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Towards IoT-based sustainable digital communities

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Abstract: Seeking continuous development, a modern community must also be able to adapt to future possible challenges using constrained or limited resources. As a revolutionary communication paradigm, the Internet of Things (IoT) empowers the cutting-edge and emerging applications which enable manifold new intelligent services towards a smart community. The sophisticated ecosystem of a digital community is made feasible by the IoT infrastructure, which also provides community control with access to a wealth of actual data. In addition, IoT platforms empower the ubiquitous computing ability, providing more potentials to the actuators in perception layer in the IoT architecture. With more and more population in the urban areas, sustainability issues have become a key factor to consider in the development of a digital community. We give a modern survey in this study on the most recent developments in IoT for sustainable digital communities. After carefully examining the most recent literature, we specifically highlight the various smart digital community application scenarios, such as smart buildings, energy management, green transportation, trash management, etc. We also look into a number of major issues facing the use of IoT technology in digital communities. Furthermore, we discuss potential future applications and future research areas for IoT, the critical component of sustainable digital communities.

Key words: Internet of Things; digital communities; sustainability; smart systems

1 Introduction

Interacting and communicating with the real world "things" and establishing standard communication protocols, Internet of Things (IoT) is a cutting-edge paradigm enabling emerging communication technologies and applications[1, 2]. IoT systems are able to flexibly adapt to changing environments, varying user requirements, and everlasting technical and infrastructure innovations. Based on the efficient machine-to-machine (M2M) communications and interactions among IoT units, the operations of smart city and community agents as well as the quality of human lives can be improved. Thanks to the autonomous and ubiquitous smart object networks[3], the entire city and community information system, from the perceptual level and communication support structure to the internet integration of relevant networks and applications, can be included in an IoT framework. Therefore, such a transformational and intelligent community management paradigm can be constructed based on IoT systems. It is not an overstatement that there will be no smart communities without IoT, as IoT has been beneficial to smart cities and smart communities via numerous real applications[4] and the IoT-based smart cities[3, 5]. For example, smart surveillance camera deployment has been widely employed for a variety of applications in urban areas. No need to mention that other smart community related domains are also being more and more involved with the IoT paradigm, such as smart sensing[6], advanced metering infrastructure (AMI)[7], edge computing[8], human behavior modeling[9], sensor networks[10, 11], subsurface civil infrastructure monitoring[11, 12], self-

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powered wearable devices[13], and so on.

Sustainable community has drawn worldwide attentions, such as the low-carbon economy proposal in the " Energy White Paper" proposed by the British government[14], the Japanese smart community motivation[15], and the Chiang Mai World Green City[16]. Sustainable community is a comprehensive and complex concept related to environmental issues and society development. The balance between energy and resource consumption and user comfort should be reached[17]. Low-carbon communities, high-quality services, as well as control technologies supported by modern information and communication technologies (ICT) construct the research goals covered by this survey, which are related to smart energy management, smart building, smart waste management, green transportation, etc., as shown in Fig. 1.

The primary concerns about the sustainability mainly come from the energy and resources. Energy generation, especially renewable energy resource, has been more and more integrated into the smart grids[18, 19]. IoT empowered smart grids are typically network connected and controllable entities. Thus, not only the low carbon goal can be achieved, smart grids can also reliably sustain the necessary energy services to meet the local demand even when power outage events occur[20]. As building is an important type of the main resource consumers in the modern city, IoT-based intelligent building energy optimization methods have been proposed to improve the energy efficiency for smart community energy management[21]. To improve the sustainability, transportation is also under consideration because transportation systems consume energies and omit wastes at the same time. Green transport is generally IoT-based and an important kind of environmentally friendly technology, including intelligent transportation systems (ITS)[22], electric vehicles[23–25], and so on. Waste management is another important topic in the modern city and community, which can be more sustainable with the help of IoT. The amount of generated waste can be enormous, like hundreds of million tons per year, including not only the solid waste but also the wastewater. IoT systems can improve the reuse and recycling rates of the wastes, and reduce the energy and material usages in the collection and processing procedures.

