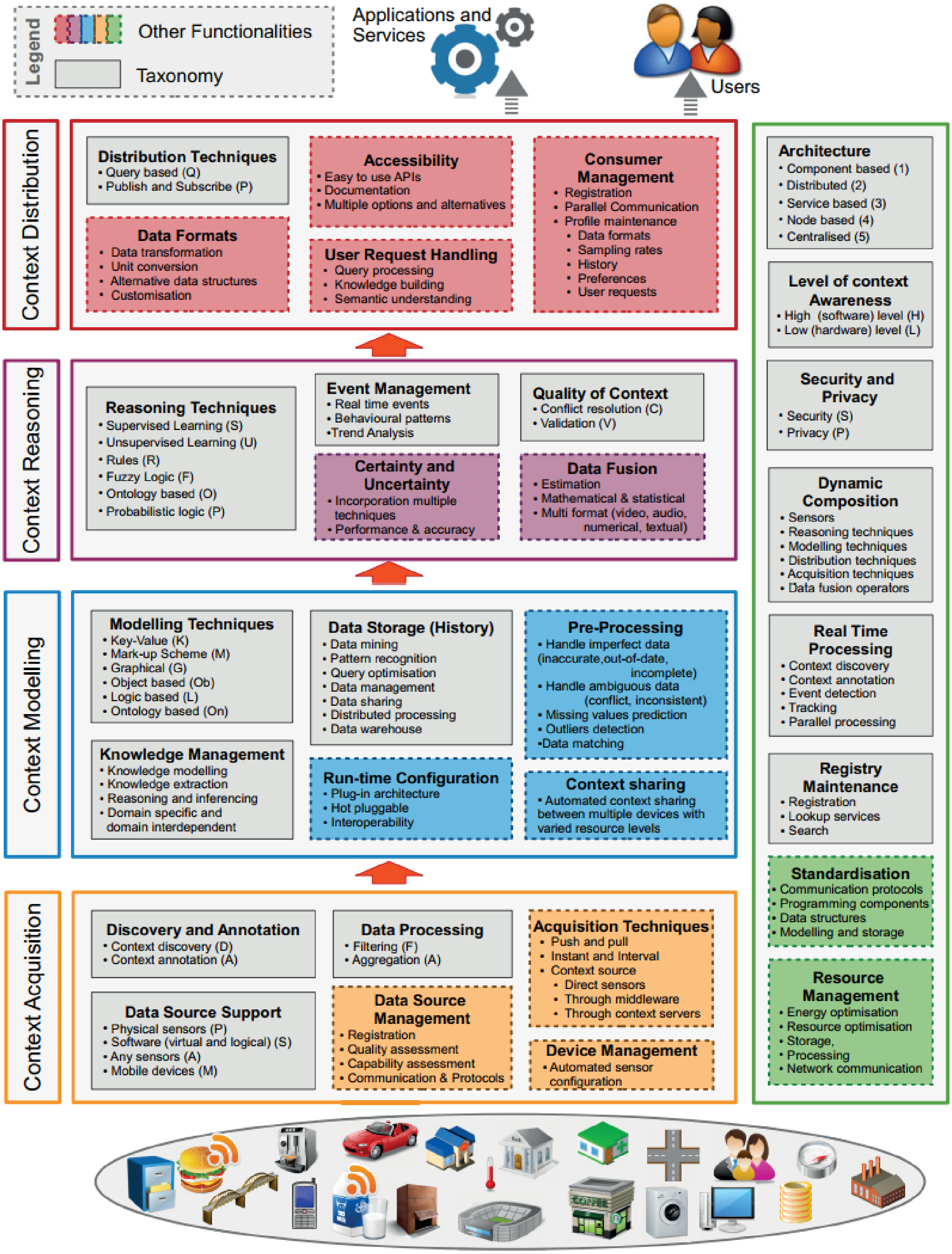


FIGURE 7. The context-aware taxonomy of the IoT middleware, which includes: i) context acquisition that performs the following duties: context discovery and annotation, information gathering and filtration, device support and management, caching and data processing, and standardization of protocols; ii) context modeling, which manages information through modeling techniques, caching the history of information, and maintaining the history in line with real time processing; iii) context reasoning: supervises the reasoning techniques, real time events, context quality, data fusion and performance accuracy, and user/data privacy and security; iv) context distribution: gives formats to the data through various algorithms, handles user requests and provides accessibility, and manages consumer registration as well as architectural components [27].

on hypothesis [27] that cannot be used to identify the new context [220]. The definition provided in [221]–[224], [226], and [227] use synonyms words, i.e., situation and environment, to signify the context and thereby cannot be used to indicate new context. To understand ''context'', the study in [225] denotes the five W's, i.e., What, Why, When, Who, and Where, as the smallest amount of information for identifying context. Dey *et al.* [220] argued that the provided delineations are too specific and therefore cannot be utilized for the context identification in a generic form. Thus, they provide their own description of context as follows:

"Context is any information that can be used to characterize the situation of an entity. An entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves [219]."

While the term context-awareness is defined as:

"A system is context-aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task [219]."

Furthermore, context model and context attributes are defined in [228] on the basis of [219] as:

"A context model identifies a concrete subset of the context that is realistically attainable from sensors, applications and users and able to be exploited in the execution of the task. The context model that is employed by a given context-aware application is usually explicitly specified by the application developer, but may evolve over time [228]."

"A context attribute is an element of the context model describing the context. A context attribute has an identifier, a type and a value, and optionally a collection of properties describing specific characteristics [228]."

