Abstract—The drastic increase in urbanization over the past few years requires sustainable, efficient, and smart solutions for transportation, governance, environment, quality of life, etc. The Internet of Things (IoT) offers many sophisticated and ubiquitous applications for smart cities. The energy demand of IoT applications is increased, while the IoT devices continue to grow in both numbers and their requirements. Therefore, smart city solutions must have the ability to efficiently utilize energy and handle associated challenges. Energy management is considered as a key paradigm for the realization of complex energy systems in smart cities. In this article, we present a brief overview of energy management and challenges in smart cities. We then provide a unifying framework for energy-efficient optimization and scheduling of IoT-based smart cities. We also discuss the energy harvesting in smart cities, which is a promising solution for extending the lifetime of low power devices and its related challenges. We detail two case studies, the first one targets energy-efficient scheduling in smart homes and the second covers wireless power transfer for IoT devices in smart cities. Simulation results for case studies demonstrate the tremendous impact of energy-efficient scheduling optimization and wireless power transfer on the performance of IoT in smart cities.

I. INTRODUCTION

The smart city solutions use communication and networking technologies for dealing with the problems precipitated by urbanization and growing population. Internet of Things (IoT) is a key enabler for smart cities, in which sensing devices and actuators are major components along with communication and network devices. The sensing devices are used for real-time detection and monitoring of city operations in various scenarios. It is projected that in the near future, common industrial, personal, office and household devices, machines, and objects will hold the ability to sense, communicate, and process information ubiquitously [1]. However, it is challenging to design a fully optimized framework due to the interconnected nature of the smart cities with different technologies. Further, smart city solutions have to be energy efficient from both users and environment point of views.

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These challenges forced network designers to consider a wide range of scenarios in different conditions for IoT-enabled smart cities. Thus, an efficient deployment of sensors and optimized operational framework that can adapt to the conditions is necessary for IoT-enabled smart cities. In other words, smart city solutions have to be energy efficient, cost efficient, reliable, secure, etc. For example, IoT devices should operate in a self-sufficient way without compromising the quality of service (QoS) in order to enhance the performance with uninterrupted network operations [2]. Therefore, energy-efficiency and life span of IoT devices are the key to the next generation smart city solutions.

We classify the energy management in smart cities into two main types: 1) energy-efficient solutions and 2) energy harvesting operations. This classification along with few examples of research topics is shown in Fig. 1. Energy-efficient solutions for IoT-enabled smart cities include a wide range of topics such as lightweight protocols, scheduling optimization, predictive models for energy consumption, cloud-based approach, low power transceivers, and cognitive management framework [3]–[5]. Energy harvesting allows IoT devices to harvest energy from ambient sources and/or dedicated RF sources. The aim of energy harvesting is to increase the lifetime of IoT devices. The research topics include within both types of energy harvesting are energy harvesting receiver design, energy arrival rate, placement of a minimum number of dedicated energy sources, scheduling of dedicated energy sources, and multi-path energy routing [2], [6].
Both academia and industry are focusing on energy management in smart cities. IEEE in partnership with International Telecommunication Union (ITU) has smart cities community with an aim to provide assistance to municipalities for the transition to smart cities. Fujitsu suggested an approach for energy management for companies and has introduced an energy management system for smart buildings as cloud service [7]. In addition, companies such as IBM, Cisco, Honeywell, Intel, and Schneider Electric are involved in various energy efficient solutions for smart cities. There are various projects on energy efficient smart cities sponsored by the seventh framework programme (FP7) for research of the European Commission in last few years. For example, the main objectives of “Reliable, Resilient, and Secure IoT for Smart City Applications” project are to develop, evaluate, and test a framework of IoT-enabled smart city applications in which smart objects can operate energy efficiently [8]. The “ALMANAC: Reliable Smart Secure Internet of Things For Smart Cities” project focuses on IoT-enabled green and sustainable smart solutions [9]. Likewise, energy-saving solutions are developed for smart cities under the projects entitled “Planning for Energy Efficient Cities (PLEEC)” and “NiCE-Networking Intelligent Cities for Energy Efficiency”.

