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# An IoT enabled Smart City:
## Assessing the Applications, Resource Constraints, Existing Solutions and Research Directions

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**Abstract:** With the advancement of Internet of Things (IoT), smart city application design, development and deployment have been emerging research paradigms. Various IoT enabled smart city applications are expected to be equipped with huge IoT devices and linking these devices through proper connectivity and control facilities provides a basis for a plethora of applications and their services. Such applications are heavily affecting our daily lives in various domains such as healthcare, transportation, parking, environmental and weather monitoring, waste monitoring, smart homes and offices. The complexity of these applications can be understood by considering the constrained nature of resources at the node and network levels. This paper presents the recent studies in IoT enabled smart city applications with main attention towards highlighting the resource constraints in these applications especially limited processing, limited energy, limited storage and limited bandwidth. To address such resource limitations in smart city applications, the paper discusses the various architectural and virtualization based solutions in IoT and its related computing fields such as mobile computing, Wireless Sensor Networks (WSNs), fog computing, cloud computing, and big data analytics. Although the discussed solutions address the resource issues in such applications, there are challenges at the hardware and software level which needs to be addressed. This paper also highlights these challenges or research directions in resource-constrained IoT enabled smart city applications and these include mobility management, heterogeneity, security, scalability, fault-tolerance, Quality of Service, interoperability, connectivity and resource issues.

**Keywords:** Virtual Machines, Wireless Sensor Networks, Fog, Cloud, Big Data, Smart City

## 1. Introduction

Internet of Things is a network of physical and virtual devices that are linked through data capture and communication technologies [1]. Such networks are characterized by a high degree of autonomous data sensing, event transfer, network connectivity, and interoperability. With the advance in wireless, sensing, and pervasive technologies, we are stepping into the era of IoT enabled smart city [2]. Using these wireless communication mechanisms in tandem with humans, IoT has become one of the important mechanisms in smart city scenarios.

The key feature in IoT is its impact on the everyday life of potential users. Several sectors of our city are being benefited by IoT such as healthcare, homes, offices/public building, waste management, transport, weather monitoring, automation of public building, water supply, supply chain, etc., thus leading to a smart city. Therefore, IoT enabled smart city applications are heavily affecting our daily lives in various domains, but most of these applications are empowered by IoT devices whose resources are scarce such as limited energy, storage, processing, and bandwidth. As such efforts are required to manage the resources of these applications.

There has been research on architectural based solutions in Internet of Things that attempt to address the resource issues in the smart city. These include fog architecture to reduce delay and energy consumption [3], resource efficient WSN architecture [4], resource management method for remote storage and processing [5], etc. Also, there has been work in virtualization based solutions to address the resource issues in IoT and related computing fields such as mobile computing, Wireless Sensor Network (WSN), fog computing, cloud computing, and big data that support the smart city applications [6].

This paper aims to get a detailed overview of resource-constrained IoT enabled smart city applications city and discuses architectural and virtualization-based solutions as the possible ways to overcome the resource issues in such applications. In the end, research directions of resource-

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constrained IoT enabled smart city applications are discussed.

The rest of the paper is organized as: Section 2 discusses the research motivation, Section 3 discusses resource-constrained IoT enabled smart city applications, Section 4 highlights the resource constraints, Section 5 discusses the existing solutions for resource-constrained IoT enabled smart city, Section 6 gives research directions, and the conclusions has been given in Section 7.

## 2. Research Motivation

Figure 1 and 2 gives the global market size analysis for IoT enabled smart city applications from the year 2016 to 2020 in billions and percentage respectively [7]. According to the global market analysis of IoT enabled smart city applications, the IoT market is mainly dominated by smart cities with 26% of the global share. Followed by smart cities is the Industrial Internet of Things (IIoT), health sector, homes, connected cars, smart utilities, and wearable as shown in Figure 3 [8]. The huge global market size of IoT enabled smart city applications gives us the motivation to work in this field.

Further, to understand the current research trend that is conducted in smart city applications, we have analyzed the number of manuscripts that have been published from the year 1996 to 2018 [9]. As shown in Figure 4, there are 29,776 articles within the "Smart city" category, 26,357 for "WSN based smart city", 22,845 for "Mobile-based smart city", 19,564 for "IoT enabled smart city". The least number of manuscripts in IoT enabled smart city applications as compared to other manuscripts of smart city shows there has not been much research in this area, but the number of manuscripts from the year 2010 shows there has been a recent trend or a hike in research in this field, giving us the motivation to work in this field.

## 3. IoT enabled Smart City Applications

IoT is a network of smart and self-configuring devices that exchange data by interacting with the environment [9] [10]. The key feature in IoT is its impact on the everyday life as several sectors are being benefited by IoT such as healthcare, homes, offices/public building, waste management, transport, weather monitoring, automation of public building, water supply, supply chain, etc., thus leading to a smart city as shown in Figure 5.