B. CONTEXT LIFECYCLE

The lifecycle of information shows that how information is delivered from one software stage to the other. Particularly, it shows that where the information was created and then where it was utilized. Pertaining to context movement, context-awareness is not only restricted to mobile, desktop, or web applications, but has turned into a service, i.e., context-as-a-service (CXaaS) [229]. Especially, context management has grown to be a crucial component in the software design and has thereby industrialized in the IoT environment. Information lifecycle can be categorized into two classes, i.e., context lifecycle approach (CLA) and enterprise lifecycle approach (ELA) [229]. The prior is a specialized context management approach but is not standardized, while the latter is a generalized approach for industry standard strategies that are used for data management.

A conventional context management includes three stages, i.e., context acquisition, information processing, and decision making [230]. In addition to these three stages, one more stage, i.e., context reasoning, is added in [27]. In the context acquisition stage, information is collected from different sources, i.e., virtual or physical sensors. The aggregated information is then modeled into a meaningful form, and the exhibited information is processed in the context processing stage. In the context reasoning stage, the modeled information is processed to obtain a high-level information from a low-level raw data. Last, the processed information is distributed among the interested consumers in the decision making stage.

Context acquisition is based on five modules, i.e., context source, frequency, responsibility, acquisition process, and sensor types.

- Based on Source: Context acquisition techniques can be classified into three groups [231] on the basis of context location. That is, the context may be acquired directly form sensor devices, from context servers, or through middleware.
- Based on Frequency: Context in the IoT environment can be generated on the basis of events, i.e., instant event that occurs instantly, or interval event which happens after a specified period of time.
- Based on Responsibility: Context acquisition is achieved via push and pull methods [232]. In the first method, a sensor device pushes information to the software unit which is responsible for data acquisition. Whereas in the pull method, the responsible software unit acquires information from different sensors via sending request messages either instantly or periodically.
- Based on Acquisition Process: In this module, the context is acquired by (a) sensing it through sensing devices, (b) deriving information through computational processes, or (c) providing information manually through predefined preferences setting.
- Based on Sensor Types: In this module, the context is obtained through various kinds of sensors [233], such as virtual sensors, logical sensors, or physical sensors [234].

C. EXISTING PROTOTYPES

Administering context in the IoT environment needs middleware solutions, which may offer robustness to information management. Middleware applications must be developed in such a way that have the ability to request context from the middleware. The Context Toolkit [220] has familiarized the idea of owning standard interfaces. Standardization allows to realize, practice, and expand the toolkit, which is influential in the IoT environment as it boosts the extendibility and interoperability. It also allows to attach various elements when required and therefore guarantees a simple communication between the old and new added elements. Moreover, Intelligibility Toolkit [235] gives descriptions to customers to ensure trust between the context-aware applications and the customers. It helps in rapid acclimatization of customers towards the IoT.

Mobility monitoring is a significant task in the IoT, where users shift from one state to the other and the IoT solutions require to follow these movements and enable context-aware features over various types of sensors. Aura [236] demonstrates the need of allowing IoT middleware to run over different sensing devices.

MoCA [237] underlines the context confirmation that has a great effect on the precision of reasoning. CROCO [232] authenticates the user privacy, which has been rarely taken into consideration by several other solutions. SOCAM [238] indicates that how information can be divided into various phases of ontologies. TRAILBLAZER [239] and EMoCASN [240] express the significance of injecting context-aware abilities in the hardware layer. One of the primary attempts to build the IoT middleware is Hydra [241], which concentrates on linking embedded devices to applications and represents that how the context modeling can be accomplished so as to model the device information. Context-awareness authorizes sensing devices to perform flexibly and save the energy. In the IoT environment, the communication is presumed to take place between the devices, thus, context-awareness turns into intensity for each particular entity to improve their activities. To conclude, context-awareness plays a fundamental role in information matching where sensing nodes may deemed as entities [242].

IX. VIRTUAL OBJECT-BASED IoT

As mentioned earlier, referring to Cisco's visual networking index (VNI) [20], the number of IoT connected nodes will reach 27 billion by 2021, it would need an infrastructure that provides flexibility and agility. Hence, virtualized cloud is the only option to tackle this issue of accommodating the massive number of IoT devices. With the big picture of IoT, which allows things or objects to communicate with each other easily, the concept of virtualization was evolved in the IoT system. To develop a smooth communication between the real and virtual world, the researchers draw attention to the virtual objects. In the early 90s, the word virtual object was composed of two interlinked objects, i.e., virtual and object [243], in order to improve the physical objects with digital information. The virtual object acts as a *"substitute for the real object"*. In other words, it performs as a bridge between the real and virtual world. It has the ability to develop, analyze, and interpret the information to provide quality benefits for the associated services.

Two exciting examples of the virtual object's evolution are IoT-A [244] and SENSEI [245]. The virtual objects, known as entities in IoT-A and resources in SENSEI, become aware of the situation in which the physical objects operate and then get the expertise to improve the obtained information. Furthermore, these projects suggest schemes to arrange IoT services so they provide flexible features to the application or to the user corresponding to virtual objects. In brief, for the successful deployment of IoT applications in large environments, virtualization is the best solution for ubiquitous infrastructure [246] and co-existence of distinct networks [247].

Virtualization architecture is composed of three layers, i.e., the application layer, the virtualization layer, and the physical layer, as depicted in Figure 8. These layers are discussed in the following subsections [28].

A. APPLICATION LAYER

This layer works as a cloud and lies above the virtualization and the physical layer. The use of cloud in virtualization enhances the practice of searching and discovery faster and smarter. Generally, it consists of services that can be accessed by the physical layer or the real objects.

B. VIRTUALIZATION LAYER

The virtualization layer acts as a middleware between the application and the physical objects to provide the communication platform. This layer is further divided into three specific functionalities, i.e., semantic description, context-awareness, and cognitive management.

- Semantic Description: When a new object joins a network, an interaction mechanism is provided to it for external communications. The dynamic nature of the network allows runtime configurations of the new objects using semantic description, which leads to the phenomenon of the virtual object model. The virtual object model may consist of all features of the new configured object [248].
- Context-awareness [249], which is the ability to develop, analyze, and interpret the IoT related information, is combined with other sources of information before it can be used by other devices.
- Cognitive management [250] is the functionality to process the collected information using different algorithms to make appropriate decisions. The decision making is based on future prediction, fault occurrence, and availability of resources.

