Internet-of-Things-Based Smart Environments: State of the Art, Taxonomy, and Open Research Challenges

Ejaz Ahmed, Ibrar Yaqoob, Abdullah Gani, Muhammad Imran, and Mohsen Guizani

Abstract

The rapid advancements in communication technologies and the explosive growth of the Internet of Things have enabled the physical world to invisibly interweave with actuators, sensors, and other computational elements while maintaining continuous network connectivity. The continuously connected physical world with computational elements forms a smart environment. A smart environment aims to support and enhance the abilities of its dwellers in executing their tasks, such as navigating through unfamiliar space and moving heavy objects for the elderly, to name a few. Researchers have conducted a number of efforts to use IoT to facilitate our lives and to investigate the effect of IoT-based smart environments on human life. This article surveys the state-of-the-art research efforts to enable IoT-based smart environments. We categorize and classify the literature by devising a taxonomy based on communication enablers, network types, technologies, local area wireless standards, objectives, and characteristics. Moreover, the article highlights the unprecedented opportunities brought about by IoT-based smart environments and their effect on human life. Some reported case studies from different enterprises are also presented. Finally, we discuss open research challenges for enabling IoT-based smart environments.

Introduction

Immense developments and increasing miniaturization of computer technology have enabled tiny sensors and processors to be integrated into everyday objects. This advancement is further supported by tremendous developments in areas such as portable appliances and devices, pervasive computing, wireless sensor networking, wireless mobile communications, machine learning-based decision making, IPv6 support, human computer interfaces, and agent technologies to make the dream of a smart environment a reality. A smart environment is a connected small world where sensor-enabled connected devices work collaboratively to make the lives of humans comfortable. The term *smart* refers to the ability to autonomously obtain and apply knowledge, and the term *environment* refers to the surroundings. Therefore, a smart environment is one that is capable of obtaining knowledge and applying it to adapt according to its inhabitants' needs to ameliorate their experience of that environment.

The functional capabilities of smart objects are further enhanced by interconnecting them with other objects using different wireless technologies [1]. In this context, IPv6 plays a vital role because of several features, including better security mechanisms, scalability in case of billions of connected devices, and the elimination of Network Address Translation (NAT) barriers.[1] This concept of connecting smart objects with the Internet was first coined by Kevin Ashton as the "Internet of Things" (IoT). Nowadays, IoT is receiving attention in a number of fields including healthcare, transport, and industry, among others [2].

Cisco reports that 50 billion objects and devices will be connected to the Internet by 2020.[2] However, more than 99 percent of today's available things in the world still remain unconnected. According to a Navigant research report, the number of installed smart meters around the world will grow to 1.1 billion by 2022.[3] Another report from *Automotive News* states that the number of cars connected to the Internet worldwide will increase from 23 million in 2013 to 152 million in 2020.[4] The forecast of such significant growth shows that IoT will become the fabric of modern societies to realize the vision of smart environments.

Several research efforts have been conducted to integrate IoT with smart environments. The integration of IoT with a smart environment extends the capabilities of smart objects by enabling the user to monitor the environment from remote sites. IoT can be integrated with different smart environments based on the application requirements. The work on IoT-based smart environments can generally be classified into the following areas: smart cities, smart homes, smart grid, smart buildings, smart transportation, smart health, and smart industry. Figure 1 illustrates IoT-based smart environments.

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[1] http://iot6.eu/ipv6_advantages_for_iot

[2] http://www.cisco.com/web/solutions/trends/iot/portfolio.html

[3] http://www.navigantresearch.com/newsroom/the-installed-base-of-smart-meters-will-surpass-1-billion-by-2022

[4] http://www.autonews.com/article/20140110/OEM06/301109910/the-race-to-market-the-connected-car

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The contributions of this survey are manifold:
- First, we investigate, categorize, and classify the state-of-the-art research efforts carried out in the domain of IoT-based smart environments.
- We devise a taxonomy of IoT-based smart environments based on the conducted survey.
- We present the potential opportunities that the integration of IoT with smart environments can contribute to human society.
- A few notable ongoing case studies of IoT-based smart environments are outlined.
- Finally, we discuss open challenges in realizing the vision of IoT integration with various smart environments as future research directions.

The remainder of this article is organized as follows. First, we present the state-of-the-art IoT-based smart environment solutions. We then discuss the devised taxonomy of IoT-based smart environment solutions. Next, we present the potential opportunities that can emerge because of the integration of IoT with smart environments. Notable ongoing case studies of IoT-based smart environments are outlined. We discuss open challenges in integrating IoT with various smart environments. Finally, we provide our conclusion.