Some of the IoT enabled applications that lead to significant growth in smart cities are:

### A. Healthcare

Sensors, integrated into the health monitoring equipment, collect information about the patients which is made available over the Internet to doctor for treatments [11] [12]. Many IoT based health applications connect patients to medical devices or sensors via smartwatches, smartphones, etc. to collect health data providing personal assistance and reminders [13]. In addition to this, the other benefits provided by IoT technologies to the health-care are real-time position tracking of objects or people in motion, identification of patients to reduce harm to patients, real-time information to patients, etc.

### B. Transportation

Several sensors are being installed in transportation such as buses, cars, trains, etc and even on roads to get valuable information such as a better route for traffic, management of depots, appropriate transportation information to tourists, monitoring of the transported goods, etc [14] [15]. IoT sensors installed on the traffic lights gather data to make intelligent decisions such as reduced traffic jams, resulting in low emissions. Further, a dynamic street lighting system in smart cities adjusts lighting intensity according to real needs and saves electricity up to 50% [16].

### C. Parking

IoT sensors are also used in smart parking systems to keep track of vehicles such as the number of vehicles left and entered, number of vehicles in the parking, number of free slots available for vehicle parking, etc [17].

### D. Environment and Weather Monitoring

Various crowdsourcing environmental monitoring systems have sensors installed across the city to measure various environmental factors such as relative humidity, nitrogen dioxide, temperature, etc. to check if any one of these goes above a set threshold and then sends an alarm to the habitat's phones [18] [19].

### E. Waste Monitoring

The IoT technology results in significant improvement in management of wastes e.g. smart waste containers can make use of sensors to determine a load of waste in containers that help to optimize the route of waste collector trucks to clean the waste quickly, thereby reducing the cost of waste collection and improving the recycling quality [20].

### F. Homes and Offices

Smart homes and offices use IoT technology to identify a set of individuals as authorized depending on some device e.g., mobile phone they have with them while they enter the house. If an individual is an unauthorized person, an alarm is sent to the house owners [21]. Also, sensors and actuators are installed in different electronic gadgets to use energy efficiently and provide extra comfort to our life in homes and offices [22] [23]. Even IoT devices are installed in homes and offices to efficiently monitor the supply of water and send alerts in case of problems [24] [25]. Table I shows the classification of recent studies and related information in IoT enabled smart city applications.

## 4. Resource Constraints

Most of the IoT enabled smart city applications are empowered by IoT devices whose resources are scarce [26]. The complexity of resource-constrained IoT enabled smart city applications can be understood by considering

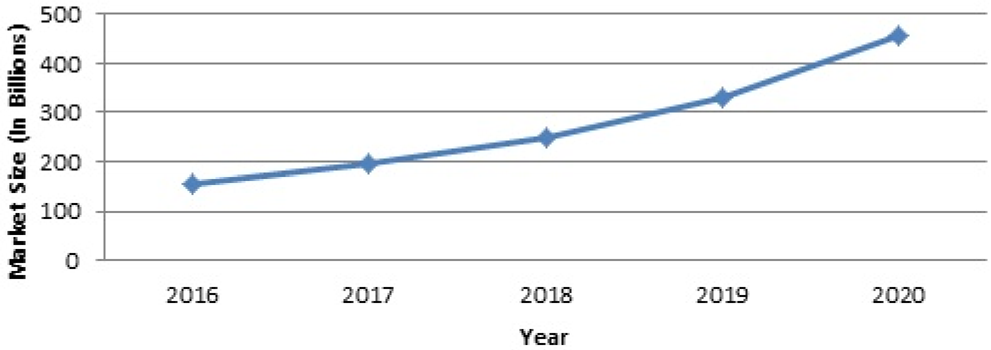


Figure 1. Global Market Size (in Billions) for IoT enabled Smart City Applications