The improved functionalities of virtualization play a vital role to enhance the efficiency of this layer. These functionalities are elaborated below.

- Addressing and Naming: In the context of virtualization enhancement, when an object joins a network, the fundamental step is to assign a name or address to that object in a traditional IoT. The assigned name and address provide access to an entity to interact with other entities on the Internet [251]. For the virtual object's identification, naming of an object is an important factor in the interaction.
- Search and Discovery: With the dynamic nature of the IoT, objects can enter, move, and leave the network accordingly. Similarly, the virtualization layer should provide access to the objects for joining, moving, and leaving the platform. In the context of mobility, it is beneficial to use virtualization in the IoT.
- Mobility Management: Mobility is one of the major issues for virtual objects. It evolves in the network when an entity or object moves from one place to another. It is important to completely migrate the virtual counterpart of the object [248]. This functionality provides a better communication platform when required.
- Accounting and Authentication: Using semantic model, the authenticity and accountability are improved in the IoT environment with the help of virtual objects [248].

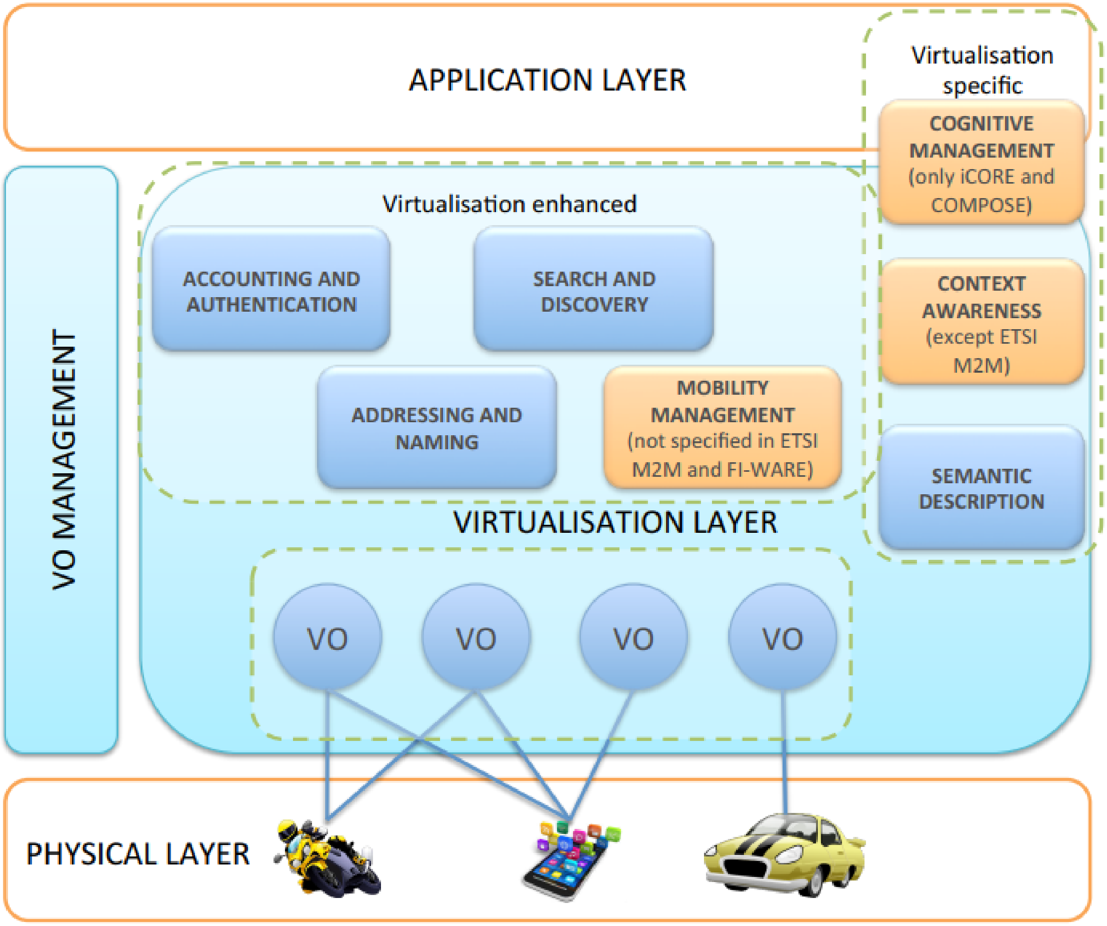


FIGURE 8. Virtualization of IoT, which underlines the basic components required to deploy a virtualization layer. The main unit is the process signifying the virtual object, i.e., the one which borders with the external services/applications and the physical object. Virtualization specific and improved modules show the semantic representation, which is believed as the only mandatory element. The virtualization layer includes virtual objects to interlink their services and the real objects. Specifically, it acts as a middleware between the application and the physical objects to provide the communication platform. The physical layer is composed of physical objects. The application layer is same as a cloud that provides services to physical objects with the help of virtualization layer [28].

Trust management can be used for securing data from autonomous entities.

C. PHYSICAL LAYER

The physical layer, also known as real world or physical world, consists of hardware devices. These real objects can communicate with the cloud or the application layer via the Internet, and the virtualization layer as a gateway or association.

X. IoT-BASED REAL-TIME ANALYTICS

As time goes by, the increasing rate in the IoT devices is persuading huge data volumes in the IoT environment [252]–[254]. The real-time IoT analytics gives a very clear picture and insights to the IoT and its applications in smart systems and business opportunities. As the current IoT network systems do not examine the constraints of real-time analytics, several network methodologies have been proposed in the literature, which well suit the real-time IoT analytics. Billions of devices are connected to each other in the IoT which leads to the creation of massive IoT data. If this bulky data [255], [256] is captured in real-time, defensive measures can be taken in order to accept new business models and also to create more spectacular services and products in different industries [257]–[259].