IoT-Based Smart Environments

In this section, we present the state-of-the-art IoT-based smart systems that are categorized and classified according to application domain. The main categories are as follows:
- Smart cities
- Smart homes
- Smart grid
- Smart building
- Smart transportation
- Smart health
- Smart industry

Smart Cities

The authors in [3] presented a comprehensive survey on the architectures, protocols, and enabling technologies for urban IoT. They discussed an urban IoT architecture by describing web-service-based IoT architecture, link layer technologies, and devices suitable for the urban IoT. A proof-of-concept implementation as a relevant example, and a set of technical solutions, best practices, and guidelines followed in the Padova smart city project were also presented.

A generic top-down IoT architecture for smart cities was proposed in [4] to enable various IoT applications. The core element of the architecture is the integrated information center run by the IoT service provider. The information center is connected to a set of services, such as electrical energy, water, and central and gas supply provided in smart cities. The architecture facilitates IoT co-building, openness, and convergence of several technologies that are essential for the realization of smart cities.

Smart Homes

A cloud-based home solution for detecting a fault in the SDN-based smart home environment was proposed in [5]. The authors defined four social relationships: IoTphysical space, IoTService, IoTNetwork, and IoTIoT, in an IoT-based smart home environment to find a faulty location. A software defined networking (SDN) controller collects information from the packets passing through SDN switches and makes a status graph that contains information on each home IoT device. An SDN-based home cloud automatically generates the four relationships that reduce the burden on users and service providers. The authors stored the device information in RDF/XML format to provide support for a semantic query. The proposed solution is beneficial for both users and home service providers.

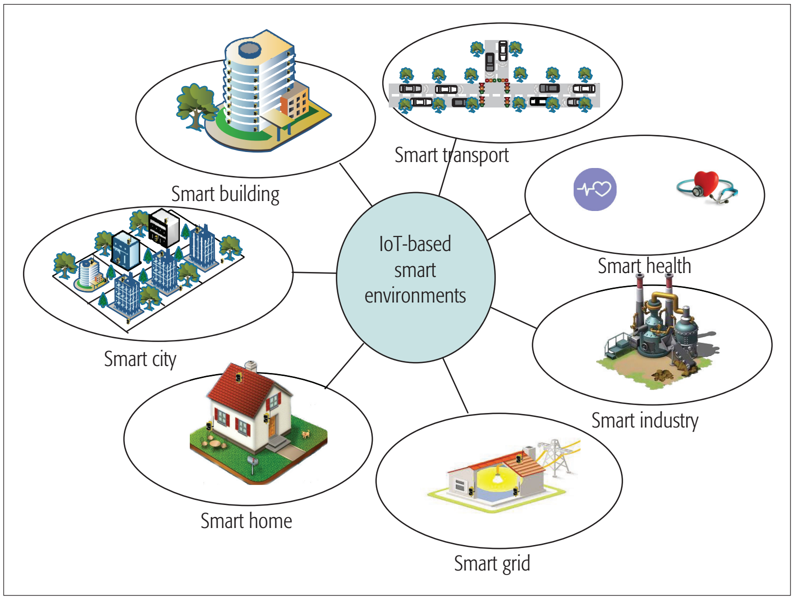

Figure 1. IoT-based smart environments.

The researchers in [6] proposed a proactive architecture that implements the eventcondition-action method to manage heterogeneous IoT-based smart homes. The proposed architecture has multiple tiers, such as a core layer and a service layer, that are involved in decision making. The core layer comprises web-based services that couple the system to its services. A home gateway in IoT-based smart homes enables access to external networks. To add new IoT systems or services, device application programming interfaces (APIs) and device stub modules are introduced to resolve the dependencies. Web-based services use stateless protocol and are not made for long-term sessions.

Smart Grid

Q. Ou *et al.* [7] proposed an IoT-based real-time monitoring system for power transmission lines to avoid disasters. The proposed system visually displays the operational parameters of the tower and power transmission lines, such as wind deviation, conductor galloping, icing, conductor temperature, and tower leaning, at the monitoring center. Therefore, real-time monitoring and early warnings of disaster can be implemented to minimize the smart grid damage caused by natural disasters.