In this article, we consider energy management for IoT in smart cities. An illustration of smart cities with the focus on smart homes is shown in Fig. 2. Our contributions can be summarized as follows:

- We provide an optimization framework for research in IoT-enabled smart cities. We present the objectives, problem type, and solution approaches for energy management.
- We cover the energy-efficient solutions for IoT-enabled smart cities. A case study is presented to show the performance gains achieved by scheduling optimization in smart home networks.
- Next, we devote a section to energy harvesting for IoT-enabled smart city applications. A case study is provided to investigate the performance gains achieved by the scheduling of dedicated energy sources.
- Finally, the conclusions are drawn and we provide future research directions for energy management in IoT-enabled smart cities.

II. ENERGY MANAGEMENT AND CHALLENGES FOR SMART CITY APPLICATIONS

An urgent need for energy management has emerged all over the globe due to a continuous increase in the consumption demands. Global warming and the air pollution are serious threats to the future generation. This is caused by the emission of fumes whose volume is increased with the increase in energy demand. On the other hand, according to the statistics provided by Cisco, there will be more than 50 billion IoT devices connected to the internet by 2020 [10]. This explosion in the devices will pose serious energy consumption concerns, and thus, it is imperative to manage energy for the IoT devices so that the concept of smart cities can better be realized in a sustained manner. Following are few examples where we can reduce energy consumption by effective management.

- **Home Appliances:** Home appliances are the major sources of energy consumption. Demand management is a key for customizing the energy use by managing the lighting, cooling, and heating systems within the residential units. On the other hand, the intelligent operation
Optimization framework for IoT in smart cities

Cost
Interference
Non-linear
Energy efficiency

Objective
Assignment
Selection
Scheduling

Mixed integer programming
Type

Branch and bound, dynamic programming, decomposition methods, outer approximation, bender decomposition
Solution

Fig. 3. A typical optimization framework for IoT in smart cities.

of activities can also facilitate the optimized management and operation of energy.

- **Education and Healthcare:** Considering the importance of educational and healthcare services, it is difficult to dematerialize them. However, it is possible to demobilize services so as for the reduction of energy consumption. For example, exploiting remote healthcare by visualizing sensors and mobile phones, distant learning education can create a significant reduction in the energy consumption.

- **Transportation:** The energy use for transportation includes public transport, daily commute to work on personal vehicles, leisure travel, etc. In addition to the energy consumed by public transport and personal vehicles, they are also a major cause of pollution in cities. IoT-enabled solutions can be employed for energy management, such as traffic management, congestion control, and smart parking. This can significantly reduce the energy consumption as well as CO2 emission.

- **Food Industry:** The energy consumption in the food industry is related to not only the storage, purchase, and preparation of food, it also includes the visitors moving into restaurants in search of food. IoT-enabled solutions can be used here for making the optimized choices in terms of food availability. On the other hand, the transportation of the food can also be optimized by incorporating the intelligent means of the transportation.

The IoT devices are generally battery operated and have limited storage space. Concerning these fundamental limitations of sensors, it is difficult to realize the IoT solutions with prolonged network life. In order to efficiently utilize the limited sensor resources, an optimized energy efficient framework is of paramount importance which not only reduces the energy consumption, but also maintains the minimum QoS for the concerned applications.

A typical optimization framework for IoT-enabled smart cities is given in Fig. 3. This framework provides details of the objectives, problem type, and corresponding optimization techniques for the energy management. For example, an optimization problem for minimizing the cost of electricity usage is presented in [11]. The authors developed the optimization-based residential energy management scheme for the energy management of the appliances. Authors in [12] presented an optimization framework for smart home scheduling of various appliances and assignment of energy resources. This results in a mixed integer combinatorial problem which is transformed into a standard convex programming problem. The goal of this study is to minimize the cost and user dissatisfaction. In [13], authors presented an energy-centered and QoS-aware services selection algorithm for IoT environments. The objective is to minimize energy consumption while satisfying QoS requirements. Similarly, objectives shown in Fig. 3 can be considered and the framework can be used as a guideline to solve the
optimization problems.

III. ENERGY-EFFICIENT SOLUTIONS FOR SMART CITIES

With the increase in IoT applications for smart cities, energy efficient solutions are also evolving for low power devices. There are some energy-efficient solutions which can either reduce the energy consumption or optimize the resource utilization. Following are some main research trends for energy-efficient solutions of IoT-enabled smart cities.