Real-time analytics is the procedure to deliver improved IoT services, such as performance improvement, control directives, and resourceful IoT business amenities by considering the huge amount of IoT data that manipulates the associated analytics resources, for instance, caching and computation, once the IoT data arrives the network in a stipulated time period. The available network architectures may not realistically support the huge amount of IoT data, which requires real-time analytics, thus, a novel architecture is needed to address this issue. The following subsections elaborate on the network requirements and methodologies for the real-time IoT analytics [29].

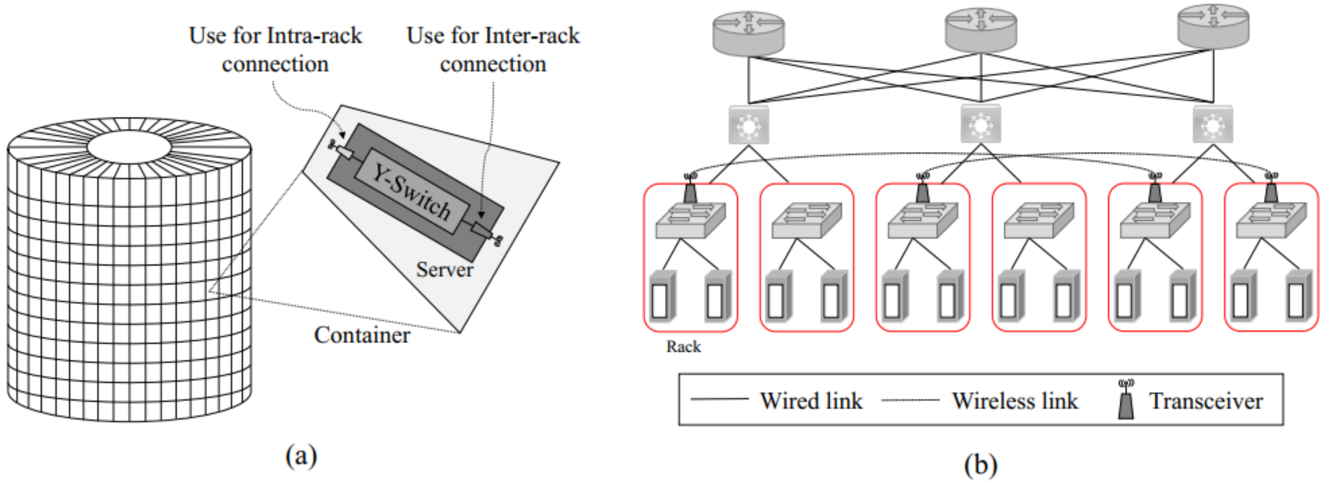


FIGURE 9. **(a) A purely wireless network that may go through several exertions, such as scalability issues, bandwidth consumption, and fault tolerance, in a data center which deals with a huge amount of data, as the wireless links' bandwidth is normally limited because of the excessive communication overhead. (b) A hybrid wireless network architecture, where a group of servers are equipped with the same set of radios, known as wireless transmission units (WTUs). As the radios are positioned above the racks, these racks do not hinder the line-of-sight propagation. Thus, a hybrid data center architecture is designed with the addition of WTUs in such a fashion that the server locating cost is nominal [29].**

A. NETWORK REQUIREMENTS

Existing research studies [260]–[262] suggest that collecting a huge amount of IoT data alone is not an appropriate method as it is difficult to evaluate each segment of data separately. For this reason, the concept of IoT analytics was introduced [263], which aims at providing analysis of all data segments straightaway so as to acquire the importance of business and make logical decisions. The nature of IoT analytics is different from that of the big data analytics [264] as the IoT analytics does not manage all features of the big data processing. In addition, without considering the big data features, the huge amount of IoT data analysis and processing are quite challenging [265]. A vigorous property of the complex IoT analytics relies on a systematic technique to recognize the bulky IoT data [266], locate it where it is needed, and perform the required actions on it when needed [267]. Obtaining the importance of business from the IoT analytics is an exciting idea [268], therefore, an inclusive classification of IoT analytics is required. To manipulate the accurate data successfully at the right time, IoT analytics holds the attention of researchers in several ways.

The IoT analytics is generally classified into historical [269]–[272] and proactive analytics [273], [274]. The former is the easiest and conventional class of analytics, which aims at obtaining visual intuitions from the extraction of historical data. While the latter manages to smooth the progress of practical insights through the factual data frames of the bulky IoT data. The practice of real-time IoT analytics is turned into a great importance in different fields, for example, transportation, disaster management, industrial IoT, smart city/home, and healthcare.

B. METHODOLOGIES

There is a significant need to explore the prevailing IoT analytics architectures and define which architecture is vigorous to effectively manage the content flow and connect the dispersed hardware resources in order to simplify the real-time IoT analytics. For this purpose, several architectures have been proposed in the literature, which are elucidated in the following subsections.

1) WIRED AND WIRELESS ARCHITECTURES

As stated in [275], most of the contemporary data centers utilize Ethernet switches to communicate with servers, where data centers (inside the network) are mostly controlled with high-speed Ethernets. The goal of a peculiar network architecture employed in a data center is to enhance the operation of data centers with respect to routing and fast content access. The wired network architecture of the existing data centers are prone to over-subscription [276], which are deteriorated when some of the servers devastate with considerably high data traffic [277]. To overcome this problem, modern wireless architectures, as in Figure 9, have set the stage for fast data transmission in line with the assurance of reliability.