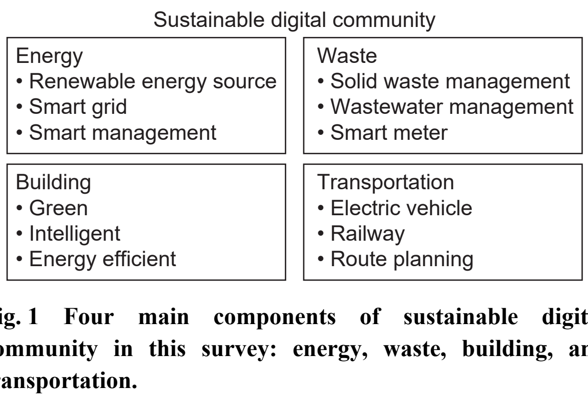

Fig. 1 Four main components of sustainable digital community in this survey: energy, waste, building, and transportation.

Conventionally, a smart community is only considered as a system consisting of a set of smart homes, which are analyzed for better electricity or water bill plannings[26]. Here, we have a bigger picture (shown in Fig. 2) of the community concept, which not only includes smart buildings but also transportation, waste management, and energy management systems. Need to mention, since this survey mainly focuses the sustainability of the digital community as a whole, other IoT related areas are not explicitly discussed. For example, the individual sustainability of human beings is not the scope of this study. Although IoT-based smart healthcare applications depend on smart and connected medical devices as well as wearable technology to realize health monitoring to improve the human well-being[27–32], they are not discussed here. Additionally, certain small-scale IoT applications, including the smart home, which consists of IoT fixtures and appliances that function in a domestic setting[33], are not discussed as well. In addition, although the IoT applications in digital communities also face open challenges, such as the limitations of IoT systems in security and multivendor interoperability, the overall expectation of IoT-based digital community is still positive or encouraging.

The remainder of this survey paper is organized as follows. First, the general infrastructure of IoT and the benefits brought from IoT for the sustainable digital community are briefly introduced (Section 2). In Section 3, the main components of the IoT supported

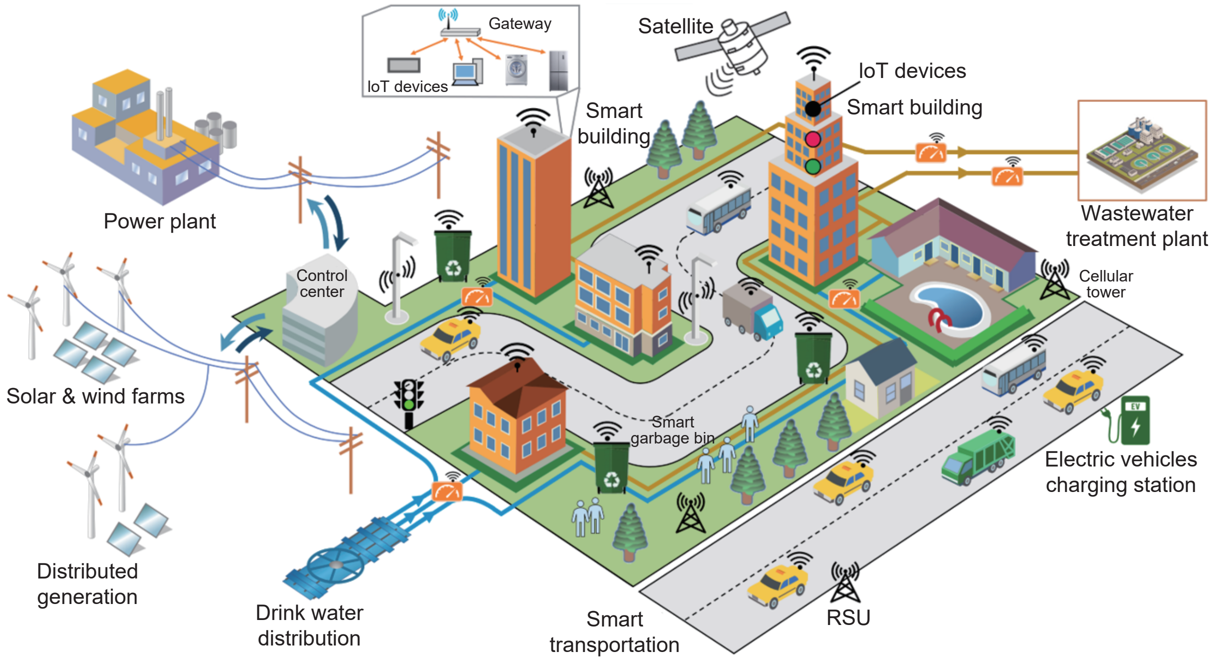

Fig. 2 IoT-based sustainable digital community which includes smart energy management, smart building, smart waste management, and smart transportation.

sustainable digital community: smart energy, smart building, smart transportation, and smart waste management are discussed about how IoT plays an undeniable role in them. Future research opportunities in terms of IoT platforms are pointed out in Section 4. In the end, a conclusion section is enclosed in Section 5. Note that the list of frequently used acronyms is shown in Table 1.