- **Lightweight Protocols**: Light weight protocol means the protocol that offers less overhead. IoT-enabled smart cities have to use various protocols for communication. There are several existing protocols in literature such as Message Queue Telemetry Transport (MQTT), Constrained Application Protocol (CoAP), Extensible Messaging and Presence Protocol (XMPP), Advanced Message Queue Protocol (AMQP), 6lowPAN, and Universal plug and play (UPnP) IoT. MQTT and CoAP are the most popular protocols. MQTT is a lightweight protocol which collects data from IoT devices and transmits to the servers. Whereas CoAP is designed for constrained devices and network for web transfer (See [14] for IoT protocols). Each of these protocols is designed for specific scenarios and applications in which it performs well. In addition, protocol conversion is an important building block for IoT which may require when the IoT devices are from different manufacturers or using different protocols.

- **Scheduling Optimization**: Scheduling optimization for IoT-enabled smart cities refers to the optimization of the resources with the concern of minimizing the energy consumption and subsequently reducing the electricity usage. In this regard, demand-side management (DSM) is of prime importance which refers to the manipulation of residential electricity usage by altering the system load shape and consequently reducing the cost. Broadly speaking, DSM comprises of two main tasks: load shifting and energy conservation where load shifting refers to the transfer of customers load from high-peak to low-peak levels and by adopting this, electricity can be conserved and provide room for other customers.

- **Predictive Models for Energy Consumption**: Predictive models for energy consumptions in IoT-enabled smart cities are indeed of vital importance. It refers to the wide range of applications in smart cities including predictive models for traffic and travel, predictive models for controlling temperature and humidity, etc. Various prediction models such as neural networks and Markov decision processes can be incorporated here. The concern of exploiting the predictive models will not only reduce the significant energy consumption but also lead to many societal benefits.

- **Cloud-based Approach**: The cloud computing has reshaped the computing and storage services which can be used to provide energy-efficient solutions for IoT-enabled smart cities. More precisely, the cloud-based approach helps in managing the massive data center flexibility and in a more energy efficient manner.

- **Low Power Transceivers**: Since the IoT devices in smart city application operates on the limited battery, low power design architecture or operation framework is of superior importance for addressing the energy management in IoT-enabled smart cities. Mostly, the existing application protocols for IoT devices are not in accordance with the energy-efficiency perspective. More specifically, the radio duty cycle for IoT devices is an important factor in the energy efficiency and, researchers are exploring methods for reducing the radio duty cycle of IoT devices and subsequently to achieve the energy-efficient architecture.

- **Cognitive Management Framework**: The IoT devices are heterogeneous in nature and associated services are unreliable. Therefore, it is important to investigate a cognitive management framework which adopts intelligence and cognitive approaches throughout the IoT-enabled smart cities. The framework should include reasoning and learning in order to improve decisions for IoT networks. A context aware cognitive management framework is presented in [4], which made decisions regarding IoT devices (when, why, and how to connect) according to the contextual background.

A. Case Study on Smart Home Networks

Smart home networks enable home owners to use energy efficiently by scheduling and managing appliances. In addition, to reduce electricity bills, smart home networks offer better life style, customized day to day schedule, etc. The smart grid has provided the ability to keep the electricity demand in line with the supply during the peak time of usage. This is called demand-side management. DSM reduces the electricity cost by altering/shifting the system load [5]. Generally DSM is responsible for the demand response program and load shifting. In demand response program, the customer’s load can be reduced in peak hours by shifting it to off-peak hours. This helps to provide more electricity for less cost.

The home appliances are becoming smart with added features of connectivity which enable the consumers to take advantage of the demand response program. The utility can contact with consumers to reduce/shift their electricity consumption, in return for certain monetary benefits. In smart home networks, appliance load can be further categorized into manageable and non-manageable loads. Here, we focus on the energy management of manageable appliance load in smart homes since it has high energy consumption and predictability in operations. The manageable load is further divided into shiftable load e.g., washing machine, dishwasher, etc., interrupt-able load, e.g., water heater and refrigerator, and weather-based load, e.g., heating and cooling. An illustration of the smart home network model for appliance scheduling is given in Fig. 2.