2) PARALLEL MINING ARCHITECTURES

The large degree data mining is the basic unit for the realization of the smart city, an important IoT initiative [278]. Besides, the massive scale data mining must deliver solutions hastily to the real-time demands [279]. However, the conventional data mining techniques utilizing parallel mining models, for instance, Hadoop and MapReduce [280] do not satisfy the requirements of real-time IoT analytics. Moreover, these architectures also face the problem of *single point failure*. To alleviate the issues of service availability and scalability, an overlay-based architecture is proposed in [281], where all devices are responsible for the performance of management and processing functionalities. Also, the overlay-based architecture not only relies on a single device (master node) and therefore accomplishes better availability of services as well as higher fault tolerance as compared to conventional parallel architectures.

3) EDGE ANALYTICS ARCHITECTURE

The edge analytics architecture has been proposed in [282] to bring computation to the edge nodes, i.e., near the subscribers, so that the network overhead is reduced in computing the large-scale data at the centralized data centers. In this architecture, the data is processed by the data sources rather than forwarding it to the main data centers [283], which minimizes the content retrieval delay – the most prominent metric for the real-time IoT analytics [284].

Furthermore, the research on edge analytics is progressing in different networks, for example, cloudlets [285] and mobile edge computing [286]. In general, the performance of these architectures need to focus on minimizing the communication overhead and processing delay. The edge analytics, in the IoT perspective, may offer novel network architectures that may be a combination of distributed and centralized processing. For understanding the concept of edge computing-based IoT analytics, the interested readers are referred to [287]–[289].

XI. LESSONS LEARNED

This section is based on the following IoT-related papers: i) smart cities [25] that consist of traffic management, virtual power plants, emergency and health systems; ii) heterogeneous IoT [5] that elaborates the functions of application, cloud, networking, and sensing layers; iii) fog computing [19], which elucidates the functionalities of cloud, fog, and device layers; iv) data mining [26], which is classified into four parts, i.e., clustering, classification, frequent patterns, and association rules; v) data centric WSN [3] with respect to four aggregated schemes, i.e., data exchange, task and/or resource allocation, sensing coverage with target identification, and prevention of DoS attacks; vi) cellular communications [1] with regard to LTE; vii) content-awareness [27], which delineates a range of middleware applications along with their solutions; viii) virtual objects [28] in terms of architectures and their roles; and ix) real-time analytics [29] with respect to network requirements and methodologies. These lessons are presented in the following subsections in detail.

A. SMART CITIES

A smart city [25] includes different classifications of end users such as inhabitants, business associates, and administrators. The main goal of a smart city is to provide innovative smart traffic services [31], virtual power plants (VPPs) [42], [43], emergency system [46], [47], and health system [50]. Smart traffic management, with the help of moving cars, acquire transport related data through smartphones or GPS. The VPPs are proposed for resolving the issues concerning load and pricing [41]. A smart VPP consists of various technologies ranging from smart meters to smart grids [290]. A smart emergency system is implied to provide citizens with better security/protection and administration in case of accidents and natural disasters. The smart health system is utilized to offer low-cost services efficiently to the citizens of a smart city [49]. A smart health system can be developed with the help of different tools and mechanisms, such as smartphones, wearable devices, and smart hospitals [50].

B. HETEROGENEOUS IoT

Heterogeneous IoT [5] consists of mixed network architectures, such as mobile network (i.e., 3G/4G/5G), WSNs, VANETs, and WiFi, and has been deployed in various areas, for instance, smart cities, smart homes, manufacturing, and environmental monitoring [72]. The mentioned architectures are then further connected to cloud servers through satellites or the Internet for information sharing [73]. IoT is a complex network with various heterogeneous systems [74], which includes four layers, i.e., application, cloud computing, networking, and sensing layers [5]. The application layer provides a number of applications, for instance, WiFi and cellular networks, where mobile users can communicate freely with one another using their cellphones. The cloud computing layer retrieves and executes information obtained from other layers [75]. It can instantly grip the massive data in a proper way. The networking layer is used to draw a network structure for the forwarding of information between the source and destination. Network structures can also supervise the nodes through resourceful network strategies. In the sensing layer, various sensors, e.g., motion sensors, camera sensors, sound sensors, and temperature sensors, gather information from different nodes and provide it to the cloud servers for decision making.

C. FOG COMPUTING FOR IoT

Fog computing [19] is combined with the IoT to improve the performance of computing resources and caching capacities because it allows processing at the networks' edges, near the subscribers. Fog computing leverages remarkable characteristics for a range of applications [89]–[91], i.e., smart grids, connected vehicles, cyber-physical systems, and smart buildings. The fog computing architecture includes three layers, i.e., cloud layer, fog layer, and device layer. The cloud layer is a blend of storage and processing model that provides special IoT applications from a global perspective. The fog layer includes network tools, e.g., routers and gateways, equipped with processing capabilities. In addition, it also includes fog devices, such as mobile phones, industrial controllers, and embedded servers, deployed either in a hierarchical fashion or above the IoT nodes. The device layer includes fixed devices, e.g., RFID tags and sensor, and mobile devices such as wearable cameras, smartphones, and vehicles [105].

D. DATA MINING FOR IoT

Data mining [26], which can be expressed via several terms, e.g., information extraction from raw data, knowledge discovery in databases (KDD), and pattern analysis and information harvesting [116], is the process of evaluating data into effective information [115]. Data mining techniques are used to manage a huge amount of data created by IoT devices [124]. Several data mining models and methods have been proposed in the last few years [125], [126]. The performance of these methods can be largely affected by some operators, such as input, output, data scan, and rules creation and revision. Data mining approaches can be categorized into four classes, i.e., clustering, classification, frequent patterns, and association rules. Implementing these approaches is a realistic way to constitute a system think as a human or make it smart.