2 Internet of Things infrastructure

The proliferation of smart sensing, edge/pervasive computing, global positioning services, flexible communication protocols, fog/cloud computing, data storage, maintenance technique, sensor networks, and so on, has promoted the IoT development. IoT is the result of the Internet's evolution to a certain extent. It is built on sensing, control, and computing technologies, which enable complete interconnection of objects and of people and objects. IoT overcomes information transmission's constraints and emphasizes the qualities of intelligence and service. IoT can provide real-time controls, alerts, scheduling and plans, as well as display services. IoT-based solutions are anticipated to be low-cost, high-energy-efficiency, high-quality-of-service (QoS), larger scale coverage, more adaptable, high-security and private, and hyper deployments. Typically, IoT systems share a similar infrastructure[34], including sensor and actuator, data acquisition, edge computing, and data center/cloud.

Sensors gather environmental data and transform it into valuable information. Actuators and controllers change the environment to produce data, which they subsequently communicate to the gateways. The data gathering and conversion processes are handled by data acquisition systems (DAS). The DAS establishes a connection with the sensor network, computes the outputs, and carries out the conversions. The combined and digitalized data are delivered to the wired and wireless Internet gateway and over Bluetooth, ZigBee, Wi-Fi, wired LANs, LoRa/LoRaWAN, celluar, or the Internet[35]. To maintain security and prevent resource waste, the data are transmitted to edge IT, where they are secured before being sent to a data center, web server, or cloud. The data center or cloud is required for the data that require more processing or feedback since it is more powerful and can manage, analyze, and protect the data. In addition, nowadays the mobile APPs are becoming a more and more popular kind of the terminal option.

Table 1 List of acronyms used in this survey.

Acronym	Definition
AI	Artificial intelligence
AMI	Advanced metering infrastructure
API	Application programming interface
APP	Application
BASN	Body area sensor network
CPS	Cyber-physical system
DAS	Data acquisition system
DCS	Distributed control system
DER	Distributed energy resource
EPC	Electronic product code
EV	Electric vehicle
ICT	Information and communication technology
IoT	Internet of Things
ITS	Intelligent transportation system
LAN	Local area network
LPWAN	Low-power wide-area network
M2M	Machine to machine
MES	Manufacturing execution system
MMO	Massively multiplayer online
MVNO	Mobile virtual network operator
OID	Object identifier
OSN	Online social network
PLC	Programmable logic controller
P2P	Peer to peer
PV	Photovoltaic
QoS	Quality of service
QR code	Quick response code
RFID	Radio frequency identification
RSU	Road side unit
SCADA	Supervisory control and data acquisition
SG	Smart grid
SWM	Solid waste management
UID	Unique identifier
WMN	Wireless mesh network
WSN	Wireless sensor network

Besides the typical IoT architecture, attentions should be paid to the IoT-based platforms which are used in practice. Elements of an IoT platform can be divided into the following categories: essential features, technologies, infrastructural components, and applications. The above mentioned essential IoT features are implemented based on communication, system, interaction, and sensing technologies, such as M2M, mobile virtual network operator (MVNO), massively multiplayer online (MMO), body area sensor networks (BASNs), wireless sensor network (WSN), distributed control systems (DCSs), and so on. IoT platforms can be used in the diverse applications, such as transportation, home, retail, healthcare, safety, consumer, food, logistics, etc. The design of an IoT platform needs full considerations of the above elements and factors for a specific scenario, which is the sustainable digital community component in our study.

3 Sustainable community components

Based on IoT, we describe the key components in the sustainable digital community in this section, which include smart energy, smart building, smart transportation, and smart waste management. In general, these components are supported and enhanced by the IoT systems, if not motivated at the first time. Without IoT platforms and the most recent ICTs, it is not possible to maintain the sustainable operations of the communities with an increasing population density.