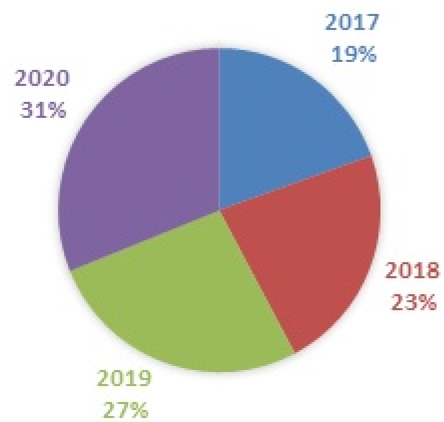


Figure 2. Global Growth Rate of IoT enabled Smart City Applications

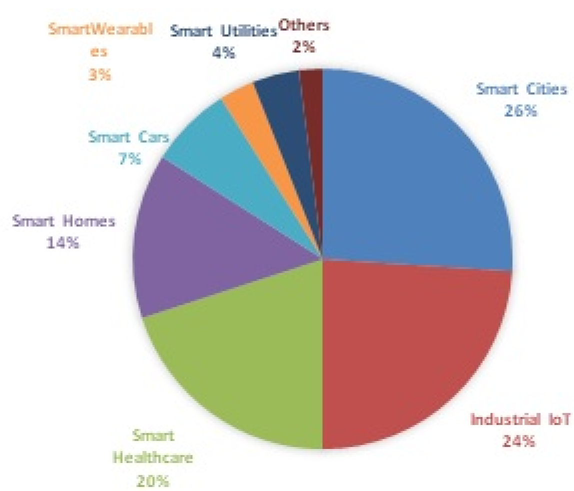


Figure 3. Global Market of IoT enabled Smart City Applications for the Year 2020

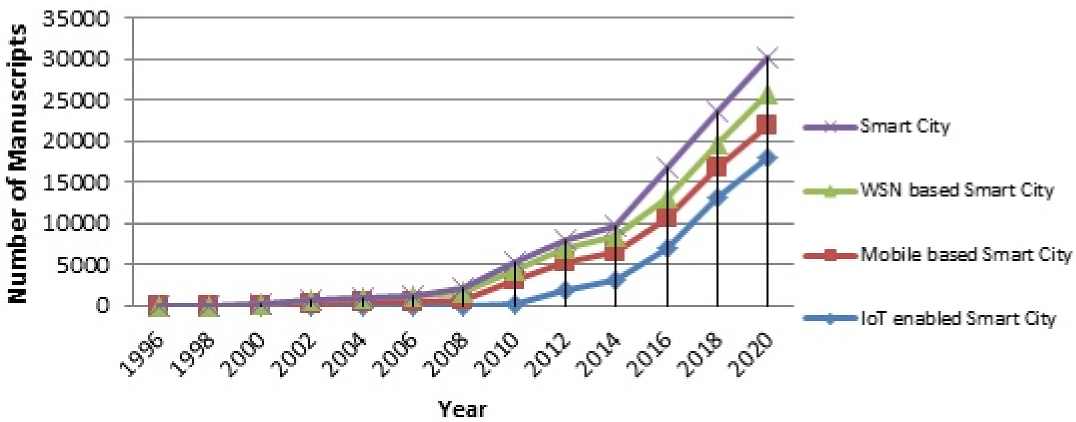


Figure 4. Number of Manuscripts in Smart City versus Year

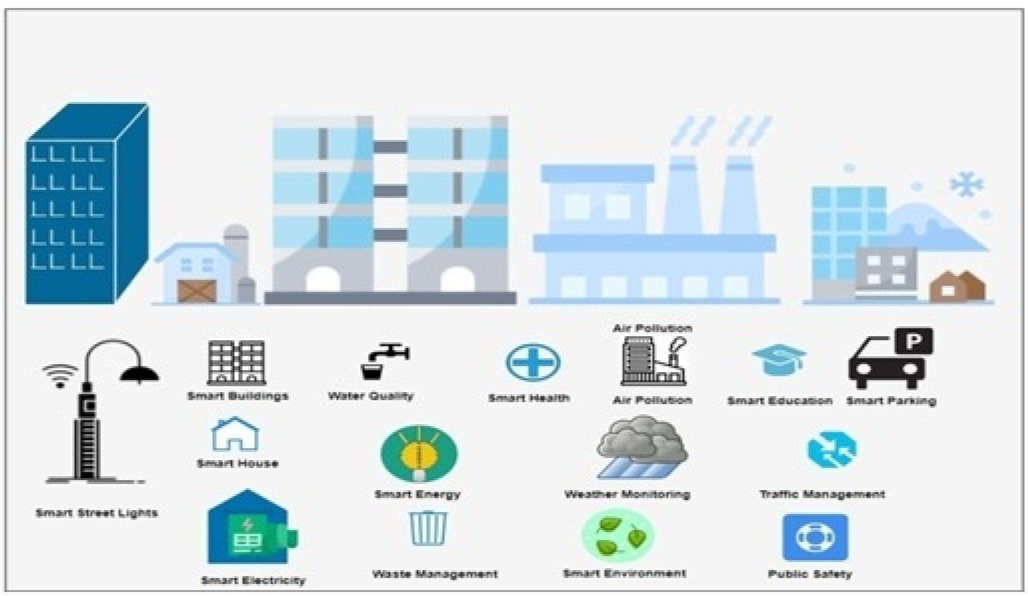


Figure 5. IoT enabled Smart City

the nature of limited resources at the node and network levels. These include limited energy, limited bandwidth, limited processing and limited storage. Table II shows the resource constraints of IoT enabled smart city applications. It is evident from this table that the IoT enabled smart city applications employ devices characterized as resource-constrained micro-systems that use sensors to monitor their environments; as such the main trade-off in such applications is to have automated environments against constrained resources.