E. WSN-BASED DATA CENTRIC IoT

Different from the traditional WSN, the IoT-based WSN [3] needs to be smarter [163], because it does not only execute ordinary tasks but also perform important functions with little human involvement. Dealing with billions of IoT devices, numerous challenges in terms of economical deployment and appropriate processing can be faced. Thus, the deployment of smart mechanisms is needed so that to provide flexibility in the adaptation of dynamic IoT systems. The most popular IoT algorithms are pricing and economic based approaches. WSNs contain a huge number of sensors for performing different tasks and therefore the coordination of these sensors is needed, which is established in either a hierarchical or homogeneous style. Resource optimization, which is a crucial problem in WSNs, generally deduces that the existing network resources, for instance, bandwidth, cannot be replaced. Therefore, to overcome this problem, pricing strategies are employed with the flexibility of resource budget.

F. IoT-BASED CELLULAR COMMUNICATION

Cellular communications [1] offer considerable coverage with flexible transmission rates [201] and have therefore attracted the researchers' attention towards this verge. The most renowned commercial paradigm is Sigfox [202], which is accompanied by the extensions of the current cellular system, known as LTE. The most noticeable objective of the LTE standard is to acquire a flexible and revolutionized communication model. For the uplink and downlink spectrums of LTE, different specifications have been defined to allow access to the network as well as data to the higher layers [211].

G. CONTEXT AWARENESS-BASED IoT

Context-awareness [27] is the fundamental aspect of pervasive and ubiquitous computing systems [217], [218], which moved forward rapidly from ubiquitous/pervasive computing to the IoT since late 2000. The idea of context-awareness was proposed by Abowd *et al.* [219] in 1999, which has been unanimously approved by the research community. Sending information from one software phase to the next is known as data lifecycle, which shows that where the information was created and then where it was exploited. With reference to context movement, context-awareness, which is not only restricted to mobile or web applications, has become a service, i.e., context-as-a-service (CXaaS) [229]. A context management, pertaining to IoT, comprises four stages, i.e., context acquisition, information processing, decision making [230], and context reasoning [27].

H. VIRTUAL OBJECT-BASED IoT

The number of IoT connected nodes will reach 27 billion by 2021 [20]. Therefore, it would require a communication model that can provide elasticity and swiftness. Virtualized cloud is the only solution to this problem. The idea of virtualization evolved in the IoT system with the aim to allow things/objects to freely communicate with each other. The word virtual object [28] was composed of two interlinked objects, i.e., virtual and object [243], with the intention of improving the physical objects with digital information. A virtualization architecture is comprised of three layers, i.e., the application layer, the virtualization layer, and the physical layer. The application layer works as a cloud and lies above the virtualization and the physical layers. The main objective of cloud in the virtualization is to improve the performance of searching and discovery more rapidly. The physical layer consists of hardware devices that can communicate with the cloud or the application layer through the Internet, and the virtualization layer as a gateway. The virtualization layer plays the role of a middleware between the application and the physical objects to provide the communication platform.

I. IoT-BASED REAL-TIME ANALYTICS

Ral-time analytics [29] is the process of providing improved IoT services, e.g., control directives and business services, by bearing in mind the huge IoT data traffic that manipulates the associated analytics resources, for example, storage, upon the arrival of IoT data into the network. IoT analytics without considering the characteristics of big data is quite challenging as the IoT analytics cannot manage all characteristics of the big data processing. The custom of real-time IoT analytics has a magnificent role in various fields, such as transportation, disaster management, industrial IoT, smart city/home, and healthcare. To know the importance of IoT analytics architectures and their dynamicity, several methodologies have been proposed in the literature, such as parallel mining [278] (e.g., MapReduce [280]), and edge analytics [282] (e.g., cloudlets [285] and mobile edge computing [286]).

The major contributions and limitations of the surveyed papers are presented in Table 3, and a summary of IoT-enabled technologies is provided in Table 4.

XII. RESEARCH CHALLENGES

This section provides an overview of the research challenges, which are based on the following papers: i) smart cities [25] in terms of service and applications, ii) heterogeneous IoT [5] with respect to WSN, WiFi, and cellular communications, iii) fog computing [19] with regard to users' privacy and trustworthiness, iv) data mining [26] in line with decentralized and heterogeneous techniques, v) data centric WSN [3]

TABLE 3. Main contributions and limitations of the existing research.

Survey	Contributions	Limitations
Smart Cities: IoT Enabling Technologies [25]	Provides a comprehensive survey of data management and security issues in a smart city.	Lakes to provide privacy challenges for smart grids and vehicular communications.
Heterogeneous IoT [5]	Proposes various prospective solutions for the challenges of heterogeneous IoT, such as data aggregation, privacy protection, and big data transmission.	Discusses the working of cloud computing in heterogeneous IoT and ignores the most vital technologies, i.e., fog and edge computing.
Fog Computing for IoT [19]	Reviews the architecture and topographies of fog computing and report serious jobs of fog devices, including, caching, information forwarding, and distributed processing.	Reviews the architectural work done on fog computing and ignores the algorithmic perceptions.
Data mining for IoT [26]	Presents an overview of the features of data mining for IoT in line with future challenges and open issues.	Ignores to present the IoT overview from various angles, such as semantics, devices, and Internet.
WSN-based data centric IoT [3]	Studies various functions of the economic and pricing prototypes, called intelligent logical decision-making techniques, to design procedures and systems for wireless sensor networks.	Lakes to provide a partition of network traffic into logical phases that affect the functionalities of WSNs.
IoT-based cellular communications [1]	Delivers a detailed explanation of the MTC development through various LTE releases and the newly designed MTC categories.	Discusses only the physical layer features and neglects other important aspects, such as end-to-end network slicing and scalability issues for mobile IoT.
Context Awareness-based IoT [27]	Presents a wide range of procedures, systems, methods, middleware solutions, and applications associated with context awareness.	Does not precisely cover methods on information processing and management, which are primarily crucial to entirely adopt IoT.
Virtual object-based IoT [28]	Provides a detailed tutorial of the virtual object in the IoT environment in terms of development, functionalities, and various IoT proposals that employ these functionalities.	Neither studies the basic working units of the middleware structure nor discusses open issues and research challenges that may encounter in the real world insight of IoT.
Real-Time analytics based IoT [29]	Defines the essentials of the real-time IoT analytics and procedures, and clarifies limitations of the system policies for their validation.	Does not discuss protocols and applications that would assist the research community to choose appropriate technologies.

concerning mobility patterns and payment security, vi) cellular communications [1] with reference to obtaining frequency and operating cell IDs, vii) context-awareness [27] pertaining to device recognition and connection, viii) virtual objects [28] regarding their lifecycle and garbage collection, and ix) real-time analytics [29] in connection with scalability, fault tolerance, and massive data transmission. These challenges are addressed in the following subsections separately.