3.1 Smart energy management

Energy is the most important factor regarding the normal operations of the modern city and community. Without energy, especially electricity, there is no way to keep the basic functionality running as designed. A smart grid is an electrical grid which includes a variety of AMI-based operation and energy measures, smart distribution boards, smart circuit breakers, energy efficient resources, and more local control units[36]. Thanks to the distributed nature and self energy generation capability, smart grids support the resilience of the power system and lessen the effects of power outages, which improves the sustainability of the energy supply. DERs, loads, and power distribution equipment can all be measured, controlled, and actuated by a wide range of network devices that are part of the smart grid architecture, which was developed by CPS and IoT. Several typical smart grid characteristics are shown in Fig. 3, where the monitoring and control system interacts locally with nearby devices over a local area network, and externally, across a wide-area network, it communicates with its corporate network or power

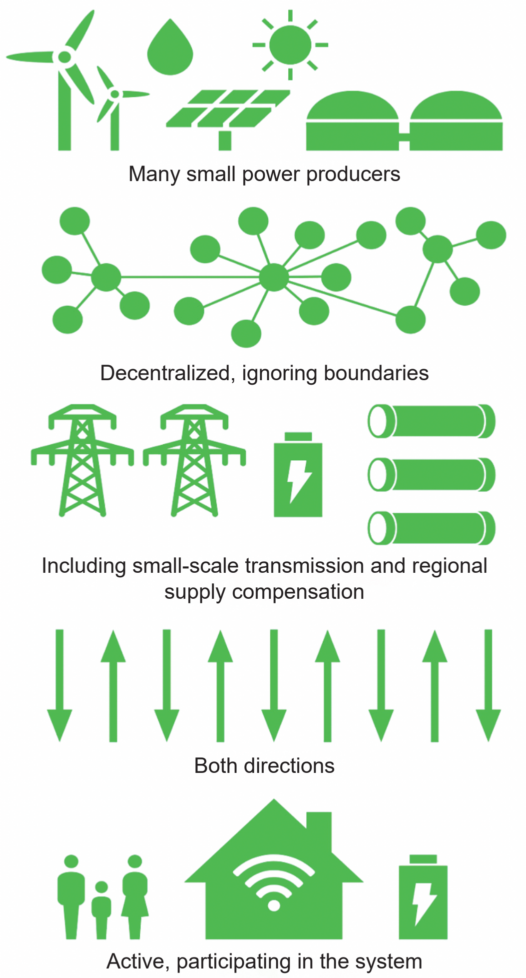

Fig. 3 Characteristics of a smart grid which include energy production, market, transmission grid, distribution network, and the participating customers (modified from Wikipedia[37]).

distribution systems. Smart grids provide decentralized energy services, ignoring boundaries with many small and flexible power producers. The monitoring and control of smart grids can be complicated since they can be viewed as an integrated power and energy system comprising DERs, loads, and distribution automation devices[38].

Smart grid is evolving into a more cooperative, highly intelligent, and adaptive power system as a result of the enormous improvement in AMI, big data, IoT, and AI. Accurately predicting the energy demand for a period of time in the future can provide strong support for many tasks, such as power grid scheduling, maintenance planning, stability analysis, new energy consumption analysis, and so on. When it refers to the operation, management, and planning of smart grids, the prediction of energy demand by end users as well as the energy generated by these green energy resources is becoming an increasingly important factor[39].

Due to the unpredictable and uncertain nature of everyday use, predicting the user's power profile is challenging. Energy management and operation of smart grids are exceedingly difficult and complicated due to the distributed deployment of DERs and the effects of dynamic pricing strategies on user power consumption behavior. On one hand, the intermittent nature of DERs makes it challenging to anticipate with accuracy how much electricity will be produced by these energy resources. The end user's energy needs, on the other hand, are variable and alter hourly, daily, monthly, and seasonally.

Recently, statistical models built using machine learning approaches for time-series analysis and in particular power load forecasting have received a lot of attention. Such an instance is the energy management in a smart community's short-term power load forecasts utilizing machine learning algorithms[39, 40]. The deep learning model has strong adaptive ability, flexible nonlinear modeling ability, and massive learning. Machine learning is an effective method to solve complex nonlinear systems and obtain accurate short-term power load forecasting results.

Wind energy is also a kind of smart energy with utilization value. There are large reserves of wind energy resources. However, wind energy is not available for all the communities. For those cities with available wind energy resources, through power system planning and operation scheduling, a large number of applications can be developed. The effective combination of wind energy and energy supply can help the development of smart green energy.