Y. F. Wang *et al.* [8] classified IoT-based smart grid applications into three types:
- Key equipment state monitoring
- Information collection
- Smart grid control

The key wireless Internet technologies are WiFi, 3G, 4G, and satellite. WiFi is mainly used in smart homes, smart cities, smart transportation, smart industries, and smart building environments; whereas, 3G and 4G are mainly used in smart cities and smart grid environments. Satellites are used in smart transportation, smart cities, and smart grid environments.

Technology	Frequency	Data rate	Range	Power consumption	Application
Bluetooth	2.4 GHz	25 Mb/s	10 m	Low	Smart home
DASH7	433 MHz (Europe)	55.5 kb/s, 200 kb/s	1000 m	Low	Smart cities, smart building, smart home, smart transport, smart health
ZigBee	2.4 GHz, 915 MHz, 868 MHz	250 kb/s	Up to 100 m	Low	Smart homes, smart health
WiFi	2.4 GHz, 5 GHz	54 Mb/s, 6.75 Gb/s	140 m, 100 m	Medium	Smart cities, smart home, smart building, smart transport, smart industry, smart grid
3G	850 MHz	24.8 Mb/s	1–5 mi	High	Smart cities, smart transport, smart industry, smart grid
4G	700 MHz, 750 MHz, 800 MHz, 1900 MHz, 2500 MHz	800 Mb/s	1–6 mi	High	Smart cities, smart transport, smart industry, smart grid

Table 1. Comparison of communication technologies used in smart environments.

The authors also highlighted the characteristics and types of IoT-based smart grids. Based on the characteristics, a reference architecture for smart grid IoT was proposed. The reference architecture has three layers: the perception layer, transport layer, and application layer. A secure access control system for security protection of IoT-based smart grids is also proposed to ensure that IoT-based smart grid devices can securely access the Internet.

Smart Buildings

K. Akkaya *et al.* [9] analyzed the existing occupancy monitoring approaches with respect to issues of cost, accuracy, intrusiveness, and privacy. They used multi-modal data fusion for improving the occupancy detection accuracy in a smart building. The information fusion techniques filter noisy measurements generated from IoT devices and predict the occupancy status. The authors also investigated how data fusion techniques could be used with occupancy monitoring techniques to reduce the energy consumption of the smart building.

The framework proposed in [10] helps to extend the security functionalities stated by the architectural reference model from the European Union Framework Programme 7 IoT, a project to devise authentication and authorization mechanisms for service access protection. The authors proposed to utilize the available localization data to implement the access control for services provided inside a typical smart building. The proposed framework is implemented on a service management platform, a city explorer that implements the key security aspects.

Smart Transportation

The concept of IoT can be applied to all aspects of transportation, such as collection of data related to passenger counting, geo services, smart ticketing, and communication. Eurotech [11] provides IT solutions that can assist in connecting every public transport element, and furnishes the technical tools to connect sensors and other devices to IT infrastructure. Similarly, the Kapsch Group [12] investigated how Internet technologies can be leveraged to ameliorate the traffic conditions in cities.

Smart Health

A system architecture based on IoT was proposed in [13] to monitor, collect, and transmit remote healthcare data. The IEEE 802.15.4 standard was used to transfer data to a gateway. Moreover, two rule engines, static and adaptive, were developed. These engine rules are involved in the decision making process while transmitting data based on important parameters extracted from the collected data. The results show that the developed rule engines help in saving energy consumption and and minimizing network traffic.

The authors in [14] presented a smart e-Health gateway based on IoT that could help in solving many issues such as reliability, performance, interoperability, scalability, energy efficiency, and security. The smart gateway can address these issues by taking responsibility for handling the burden of sensor networks implemented in the remote healthcare center. By presenting a case study called *UTGATE*, the authors demonstrated that a smart e-Health gateway could also provide services such as storage, fast data processing, and embedded data mining.

Smart Industry

F. Shrouf *et al.* [15] presented an architecture for an IoT-based smart factory and defined the key characteristics, such as flexibility, optimized decision making, mass customization, and remote monitoring, with respect to energy management. The proposed mechanism improves energy consumption in a smart factory by incorporating energy data into production management.

Taxonomy

Figure 2 illustrates the taxonomy of the IoT-based smart environment. The devised taxonomy is based on the following parameters: communication enablers, network types, technologies, wireless standards, objectives, and characteristics.