A. SMART CITIES

There are numerous research challenges that reduce the insight of a smart city. The most illustrious of them, which can considerably improve the practicality and achievability of a smart city, are fog computing and the integration of softwarization with 5G. In a smart city, services and applications need to bring the computation and processing near the subscribers. This can be achieved with fog devices, which are more powerful than the smart nodes and much smaller than the cloud devices. The integration of LTE of 5G into the IoT network is another serious elementary open research challenge. In other words, the integration of smart nodes with the 5G enabled nodes remains an open issue for evaluating the operation of available softwarization tools [291]. Hence, combining the features of fog computing and softwarization can help empowering an agile framework that may enhance reliability of the IoT for a smart city [25].

B. HETEROGENEOUS IoT

Heterogeneous IoT is a multifaceted network that includes several units, such as WiFi, cellular networks (i.e., 3G/4G/5G) and WSN, where their characteristics are quite different from each other [292]. An important open research issue is the development of a balanced heterogeneous network model where all network units can coordinate and strengthen their juxtaposition [293]. For addressing this issue, some models have been proposed in the literature, such as Petri Net and Queuing Networks [294]–[296]. However, these models are restricted to solve only the issues of a single network framework and therefore go on the blink when different networks work together. In addition, in a large-scale heterogeneous IoT, the optimal path strategies and routing protocols are feeble in robustness capacity [297]. Thus, self-organization of the large-scale heterogeneous IoT nodes is a critical challenge to explore. Smart hardware design is another open research issue in heterogeneous IoT [298], where the components of Blutooth, Infrared, and RFID modules face challenges in smart sensing, data aggregation, and trust provisioning [5].

TABLE 4. A summary of IoT-enabled technologies surveyed in this paper.

Topic	Description
Enabling technologies	Al-Fuqaha *et al.* [25] have rigorously surveyed enabling technologies, applications, protocols, and future challenges that would assist the IoT research community to choose their applicable technologies.
Protocols adapted for delivery and sensing networks	Tie *et al.* [5] have surveyed a four-layer architecture for heterogeneous IoT comprising networking, sensing, applications, and cloud computing in line with various possible solutions for dealing with issues that heterogeneous IoT faces. It also includes discussions on data integration and processing, privacy protection, big data transmission, and self-organizing in heterogeneous IoT.
Features of fog computing for sensing networks	Ni *et al.* [19] have surveyed the basic paradigm and characteristics of fog computing along with significant responsibilities of fog nodes, such as transient storage, real-time services, and information sharing. In addition, they have also examined privacy and security threats corresponding to fog-supported IoT applications.
Roles of data mining in sensing networks	Tsai *et al.* [26] have presented the role of data mining in making this type of network sufficiently smart to deliver more appropriate features. They have systematically described data mining that how it can be connected to the IoT in order to specify recommendations for academicians concentrating on data mining for IoT to move to the future Internet paradigm.
Pricing models for determining communications and data gathering glitches in delivery networks	Luong*et al.* [3] have provided economic models to determine communications and data aggregation issues in the IoT environment.
Long Term Evolution (LTE-A)-based delivery networks	Elsaadany *et al.* [1] have presented the LTE-A's uplink and downlink scheduling techniques for the future IoT. They have also highlighted a few ideas related to different categories of the MTC along with open challenges and future research directions.
Security measures for delivery, sensing, and computing networks	Perera *et al.* [27] have presented various security methods for the IoT-based context-aware computing.
Roles of virtual objects in heterogeneous networks	Nitti *et al.* [28] have provided the role of virtual objects in the IoT environment in terms of historical background, existing functionalities, and major challenges to the IoT.
Network methodologies for the real-time analytics of IoT applications	Verma *et al.* [29] have surveyed the fundamentals of real-time IoT analytics and software phases corresponding to the limitations of network methodologies. They have also provided a detailed explanation of network methodologies that may be used for the real-time IoT analytics.

C. FOG COMPUTING FOR IoT

The dispersion of fog nodes in line with the awareness of location provides local data management and real-time services [299], [300], but unluckily, because of the characteristics of localization, the users' locations are naively visible in fog computing. Thus, the privacy of a user is difficult to be protected in fog computing, as the fog nodes always seek information regarding the locations of users. Furthermore, the architecture of fog computing is exposed to a huge number of cyber-attacks and therefore IoT devices and fog nodes have enormous chances to compromise [150], [301]. Due to the dynamicity, scalability, and decentralization of fog computing architecture, building a secure and trustworthy infrastructure is a huge research challenge [19].

D. DATA MINING FOR IoT

The IoT-based mining problems are somehow different than those of the traditional mining system, but there is still some resemblances in the issues, such as scalability for a huge databank. Some of these challenges are as follows: i) heterogeneity and decentralization of the IoT [302] severely affect the development of algorithms for data mining. Thus, it needs to study that how vigorous decentralized mining techniques can be developed for the IoT. Another prominent issue is the collection of data, which is gathered by different sensor nodes from different locations. Therefore, without having an efficient data collection technique, every node will collect data in its own way. ii) The users' concerns about the security and privacy make the IoT system defective, for example, the health related applications in a smart hospital. In this regard, the confidential information of patients, e.g., behaviors, needs to be kept secret [26].