3.2 Smart building

With the IoT development, a few of the subsystems include interaction with building maintenance services, life safety, telecommunications, user systems, object management systems, and building automation that make up today's buildings into sophisticated intellectual systems. Modern smart buildings can be regarded as intelligent, green, and energy-efficient thanks to cutting-edge ICTs. There are great differences between the traditional buildings and smart buildings in terms of the sustainability impact on the communities. Water and energy usage can be reduced by up to 30% and 40%, respectively, in smart buildings. Building maintenance expenses may also be reduced by 10% to 30% in these structures[21]. The adaptive energy management concept for low-carbon communities is largely considered in terms of its architecture and energy costs. For example, multi-objective energy optimization has been implemented to achieve the intelligent energy consumption management in smart buildings[41]. In general, the purpose to implement a smart building is to maximize the use of local and sustainable energy sources, reduce emissions, and minimize their impact on the environment.

To fully utilize the possibilities of a smart building and maximize the general performance of a building using predictive analytics, a comprehensive analysis of big data is necessary. Due to the presence of sophisticated IoT infrastructure, many features such as temperature, light, energy consumption, or security can be handled and regulated separately or with the least amount of human participation. It is shown in Fig. 4 that the smart building infrastructure is a complex hierarchical system, including sensors measuring building status, smart devices, transport network, IoT service platform, cloud service, and the Internet. The hardware components build the foundations of the smart building, while the smart IoT services enable the intelligent functions.

3.3 Smart transportation

Transportation system has a strong connection with the energy consumption and air pollution emissions, which are both related to the sustainability of the digital communities. One of the most significant and persistent issues in transportation is energy usage[42]. In addition to energy use, transport is responsible for 26% of the world's carbon dioxide (CO_2) emissions. Finding more environmentally friendly transportation options is therefore more crucial than ever. CO_2, carbon monoxide (CO), nitrogen oxides (NO_x), nitrous oxide (N_2O), sulfur oxides (SO_x), fine particulates (PM10, PM2.5), and others are the principal air pollutants produced by petroleum-powered vehicle tailpipes[43]. In order to achieve optimal energy dispatch in low-carbon communities, smart and green mobility must be taken into account as controlled loads due to the global energy crisis and environmental concerns[44, 45]. Therefore, two main goals of the smart transportation in our study include making the transportation energy use more efficient and reducing the air pollution[46].

The two key components of smart transportation in a smart community are autonomous vehicles and smart traffic control management. Among other things, the IoT sensors installed in the vehicles can be used to

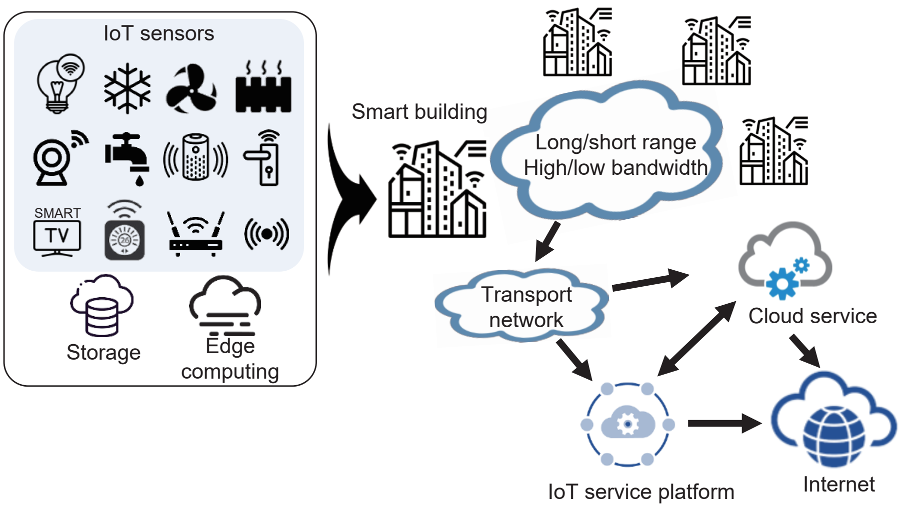

Fig. 4 IoT-based smart building infrastructure, including sensors, transport network, cloud, and IoT services.

track battery life, detect weather conditions, and provide directions, such as security[24, 25]. The IoT-based smart transportation system is briefly demonstrated in Fig. 5. Besides the sensors installed on the transportation tools, such as electric vehicles, buses, electric motors, subways, and bicycles, the IoT sensors are also used in the charging stations and the traffic flow control systems. Furthermore, to maintain the large-scale smart transportation system, it is necessary to utilize the wired and wireless communication technologies, such as telecommunications, and the cloud services. Thus, there is a plenty additional room for development to enhance sustainability, safety, and efficiency.