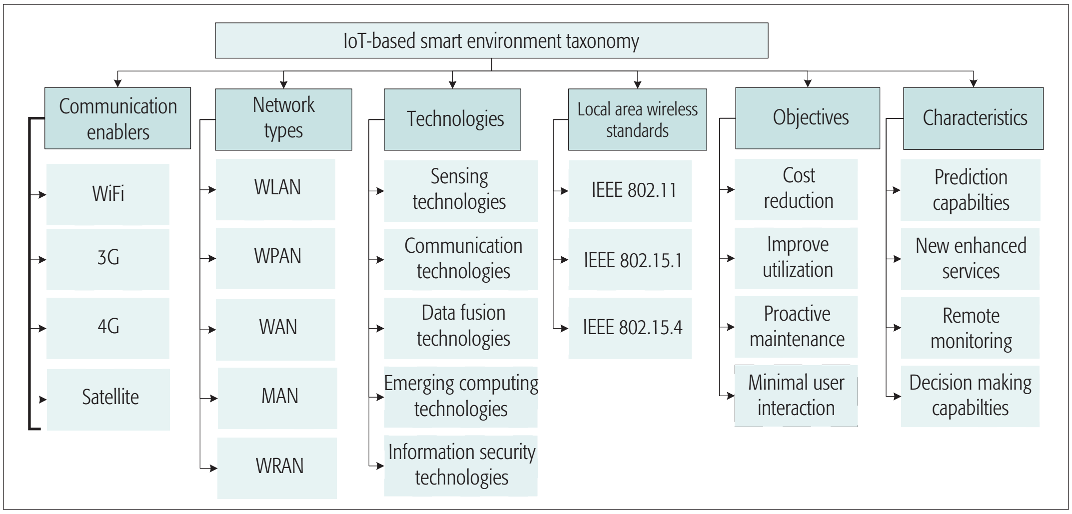

Figure 2. IoT-based smart environments taxonomy.

Based on the requirements and implemented functionalities, smart environments have different predefined objectives. The key objectives of the IoT-based smart environment are cost reduction, utilization improvement, proactive maintenance, and minimal user interaction.

Communication Enablers

Communication enablers refer to wireless technologies used to communicate across the Internet. The key wireless Internet technologies are WiFi, third generation (3G), 4G, and satellite. WiFi is mainly used in smart homes, smart cities, smart transportation, smart industry, and smart building environments, whereas 3G and 4G are mainly used in smart city and smart grid environments. Satellites are used in smart transportation, smart city, and smart grid environments. Table 1 presents a comparative summary of the communication technologies used in IoT-based smart environments.

Network Types

IoT-based smart environments rely on different types of networks to perform the collaborative tasks for making the lives of inhabitants more comfortable. The main networks are wireless local area networks (WLANs), wireless personal area networks (WPANs), wide area networks (WANs), metropolitan area networks (MANs), and wireless regional area networks (WRANs). These networks have different characteristics in terms of size, data transfer, and supported reachability.

Technologies

IoT-based smart environments leverage various technologies to form a comfortable and suitable ecosystem. These technologies include sensing, communication, data fusion, emerging computing, and information security. Sensing technologies are commonly used to acquire data from various locations and transmit it using communication technologies to a central location. The emerging computing technologies, such as cloud computing and fog computing, deployed in the central location leverage the data fusion technologies for integrating the data coming from heterogeneous resources. In addition, smart environments also use information security technologies to ensure data integrity and user privacy.

Local Area Wireless Standards

The commonly used local area wireless standards in IoT-based smart environments are IEEE 802.11, IEEE 802.15.1, and IEEE 802.15.4. These standard technologies are used inside the smart environment to transfer the collected data among different devices. IEEE 802.11 is used in smart homes, smart buildings, and smart cities. IEEE 802.15.1 and IEEE 802.15.4 have relatively shorter coverage than IEEE 802.11, and are used mainly in sensors and other objects deployed in the smart environments.

Objectives

IoT-based smart environments are deployed to facilitate inhabitants' lives in different situations, such as elderly monitoring and facilitating, while traveling in the form of geo service provisioning and smart ticketing. Based on the requirements and implemented functionalities, smart environments have different predefined objectives. The key objectives of the IoT-based smart environment are cost reduction, utilization improvement, proactive maintenance, and minimal user interaction.

Characteristics

IoT-based smart environments have some unique characteristics that make them unconventional. These characteristics are prediction capabilities, newly enhanced services, remote monitoring, and decision making capabilities. The prediction capabilities can be beneficial in smart buildings, where predicting the air quality in varying conditions is highly valuable. The predicted information can be utilized to evaluate alternative methods of clean air provision.