## 5. Existing Solutions for Resource-Constrained IoT enabled Smart City

There has been work in architectural solutions, designed to have efficient management of resources in such applications. These solutions aim at resource optimization by incorporating high-end devices to carry out the computation and hence improve the overall performance of such applications. Also, virtualization based solutions help to optimize the available limited resources by creating multiple virtual instances of physical resources that can be used by multiple devices or applications. Various architectural and virtualization-based solutions are discussed below.

### A. *Architectural Solutions*

Depending on the specific requirements and design constraints of smart city applications, the architecture may vary e.g. EPC global IoT architecture for smart IoT network [27], smart office IoT architecture [28], etc. There is no standard architecture that is appropriate for the smart city applications but based on the available literature, IoT architectures can be classified into centralized, distributed,

TABLE I. classification of recent studies and related information in IoT enabled smart city applications

| IoT enabled Smart City Applications | Related Work | Proposed Solution | Performance Parameters | Benefits | Limitations |
|---|---|---|---|---|---|
| Healthcare | Disease management [11] | Algorithm | Cost, Reliability | Better reliability | Evaluation is hypothetical |
| | Healthcare Monitoring [12] | Algorithm | Response time, cost, throughput | Low response time | Cost overheads |
| | Remote Medical Monitoring [13] | Architecture | Response time, energy consumption | Better rapidity and precision of sensed data | Cost is not taken into consideration |
| Transportation | Vehicular Monitoring [14] | Framework | Response Time | Low response time | Cost is not taken into consideration |
| | Traffic Management [15] | Algorithm | Response time, energy | Low response time, latency, and energy usage | Scalability is less |
| Parking | Vehicle Tracking [17] | Algorithm | Response time | Vehicles left, entered, free slots available | Cost is not evaluated |
| Environment and Weather Monitoring | Crowdsourcing environmental monitoring [18] | Architecture | Response Time | Temperature, humidity, carbon- dioxide, etc | Cost is not taken into consideration |
| | Weather Monitoring [19] | Architecture | Response time, reliability | High scalability, reliability | Cost is not taken into consideration |
| Waste Monitoring | Domestic waste treatment and disposal [20] | Model | Response time | High efficiency and accuracy | Cost and power are not evaluated |
| Homes and Offices | Integrated message-oriented architecture for smart home [24] | Architecture | Energy, bandwidth, storage, processing | Improve reliability, low resource overheads | Cost is not evaluated |
| | Smart offices and homes [22] | Model | Energy consumption | Improved energy | Cost is not supported |
| | Smart Energy [25] | Architecture | Energy | Remote control of home electrical devices | Not evaluating cost |

and service-oriented architectures as discussed below.

- Centralized Solutions: The work in [28] presents a centralized scheduling method, 6TiScH that aims at the optimization of resources. The work in [29] also presents a centralized architecture, based on web resources, to decouple the domain of heterogeneous devices from the application development. But due to the no scalability and interoperability problems, it is considered less suitable for smart city applications.
- Distributed Solutions: To overcome the disadvantages of centralized architectures, the distributive IoT architectures have been introduced in a smart city [30]. Figure 6 depicts a distributive IoT application consisting of communication among the Edge, IoT server cloud, and end-user. In this architecture, the devices can retrieve the process and present the data for other devices and end-users. A distributive IoT enabled smart city is characterized as a collection of autonomous devices communicating over a communication network and have a common goal. The disadvantages encountered in this approach are a security breach and excessive energy consumption

TABLE II. classification of recent studies and related information in IoT enabled smart city applications

| IoT enabled Smart City Applications | Energy Constraint | Storage Constraint | Processing Constraint | Bandwidth Constraint |
|---|---|---|---|---|
| Waste Monitoring | ✓ | ✓ | ✓ | ✓ |
| Healthcare [11] | ✓ | ✓ | ✓ | ✓ |
| Transportation [14] | X | ✓ | ✓ | ✓ |
| Parking [17] | X | ✓ | ✓ | ✓ |
| Environment and Weather Monitoring [18] | ✓ | ✓ | ✓ | ✓ |
| Waste Monitoring [20] | ✓ | ✓ | ✓ | ✓ |
| Homes and Offices [22] | X | ✓ | ✓ | ✓ |

[31].

- Service-Oriented Solutions: In smart city applications, the Service-Oriented Architecture (SOA) consists of autonomous services executing on devices with many service providers. It enables the decomposition of large networks into well-defined networks [32]. Considerable work in Service-Oriented Architectures for IoT enabled smart city applications to include OASIS Service Oriented Architecture [33], a micro-subscription management system (mSMS) [34], Knowledge Aware and Service-Oriented architecture (KASO) [35], Ambient Intelligent middleware [36], etc. SOA is considered applicable for IoT enabled smart city applications but there are many challenges in these such as security, limited resources, etc [37].