In order to make educated judgments in a safe and effective environment, smart traffic control ultimately aims to create a system that enables all vehicles, traffic signs, and control bases to communicate data with one another. Smart traffic control systems guide vehicles to avoid congestion through traffic signs and feed back vehicle travel information to the control base at the same time. The control base timely adjusts traffic signs based on road condition information and directs traffic. Large-scale data interchange is necessary for smart transportation. The capacity to predict the control flow based on traffic data is crucial in the field of smart traffic control. The traffic flow data can be collected not only through the surveillance cameras along the roads but also the GPS positioning information of the vehicles.

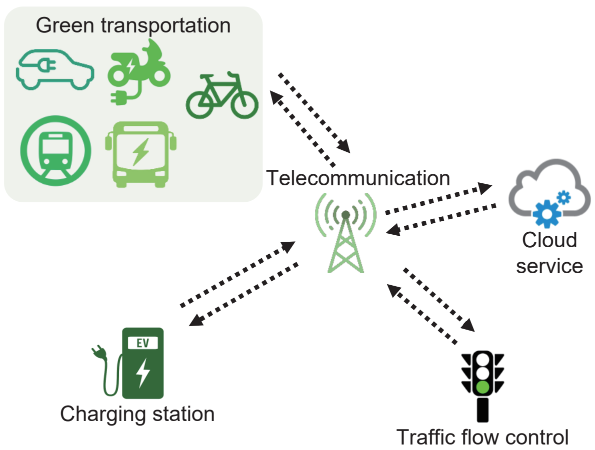

Fig. 5 Smart transportation system built on smart sensors and IoT-based public transportation networks.

Smart roads and traffic signs are equally crucial. The traffic signs and other road infrastructure may make decisions based on the traffic data gathered from the vehicles and the cameras that monitor all of the roads and intersections. Real-time data on the start, destination, and traffic flow will be all gathered, and based on the calculations that need to be done on them, the proper decisions will be sent to each component of the smart transportation system. Therefore, the traffic efficiency can be improved, leading to the reduction of energy consumption and the air pollution.

The driverless or autonomous vehicles of the future, which do not require people to make judgments, will play a significant role in transportation. The necessary data will be shared throughout all components of the smart transportation systems, and after conducting the proper analysis, the right decisions will be taken. IoT platforms can connect large-scale devices to the network for data transmission services and have high reliability for data communication and transmission. As a result, IoT-based solutions would gain popularity.

3.4 Smart waste management

In the digital community, waste management is a crucial component of an environmental management system. New sustainability and recycling targets are being established as a result of growing populations and shifting regulatory constraints. We produce a staggering amount of rubbish: in 2017, 267.8 million tons were estimated to have been produced, which not only consumes the resources but also affects the community's sustainability. Waste management has received widespread attentions. For example, a long-term waste management plan with elements of the circular economy and zero waste was authorized by the City of Toronto[47]. And the municipal solid waste recycling rate is set to be 70% by 2022[48].

IoT offers a significant opportunity to decrease trash, lower the operational costs of waste management enterprises, and enhance the level of service provided to citizens and businesses. In general, smart waste management has two main components: solid waste management and wastewater management, as shown in Fig. 6. IoT applications in smart waste management