The integration of IoT with smart environments can bring opportunities for several new enhanced services such as smart transportation systems, which can utilize the information collected by multiple connected cars and roadside infrastructure for enabling better traffic coordination. It can also enable remote access and monitoring of smart environments such as homes, buildings, and appliances within them. Moreover, it can collect a variety of data from different sources, and apply data fusion and mining techniques to make intelligent decisions.

Opportunities

The integration of IoT with smart environments has brought about unprecedented opportunities. This section highlights the

Case study	Devices/ Sensors	Business needs	Solution	Assessment	Company involved	Country
Rio Operations Center	IP cameras, wearable devices, traffic monitoring systems	To help residents in many aspects of quality life	IoT-based smart city	Success	Rio Tinto, Cisco	Brazil
SK Solutions	Light sensor switches, hour meters, IP cameras, IP switches	To ensure construction site safety	IoT-based smart cranes	Success	SAP	Dubai
Yellow River Conservancy Commission	Smart water sensors, level pressure sensors, Doppler velocity meters	To monitor the infrastructure stability of the Yellow River	IoT-based early warning flood system	Success	AGT	China
BC Hydro	Smart meters, smart transformers, capacitor banks	To improve meter efficiency and grid stability	IoT-based smart grid	Success	Cisco, Itron, Cap Gemini	Canada

Table 2. Comparison of case studies.

main opportunities offered by such an environment.

Cost-Effective Cloud-Based Applications: Cost-effective, secure, and flexible cloud-based applications can transform a smart environment into a decision making platform by collecting data from the environment and transferring them to the cloud through IoT. The analysis of the collected data, decision making, and prediction of environment parameters are the key tasks performed in the cloud server.

New Business Models: IoT enables companies to build new business models and revenue streams that can create many new business opportunities. IoT has the capability to alter the way consumers and businesses approach the world. Accordingly, consumers and businesses will require new services that can assist them to explore this ultra-connected changing landscape.

Real-Time Information: In an IoT-based smart environment, organizations can collect data about products and processes for analysis in a real-time manner and provide the analyzed information for making appropriate decisions. The smart environment can rapidly adapt based on the decisions made and improve operational efficiency that results in higher customer satisfaction.

Diversification of Revenue Streams: IoT can enable companies to create new revenue streams and services on top of traditional services; for example, vending machine companies offering inventory management to those who supply the goods in the machine.

Intelligent Operations: With rapid growth in IoT devices, the data produced by the IoT also grow exponentially. The management of such large amounts of data will be a challenge in terms of performance. Designing intelligent cloud operation management solutions that can ensure the working of a cloud infrastructure at an optimal level will also be necessary.

Case Studies on IoT-Based Smart Environment

This section describes a number of reported case studies provided by different enterprises that deployed IoT environments in their businesses. A summary of these case studies is provided in Table 2.

Rio Operations Center

The deployment of IoT in the Rio Operation Center[5] has enabled Rio de Janeiro to rise as one of the official smart cities in the world. Cisco, IBM, and Samsung were involved in this project. The goal of the project was to facilitate residents in many aspects of quality of life, such as safety, fast emergency response time, and better traffic control and communication among agencies. For this purpose, the technology partners established an operation center for timely and better decision making based on data collected through sensors and other devices from the entire city. The results show that the deployment of IoT improved 20 percent of response times and facilitated 6.3 million residents of the city in terms of quality of life. In addition, IoT improved the security services during events organized in the city such as the World Cup and the Olympics.

SK Solutions

To ensure the safety of construction sites, a Dubai-based company called SK Solutions[6] deployed an IoT environment which is built on SAP Hana. SK Solutions collects information from different sensors deployed in the machinery throughout the customers' site. Collected information is analyzed in a real-time environment to obtain the contextual details of activities, such as machinery's weight, position, movement, temperature, and speed at different locations. By using this dataset, SK Solutions developed a software suite that enables mobile devices to obtain actionable data details. SK Solutions claimed that their customers saw significant benefits, such as worker safety, improved construction time, and 30 percent reduced downtime.

Yellow River Conservancy Commission

An IoT environment was deployed by the Yellow River Conservancy Commission (YRCC)[7] to monitor the infrastructure stability of the Yellow River in China. The YRCC built an application called Flood Early Warning System based on AGT's IoT platform that captures and analyzes the information generated from the sensors. The real-time dashboard is used to show the status of water and alarming information on any unusual activity. The YRCC claimed that the deployed IoT-based application enables them to predict water flood level and assists them in minimizing

[5] http://www.networkworld.com/article/2848714/cisco-subnet/10-enterprise-internet-of-things-deployments-with-actual-results.html

[6] http://www.sk-group.fr/en/

damage costs. Furthermore, the application helps in the maintenance of infrastructure efficiency.