### B. Virtualization based Solutions

Virtualization has a wide research area that has many applications in smart city e.g; it can be used in IoT devices such as laptops, notebooks, smartphone, tablets, wearable sensors, IoT sensors, etc. which play an essential role in common life and can turn any city into a smart city [38]. Virtualization creates a virtual version of a device or resource e.g., desktop, operating system, server, etc [39]. Resource optimization is one of the key drivers for deploying virtualization-based solutions in IoT enabled smart city. It provides one of the best means to improve resource utilization and simplify data center management [40] [41]. The research in virtualization-based solutions for IoT enabled smart cit applications is still going on. Some of the prominent works in this include an OpenFlow framework that aims to virtualize the IoT environment [42], device virtualization by containerization [43] [44], docker, and LXC container virtualization [45] [46], etc. There is a diverse set of applications in which virtualization allows cities to efficiently utilize its assets and resources to become smart. For example, by using network Virtualization in a city, it is possible to build flexible, programmable, and interoperable networks offering better connectivity.

Similarly, virtualization when integrated with devices (e.g.; desktop, servers, storage, etc.) allows pervasive access to useful data generated in smart city applications. Virtualization also allows efficient utilization of smart city infrastructure (e.g. storage, network, etc.) and even applications can be managed efficiently in smart cities. Due to the advancement in related fields of IoT such as Mobile Computing, WSNs, Fog Computing, cloud computing, and big data that enable a multitude of day to day applications, smart cities are becoming a reality. These computing environments play an important role to deploy applications in smart city and virtualization-based solutions help to optimize the resources in such applications, creating an environment that can understand its surroundings, improves the quality of life, and therefore creates a smart city against resource-constraints.

- Mobile Computing: Mobile computing is an important player for IoT related applications in Smart Cities. It is a paradigm that describes the use of computing devices such as cellular phones, Wi-Fi/Bluetooth enabled PDAs, WSN nodes, etc. Due to the increased number of IoT devices, mobile computing has become very important especially in smart cities. But mobile devices are resource-constrained devices due to their limited computing capabilities like data storage, data processing, etc [47]. Mobile Cloud Computing is a fast-growing research field that shifts the computation from mobile devices to the

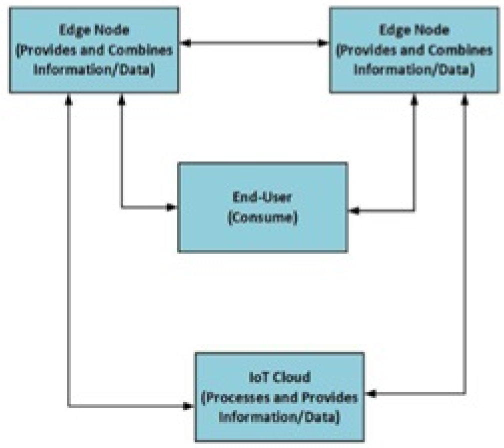


Figure 6. Distributed IoT enabled Smart City Scenario

TABLE III. Offloading Frameworks

| Offloading Frameworks | Benefits |
|---|---|
| Cuckoo [49] | Enhances performance and reduces battery usage |
| CloneCloud [50] | Reduces workload and enhances computational capability |
| Multi-site adaptiveoffloading (MaMoc) [3] | Leverages the power of multiple offloading destinations |
| ThinkAir [51] | Enhances computational capability |
| Cloudlet [52] | Resource assistance to mobile devices |
| Mirror Server [4] | Provides resource-rich aid and reduces workload in smartphones |

cloud [48]. Various offloading frameworks that use virtualization as the basic principle include Cuckoo [49], CloneCloud [50], Mamoc [3], Thinkair [51], Cloudlet [52], Mirror Server [4] (see Table III). Virtualization in Mobile Computing is emerging in importance, besides offloading in mobile computing, there are many other limitations in mobile computing for which virtualization will be fruitful which includes: Security Compatibility Issues, Cost Savings, etc.

- Wireless Sensor Networks: Wireless Sensor Networks has been a prominent part of IoT with the advancements in wireless communication and pervasive technologies [53]. The WSNs find important applicability in smart city domains but there are demerits in WSNs and these include limited computation, memory, and bandwidth [54].The use of virtualization in WSNs addresses these issues by optimizing the processing, storage, and energy usage [6] [55]. Virtualization in WSNs can be done at the device (node) level or the system (network) level [56]. In node level virtualization, a physical node is converted into multiple logical instances with different tasks running on each of these logical instances. While as in network-level virtualization, the physical network is virtualized in such a way multiple applications run on these multiple virtual networks. Software-Defined Networks (SDN) and Network Virtualization (NV) are two technologies that allow virtualization of devices like network interface cards, switches, bridges, LAN, routers, etc. to provide benefits such as reduced deployment costs, scalability, versatility, etc. For example, HyperFlex is an SDN hypervisor architecture supporting virtualization [57] [58]. The concept of virtualization in Software Defined Networks is a key enabler for sensor node deployments in WSNs. The other benefits of virtualization in WSNs include redundant data management, fault tolerance, heterogeneity in devices, less energy consumption, etc [59].