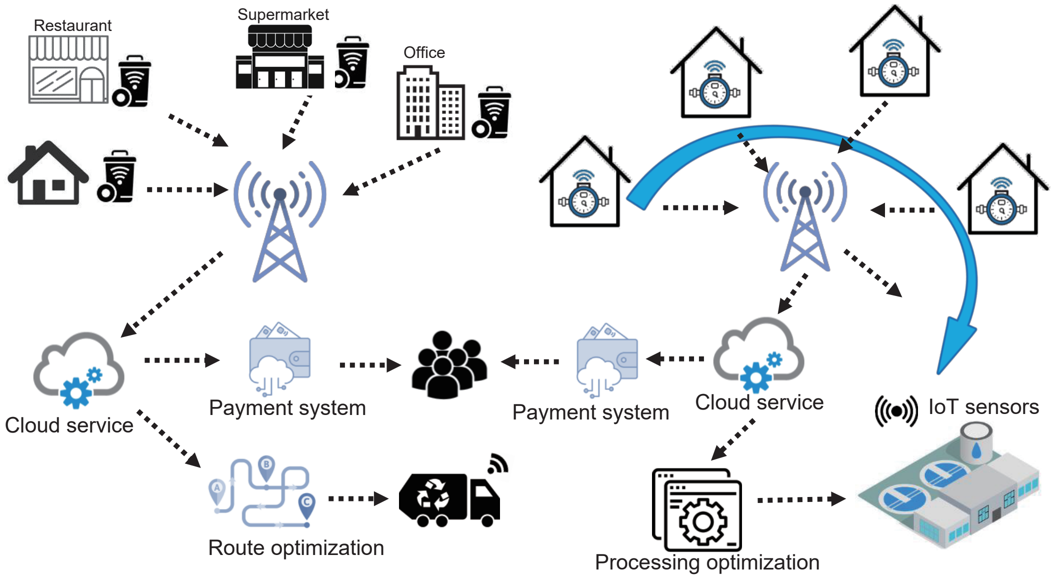

Fig. 6 IoT-based smart waste management infrastructure for solid waste and wastewater.

help our waste practices be more sustainable, therefore the whole community will be more sustainable.

(1) Smart solid waste management

The following is a summary of the solid waste management principles: "reduce", "reuse" , and "recycle" (3R), which are practical and effective to establish sustainability[49]. Leaner operations and better service delivery are the main aims of IoT applications in solid waste management. Urban operations are being managed by a growing network of interconnected autonomous systems, which is also reducing carbon emissions and increasing citizen experiences.

As an example of solid waste management, optimizing garbage collection can be improved by IoT solutions as a service for smart cities[50], as shown in the left part of Fig. 6. Data from numerous sensors and information systems are gathered and processed by the waste management system to provide important information about the degree of container filling, road congestion, and garbage truck location. Smart garbage bins with sensors can gather data on fill level, temperature, location, or any other types of information that the sanitation service deems helpful[51–53]. The collected data are then transferred to the cloud, where various waste management companies can access it, analyze it, and make predictions. The container can display information about the waste level or ongoing collection. The garbage truck will then only collect full or overdue containers, prompting the optimization of garbage truck routes. Clearly, IoT essentially contributes to continuously improved, sustainable, and cost-effective waste administration[54].

(2) Smart wastewater management systems

Water scarcity and water environment deteriorating become more and more serious issues in cities due to the fast urban growing population, which is projected to be 68% of the whole population and 6.3 billion in 2050, in the urbanization process[55]. The reuse of recycled water contributes to the decrease of the water scarcity[56]. As a result, wastewater treatment for both urban and industrial waste has become critical for smart cities, as shown in the right part of Fig. 6.

Smart wastewater management systems fulfil the requirements for freshwater in smart cities by using IoT sensors to detect and prevent combined sewage overflows and substances in wastewater. To monitor wastewater treatment process (WWTP), various types of sensors are involved, as wastewater contains dissolved organic and inorganic substances, as well as toxic elements, such as cadmium (Cd), zinc (Zn), copper (Cu), chromium (Cr), arsenic (As), mercury (Hg), lead (Pb), etc.[57] Smart sensing system includes pH sensor, temperature sensor, dissolved oxygen sensor, flow sensor, photo sensor, pressure sensor, gas sensor, chlorine sensor, water quality sensor, and so on.

Supervisory control and data acquisition (SCADA) systems can be used to describe current wastewater management systems, implement the water wastage reduction, prevent combined sewage overflows (CSOs), trace chemical detection, and indicate the necessity of leaky pipe replacement. However, SCADA systems have a number of drawbacks, including difficult installation and maintenance problems, increased prices, and difficulties with data analytics. The installation and maintenance difficulties can be solved by the development of IoT paradigm[58]. AI can then assist in data analysis to discover patterns for monitoring WWTPs and water pipelines. Water utilities may be able to improve the management and treatment of wastewater across facilities with the aid of IoT-enabled sensors and AI-driven big data analytics in smart wastewater systems. Through big data analysis, the wastewater treatment plant can quickly detect the abnormal conditions in the treatment process, adjust the operation content in time, and ensure the treatment effect. For example, by identifying sludge bulking fault variables, it is possible to identify whether sludge bulking occurs and solve it in time.