BC Hydro

To improve meter efficiency and grid stability, BC Hydro[8] deployed an IoT-based platform across seven Canadian provinces for air firmware updates and remote monitoring. BC Hydro invested $900 million for this project. Many companies, such as Cisco, Itron, Cap Gemini, and Accenture, were involved in completing this project. BC Hydro claimed that the solution reduced theft by 75 percent, which translated to savings of $330 million in meter readings and $224 million saved in self-service tools.

Open Research Challenges

This section highlights the open research challenges in the integration of IoT with smart environments. This discussion aims to give research directions to new researchers in the domain.

Precision

In many smart IoT environments such as healthcare, transportation, and unmanned aerial vehicular networks, where devices and systems are connected globally, precision is one of the most important challenges that need to be addressed. When dealing with precision machines that can fail if timing is off by a millisecond, adhering to strict requirements becomes pivotal to the health and safety of machine operators, machines, and related businesses. Network latency and available bandwidth are the key factors that can affect the precision of distributed IoT delay-sensitive mission-critical environments. Therefore, these parameters need to be considered when deploying IoT in a smart environment. For example, in the case of vehicle-to-vehicle communication in smart transportation environments, longer network latencies can cause delays in applying car brakes, which can be very dangerous. High-precision systems should be developed to make IoT deployment successful in smart environments.

Big IoT Data

IoT is one of the largest sources of collecting large amounts of data (i.e., big data). As mentioned earlier, more than 50 billion devices will be connected with each other by 2020 that can lead to big data production. Special attention should be given to storage, access, and processing of such big data generated by devices forming an IoT environment. The performance of most of the IoT applications depends on the data management services. Therefore, IoT data require highly scalable computing platforms that can manage the big IoT data in terms of processing, access, and storage without affecting the performance of the application.

Compatibility

Compatibility is one of the greatest challenges in an IoT smart environment, where different products are connected to each other. Most of the products are unable to connect with each other because of the unavailability of a universal language, thus leading to compatibility issues. Connecting devices with each other requires collaboration among enterprises, such as Samsung, Philips, and LG. The collaboration among these companies can enable developers to obtain the infrastructure information of each product and design a universal coding language accordingly. Otherwise, people will be frustrated if they are only capable of using one brand. The solution of compatibility issues can ensure the success of IoT.

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Investment

Deploying an industrial IoT environment requires massive investment. The investment decision in such a scenario where things are not open and interoperable in terms of hardware and software makes it difficult for companies to adopt this technology. For deployment in companies, open and integrated hardware and software-based IoT solutions should be built. Moreover, the solutions should be flexible enough to enable companies to evolve and adapt to changes instead of replacing them with new systems. Generating innovation within existing hardware and software architectures requires expertise and investment.

Security and Privacy

Despite limitless opportunities and merits of IoT in smart environments, security and privacy are always key concerns. Only small amounts of data can be stored within a device because of the limited storage capacity of memory cards. Storing data in other sites demands high security and privacy because users do not want to reveal their information to others. New technology that enables users to dynamically verify whether the company obeys their service level agreement or not in terms of security, privacy, and governance rules is required. Researchers have already warned industries about "smart home hacking" which is a realistic threat to the IoT community in the future.

Conclusions

Momentous developments in wireless technologies have paved the way for realizing the vision of deploying IoT in smart environments. In this article, we provide a review of research efforts made to integrate IoT with smart environments. A discussion on state-of-the-art IoT-based smart environments is presented to help readers understand the recent efforts in this direction. We also devise a thematic taxonomy considering communication enablers, network types, technologies, local area wireless standards, objectives, and characteristics. Moreover, we present reported case studies and discuss the unprecedented opportunities brought about by the integration of IoT with smart environments. Furthermore, we discuss the open research challenges as future research directions. Finally, we conclude that the deployment of IoT could be one of the future platforms to enable the objects of the physical world to communicate with each other by ensuring high functionality, energy efficiency, rich interactivity, and crisp responsiveness in a dynamic manner.

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[7] http://www.icewarm.com.au/page.php?pId=307

[8] https://www.bchydro.com/index.html

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