- Fog Computing: Fog computing enhances the cloud capabilities and services to the edge of the IoT network [60]. There are advantages of fog computing such as reduced delay, data accuracy, improves QoS, etc in several domains that play an essential role in smart city application design and deployment but there are also many issues (e.g., migration of services among devices and between device and cloud level) [61] [62]. To address these issues, virtualization plays an essential role in fog applications. Various virtualization-based fog computing simulation tools are employed to allow offloading of computation. It helps in pushing more applications and computing ability to the network edge with security in place by incorporating virtualization at the network edge.

- Cloud Computing: Many of us confuse cloud computing with that of virtualization but these are different. Cloud aims to provide information technology as a service to the cloud user on-demand basis while virtualization abstracts compute resources with associated storage and network connectivity [63]. Figure 7 shows the concept of virtualization in Cloud Computing [64]. The IoT devices in smart cities lead to the explosion of data and it demands more computational capabilities for data processing [65]. Due to this, the huge device number and enormous data size are the main concerns in IoT enabled smart city environment. Internet of Things and Cloud computing are the technologies that have become part of our life and adoption of these technologies is expected to be more pervasive, making them important components of the Future Internet [66] [67]. The IoT devices sense the environment and send it to either other devices (IoT or edge devices) or to cloud for further storage and processing of datasets. From the IoT side, it is virtualizing the physical devices into virtual devices before the data is uploaded to the cloud. On the cloud side, programmers must introduce the means for the cloud to discover devices that are located in different places. Thus, the cloud is an interface between the physical sensing IoT devices and applications utilizing data generated by these IoT devices.
  Network virtualization plays an important role in integrating IoT devices with the cloud to deal with the inherent complexity in such environments [68]. Many cloud-based virtualization solutions improve the hardware utilization of IoT devices [69]. Thus, IoT enabled smart city applications have adopted the cloud as the universal solution to meet many challenges especially the resource constraints in IoT environments.

- Big Data: Big data processing and analysis need to be done on the voluminous data generated by IoT objects [70]. The collaboration of Big data with IoT creates numerous opportunities for processing, transformation, and analysis for IoT systems. In IoT, the data in huge amounts and variety is gathered from sensors and actuators, and finding valuable information in IoT data has become a key concern. Thus, IoT is considered to be one of the largest sources of big data i.e., the devices connected to the IoT result in data explosion which tends to the growth of big data to perfectly overlap with the IoT. The real-time IoT based applications demand analysis of the data on the go. The various real-time analysis employs data learning techniques to get the hidden insights in big data and extract patterns or useful information. These include machine learning techniques for data analysis [71], Reinforcement learning for data analysis [72], deep learning techniques [73], etc. But the main problem in these includes the resource-constrained IoT devices that cannot be used to carry out the real-time analysis at the node level. Also, due to the rapid growth of heterogeneous data in computation-intensive applications of smart cities, there is a need for management of these highly distributed data stores in such environments. Virtualization based solutions help to make these highly complex environments a reality by providing the added level of efficiency to such scenarios. Considerable work in this includes a context-aware system for IoT-cloud data analysis [74], node virtualization aware data analysis [75], network-level virtualization for analysis of data [76], etc.

Table IV shows the classification of the above-discussed papers and related information.

**Limitations of existing solutions**: Most of existing solutions for resource constrained IoT enabled smart city focuses on one or more resources especially energy. None of the solution focuses on all resources.

## 6. Research Directions in Resource-Constrained IoT enabled Smart City

Although a large number of small-sized IoT devices have been largely deployed in IoT enabled smart city applications, there are several challenges at the hardware and software level. The challenges pay a way to research IoT enabled smart city applications. These are:

### A. Mobility Management

In IoT enabled smart city applications, where devices are mobile, the resource consumption occurs at a higher rate because there are frequent calculations involved in determining the location and distance of mobile devices [77]. The resource-constrained IoT enabled applications of smart city face a major challenge in terms of mobility, as it impact the performance of the IoT network in terms of storage, processing, communication and energy overheads. In addition to these, connectivity, Quality of Service (QoS), reliability, stability, etc is also affected by mobility. Several efforts have been to support mobility and these include mobile cluster heads (sink) which gather information from stationary IoT devices instead of having mobile IoT devices [78] [79]. It improves the resource efficiency of IoT applications in smart city.