4 Future research opportunities

As a novel prototype, IoT has rapidly gained ground in the scenario of modern wireless communications and been applied in digital community applications. Besides the general research opportunities for IoT systems, such as the AI, distributed optimization, transmission efficiency, etc., future research prospects could include a number of unresolved difficult problems and fresh research trajectories.

4.1 Security

The concept of security is one difficult topic that currently tops the list of issues facing the digital world and will garner a lot of attention in the upcoming years[59, 60]. IoT-based infrastructure in the digital community makes cyberattacks a risky possibility. For example, smart home[33] and smart transportation[61] have shown vulnerabilities. In order to assess their customers' daily routines, smart device makers, for instance, gather data about their customers. As a result, the data collected by smart IoT devices may present a difficulty for data privacy during internet transmission[62]. Data from IoT applications must be protected from theft and tampering and stay confidential. For example, the intersection between the IoT and blockchain technologies has emerged, which provides a kind of secure solutions[61, 63, 64]. Although device-to-device communication has improved, there are still problems with scalability, availability, and response time. So, providing the secured environment is an important challenge in practical sustainable digital community implementation. Many security solutions, such as data-driven approaches using machine learning and deep learning solutions, have been developed for the existing systems and become more and more common in IoT security applications[19, 65, 66]. In order to ensure security and privacy in the smart communities, a general IoT security architecture typically relies on trusted third party authentication, which has other recognized problems. For example, the security standard scenario is not targeted enough, and there is a lack of a unified standard IoT security protocol. The recognized problems may result in a single point of failure[64].

4.2 Lack of common standard

The IoT platforms for devising applications and various smart devices have different origins. There are so many different manufacturers in the industry producing the IoT components. Therefore, we are facing an obvious difficulty of multivendor interoperability[67, 68]. The requirement is actual mutual. On one hand, every component of the whole IoT architecture requires the organized and formatted data from other components to effectively extract the target information. On the other hand, the generated data or results from one component should also be able to be used for the following processing and analysis steps. Otherwise, the data traffic among IoT components cannot be fully utilized or analyzed at all. Therefore, the manufacturers and vendors need to provide data format instructions to ensure that their data can be used. However, as a consequence, currently, there are too many IoT device and manufacturing industry standards. This is another challenge of the multivendor interoperability that IoT management platform needs to deal with. First, due to the varied standards, it is challenging to discern between devices linked to IoT systems that are approved and those that are not. Second, the latency of the IoT systems should be as small as possible, while the large amount of standards lower the IoT transmission efficiency. Thus, common standard and multivendor interoperability should be research focuses in the future real world digital community applications.

4.3 Network capacity

Thanks to the increasing wide usage of IoT devices, the data and information transmitted over the network are spiking every day. In order to deal with the increasing traffic among IoT devices, there is a great need to increase network capacity. So it is observable that different network technologies are emerging one by one. Narrowband IoT (NB-IoT) is a radio technology for low-power wide-area networks (LPWAN)[69], while the sixth generation standard (6G) currently under development for wireless communications technologies is based on satellites for larger areas with broadband services[70, 71]. Besides, another difficulty is storing the vast amounts of data on cloud servers for analysis and subsequent final storage. Therefore, improving the cloud services in terms of network speed and enlarging the database capacity also belong to the network capacity enhancement, which require research and engineering advancements. In addition, there is another possible way to increase the network capacity without large scale hardware replacement. It is possible to deploy the adaptive network planning or control strategies lower the peak network usage while maintaining the whole IoT system working on purpose.

5 Conclusion

We have provided a survey of a smart, IoT-based, sustainable digital community in this article. We began our investigation with some background information, including brief overviews of IoT technology, smart building, smart energy management, smart transportation, and smart waste management. The difficulties of IoT and the viability of the digital community have also been covered. Then, in terms of application scenarios and functionality, we have carried out a systematic and thorough analysis on the IoT paradigm in sustainable digital community. Finally, we have made an effort to briefly discuss potential directions for future research in this area. In conclusion, it is anticipated that IoT technology will considerably advance the digital community and empower the sustainability in terms of environment friendly and energy efficient development. We hope this survey paper can help forward the research community to a sustainable community.

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