In accordance with these surveillances, a professional way that maintains the mining performance with respect to computational complexity also has to protect the private data. To alleviate these challenges, researchers have proposed some approaches in the last few years, such as encryption [303], temporary identification [304], and anonymization [305].

E. WSN-BASED DATA CENTRIC IoT

Most of the existing auction methods care about the auction alone for the WSN-based IoT system. In reality, to achieve flexible policies or better performance of the system, the auction features may be combined with other non-auction strategies. Therefore, the auction payment policies may be used in the pricing schemes for attaining the property of honesty and improving speed of the strategy. Cellphone users in the reverse auction-based data gathering methods [306], [307], are supposed to be immovable, and their price offers are submitted prior to send their information to the servers. However, there can be a situation where a cellphone user with the lowest price may be selected as the winner to send information, and then move out of the interest area, which may exacerbate the effectiveness of the platform. Hence, the server should keep track of the pattern of mobility of each individual cellphone user [308]. In addition, payment security and bids' confidentiality [309] are two other prominent open research issues [3].

F. IoT-BASED CELLULAR COMMUNICATION

Link estimation in different equalization and chain processing are the key issues for the LTE-MTC systems. In these systems, usually reference signals are interleaved with the original signal to help the link estimation procedure, which is needed for noise recognition. Various link estimation strategies that differ in their implementation and execution have been proposed, such as [310]–[312]. However these strategies depend on the information of the link measurements that is normally unidentified. The NB-IoT aims at occupying a minimum bandwidth, which is more little than the supported bandwidth of the traditional LTE [313]. The cell ID in the NB-IoT is different than that of the traditional LTE, therefore, acquiring frequency and effective search for the operating cell ID is one of the noticeable issues. Hence, link estimation techniques need improvement in order to provide realistic operations with the support of mobility [1].

G. CONTEXT AWARENESS-BASED IoT

In ubiquitous/pervasive computing, a small amount of sensors are connected to the applications (e.g., smart home, smart hospital). On the other hand, the IoT envisages billions of tiny connected nodes over the Internet. Consequently, a distinctive challenge may appear on the configuration and connection of applications to sensors. Since it is not possible to connect sensing devices to the applications manually [314], an automated method is required for connecting these entities. To achieve this goal, applications must be capable of recognizing sensing devices. In other words, once sensing devices are connected to an application, there should be a technique to recognize the sensors' produced information as well as its context automatically. Nevertheless, recognizing this information and properly interpreting it automatically in the IoT paradigm is a challenging subject [27].

Modern expansions in linked information [315], [316] and semantic technologies [317]–[319] provide further guidelines for future research. In addition, for proper acquisition, modeling, distribution, and reasoning in the IoT environment require standardization of the policies with a common standard interface [220], [235] so that to provide interoperability among these policies. Furthermore, trust, privacy, and security for context-aware computing have been critical challenges since the beginning. Thus, privacy and security in the IoT must be protected for the smooth and reliable transmission in order to win users' trust [27].

H. VIRTUAL OBJECT-BASED IoT

The predictable increase in the number of IoT nodes [165] would deteriorate the issue of scalability in the near future. The lifecycle of virtual objects must be managed adequately so that these objects are removed immediately if they are no longer required. Regarding virtualization, one of the major issues is the garbage collection of virtual objects. The development of an efficient IoT will steer the description of virtual objects and incorporate the abilities to make a network with the nearby nodes so as to freely employ applications for the humans' benefit in order to improve their quality of life. However, it is still not clear that which rules and values should administer the behavior of virtual objects [28].

I. IoT-BASED REAL-TIME ANALYTICS

The modern data center model follows a three-tier hierarchical structure, which includes the access, the aggregation, and the core layers. The evolution in size and complication of the data centers can bring about the issue of scalability [320]. This is due to the nature of the available data centers that are intended for the unexpected data growth from the web analytics [321]. The issue of scalability can be solved by taking the advantages of flexible data centers, which are transferable and can be affixed to an accessible data center [322]. Hierarchical data centers have a poor distribution of bandwidth and are also vulnerable to instabilities because of the increased number of node failures. To add more, the analytics systems that continuously receives a huge number of IoT information, should be able to assign services to the servers effectively and troubleshoot the topology in real time [323]. The real-time analytics of the huge amount of IoT information needs a fault tolerant system with the aim of reporting the results and perceptions within the stipulated time period. A critical challenge can be created by massive data with respect to data transmission for offering real-time analytics. The issues of network delay, which result from various situations in the analytics network, must be vigilantly recognized at the time of scheming the analytics systems [29].

XIII. CONCLUSION

The IoT paradigm has acquired a remarkable attention from the research forums since the early 2000. Due to technological advancements in the sensing nodes, sensors are likely to be affixed to all things in the environment and thereby communicate freely without or with little human interference. However, the recognition of sensor information is one of the noticeable issues that the IoT may encounter. This idea has been admired by government agencies, research institutions, and companies.

This survey investigated the IoT enabled technologies in terms of smart cities, heterogeneous IoT, fog computing, data mining, WSN-based data centric IoT, cellular communication, context-awareness, virtualization, and real-time analytics. To realize the inspirations of utilizing various IoT modules, we introduced the essentials of different IoT aspects with their generic goals. Next, we provided a review of lessons learned from different studies that were reviewed throughout this paper. Finally, some open research challenges related to the mentioned areas were also discussed for the intuition of the IoT acceptability.

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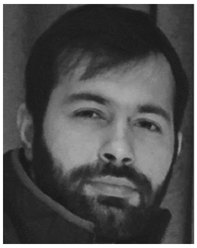

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