### B. Heterogeneity

Heterogeneity is an important research topic in Internet of Things. Since heterogeneity appears at the data and device levels, therefore managing heterogeneity becomes a challenging tasks in IoT network [80] [81]. Heterogeneity is also experienced at resource level such as energy,

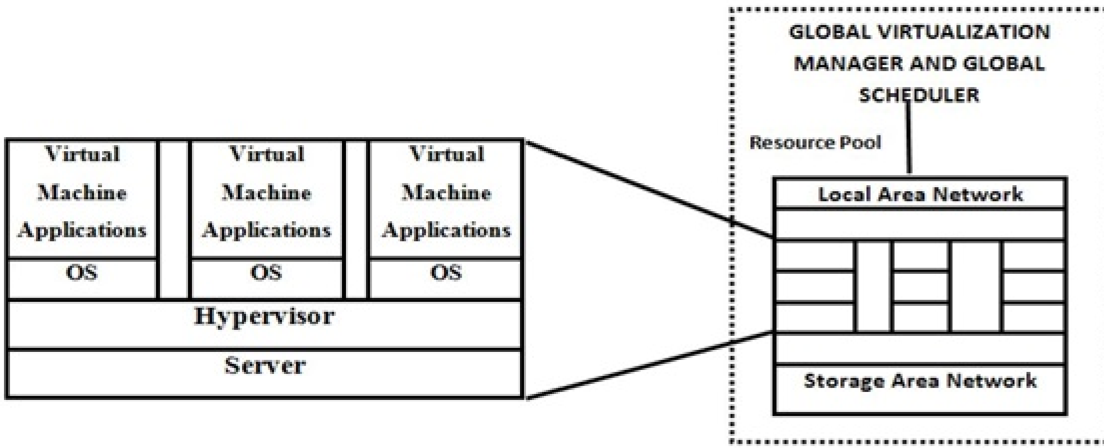


Figure 7. Virtualization in Cloud Computing

TABLE IV. classification of the existing solutions and related information

| **Related Fields of IoT in Smart City** | **Virtualization based Solutions** | **Performance Parameters** | **Benefits** | **Limitations** |
|---|---|---|---|---|
| Mobile Computing | Offloading Frameworks based on virtualization [50] [51] | Computation, Latency | Offloads the computation from devices to the cloud | Existing Work in IoT is less at the node level |
| Wireless Sensor Networks | Tiny virtual machines in WSNs [56], SDNs and network virtualization [59] | Energy | Sensor devices have the processing power, storage, and energy usage | Exploration of Work at the Node level |
| Fog Computing | SDN based Fog computing solutions [61] [62] | Latency | Shifts the computation from IoT devices to the cloud | Less work in Fog virtualization |
| Cloud | Processing of sensor data on the cloud [66] [67] | Storage, Latency | Cloud-based virtualization improves the hardware utilization of IoT devices | Exploration of Work at IoT Node level |
| Big Data | Machine learning for data analysis [70], Reinforcement learning for data analysis [71], deep learning techniques [75] | Storage | manages issues in data such as heterogeneity, performance issues, complexity, real-time analysis, etc. | Balancing resource limitations and big data |

storage, processing, communication unit, etc. The resource-constrained IoT devices should be supported at the resource level for the network to operate efficiently for a longer time with efficient resource management.

### C. Security

Security is a challenging research task for IoT applications having limited resources. Predominant research is done on lightweight key management protocols for resource constrained IoT devices that guarantee data confidentiality and constrained node authentication during data transmission along the channel. The limitation of the work is that the security protocol does not specify resource overheads in IoT environments [82] [83] [84].

### D. Scalability

Scalability is a common challenge that is faced in resource-constrained IoT enabled smart city applications. Due to large number of devices, IoT network should be adopted to scalable i.e. support thousands of devices to keep the network connected [85]. Increasing the number of devices in IoT network leads to transmitting data at a shorter distances that leads to more control packers in the network thereby adding to more consumption of resources especially energy to an already resource-constrained IoT device. Therefore, scalability becomes an important challenge in resource constrained IoT environments.

### E. Fault Tolerance

Resource limitations especially energy limitation in IoT device causes node failure in IoT. Node failure can also lead to connectivity or coverage failure which leads to data loss if it happens to resource-constrained sensors. To avoid such issues, various fault tolerance mechanisms are employed to replace failed devices and keep IoT network stable [86] [87] [88].

### F. Quality of Service

Supporting Quality of Service in IoT has always been a challenging task. Since most of the IoT enabled smart city applications are resource constrained, there needs to be a balance in these resource parameters. In addition to this, there are different aspects such as jitter [89], delay [90], throughput [91], etc that are to be taken into consideration to support QoS in IoT.

### G. Interoperability

Smart city applications require connecting heterogeneous IoT devices, heterogeneous applications and services among themselves. Interoperability is a major challenge in IoT applications which requires efficient management of resources. Interoperability issues occur at the protocol level which affects the hardware and software implementations. Interoperability issues are also seen at the data level e.g. interpretation of data contents [92] [93].

### H. Connectivity

Device connectivity in IoT networks is a challenging issue in which lots of research is carried out nowadays. As the IoT devices ae designed by different standards and technologies, there exists a major challenge of connectivity in applications deploying these devices. There are various challenges of IoT connectivity such as signaling issues, security, presence detection, resource limitations, etc. There are many aspects such as fault tolerance, reliability, communication, etc that depends on the connectivity in IoT networks. Various cluster based mechanisms are used to improve the connectivity issues in smart city IoT environments [94] [95].

### I. Resource constraints

IoT uses embedded devices that are resource-constrained when it comes to storage, computation, communication, bandwidth, energy, etc but the following aspects demand it to be resourceful [27]:

- It should also possess communicational capabilities to integrate the huge number of devices with the Internet.
- It should also possess storage capabilities to store the bulk of data generated by the IoT devices.
- It should also possess processing capabilities to process the bulk of data generated by the IoT devices.
- These are resource-constrained when comes to energy and bandwidth as well.

Efforts need to be made to make resource-constrained behavior of IoT devices into resourceful, which is considered as one of the major open challenges in IoT enabled smart city applications. Table V shows the number of manuscripts published from the year 2011 to 2020 in each of the above discussed research directions of resource-constrained IoT enabled smart city applications.

## 7. Conclusions

With the advance in wireless, sensing, and pervasive technologies, we are stepping into the era of IoT enabled smart city. These applications are heavily affecting our daily lives in various domains but most of these applications are empowered by IoT devices whose resources are limited. Various architectural and virtualization-based solutions in Internet of Things and its related computing fields such as mobile computing, Wireless Sensor Network (WSN), fog computing, cloud computing, and big data to support the smart city applications. The architectural and node-level solutions need to be designed to operate efficiently on the small-sized resource-constrained environments. An efficient resource management architecture is required that manages the limited resources of IoT devices to optimize the overall performance of IoT systems. As the number of IoT enabled smart city applications is increasing, more focus on virtualization has been on resource management

TABLE V. Number of Manuscripts in Research Directions from Year 2011-2020

| Year | Mobility | Heterogeneity | Security | Scalability | Fault Tolerance | Quality of Service | Interoperability | Connectivity | Resource-constraints |
|---|---|---|---|---|---|---|---|---|---|
| 2011 | 4 | 140 | 110 | 19 | 14 | 210 | 7 | 50 | 410 |
| 2012 | 6 | 150 | 120 | 39 | 16 | 220 | 16 | 120 | 320 |
| 2013 | 20 | 160 | 130 | 40 | 120 | 230 | 27 | 130 | 530 |
| 2014 | 25 | 173 | 143 | 45 | 125 | 243 | 78 | 243 | 433 |
| 2015 | 45 | 156 | 145 | 55 | 145 | 245 | 56 | 255 | 435 |
| 2016 | 50 | 143 | 160 | 70 | 150 | 260 | 75 | 260 | 401 |
| 2017 | 40 | 244 | 250 | 65 | 140 | 350 | 67 | 250 | 501 |
| 2018 | 60 | 333 | 350 | 50 | 160 | 450 | 97 | 350 | 611 |
| 2019 | 40 | 343 | 300 | 80 | 140 | 400 | 79 | 300 | 410 |
| 2020 | 30 | 205 | 190 | 70 | 80 | 290 | 89 | 190 | 378 |

in such environments. Virtualization in the following forms can help in dealing with issues arising due to resource-constrained IoT enabled smart city applications. With server virtualization, IoT enabled applications can handle data of large volumes and varied types. Data virtualization allows us to access heterogeneous infrastructure as if it were one unified resource. Application virtualization manages applications and improves the overall portability of the IoT environments. Further, virtualizing the network improves the capability to manage the large distributed IoT devices and help in big data analysis. Processor virtualization optimizes the performance of processor which is the need of the hour for IoT applications in smart cities dealing with extra processing and data analysis requirements. The virtualization of memory decouples memory from the servers. Also, the advanced big data analytics in the smart city environment requires lots of memory (RAM) and memory virtualization helps to solve this problem. Storage virtualization manages data efficiently in smart cities with minimum storage costs. Therefore, with architectural and virtualization-based solutions for resource-constrained IoT enabled smart city applications; the information can flow to the end-users seamlessly. Although a large number of resource-constrained IoT devices have been deployed in IoT enabled smart city applications, there are several potential open challenges at the hardware and software levels, which need our special attention.

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