We consider a smart home network in which $N_A$ is the set of load types, $A_n$ is the set of appliances in the $n$-th load type and $A$ is the set that is a union of all appliances. We define $T$, $C^t$, and $P_{na}$ as number of time slots in a day, tariff/cost in dollars in the time slot $t$ and $P_{na}$ power of the $n$-th load type’s $a$-th appliance in the time slot $t$, respectively. We formulate
a problem for scheduling of smart home appliances while considering the tariffs and peak load. The overall objective is to schedule the appliances in a way such that total cost is minimum, i.e., minimize the $x_{nt}^C P_{nt}$ for whole set of $N_A, A$ for all $T$ time slots, where $x_{nt}^C$ is a binary variable with value 1 when $n$-th load type’s $a$-th appliance in the time slot $t$ is on; otherwise 0. We consider practical constraints on time occupancy and time consecutiveness that need to satisfy for realistic execution of appliance scheduling. The constraints ensure that each appliance should not occupy time slots more than the required, and the time slots for shift-able loads are consecutive. The optimization problem here is integer programming, such problems are generally NP-hard and require very efficient algorithms. We solved the optimization problem using an efficient heuristic algorithm.

B. Performance Analysis

For illustration purpose, we consider only four types of appliances namely washing machine, dryer, dishwasher, and electric vehicle. Fig. 4 (a) shows the tariff, slot time for appliances with (thick slots) and without DSM (thin slots). It is considered that dryer cannot be activated before washing machine. It is evident that with DSM the appliances are activated when the tariff is low. However, in the case of without DSM, there is no scheduling for appliances and they can be activated at any time. For instance, all the appliances are scheduled at the time when the tariff is low in case of DSM. In contrast, only dryer is activated when the tariff is low in the absence of DSM. Similarly Fig. 4 (b) shows that the total load is less in the case of optimum energy management when the tariff is high. It is important to notice that at some times the total load for both optimum energy management and without energy management is same. This is because of the fact there is no shiftable load at this time.

IV. ENERGY HARVESTING IN SMART CITIES

Energy harvesting is considered as a potential solution to increase the lifetime of IoT devices in smart cities. Energy harvesting can generally be classified into two categories:

- In ambient energy harvesting, IoT devices harvest energy from ambient sources such as wind, RF signals in environment, vibration, and solar. However, harvesting from ambient sources depends on their availability which is not always guaranteed.
- In dedicated energy harvesting, the energy sources are intentionally deployed in surroundings of IoT devices.

The amount of energy harvested by each IoT device depends on the sensitivity of harvesting circuit, the distance between IoT device and energy source, environment, etc. Thus, the success of energy harvesting for IoT devices in smart cities has to face several challenges that are discussed below.

- Energy Harvesting Receiver Design: The harvesting circuit design is the primary issue in RF-based energy harvesting. The sensitivity required for the harvesting circuit is higher than the traditional receivers, which can result in fluctuations in energy transfer due to the environment and mobility (energy source and IoT devices). Therefore, efficient and reliable harvesting circuit design is required to maximize the harvested energy. In addition, RF-to-DC conversion is the fundamental ingredient of RF energy harvesting. Therefore, circuit designers should enhance the efficiency of RF-to-DC conversion using advanced technologies.
- Energy Arrival Rate: The level of uncertainty of energy arrival rate is higher in energy harvesting from ambient sources than dedicated energy harvesting. This is because the former uses renewable energy sources, whereas the latter uses dedicated energy sources for which the location is set by network designers based on the harvesting requirements of IoT devices. The accurate and detailed modeling of energy arrival rate is indispensable in order to analyze the performance of energy harvesting systems in smart cities.
- Placement of Minimum Number of Dedicated Energy Sources: The IoT devices which are spatially distant from the energy sources can result in uneven energy harvesting. This can result in energy depletion of devices which are far from the dedicated energy sources and thus reduce the lifetime of network. We can not do much in the case of ambient energy sources; however, optimal placement and number of dedicated energy sources are crucial issues in dedicated energy harvesting.
- Scheduling of Energy Transmitters: Energy consumed by dedicated energy sources can be reduced by introducing task based energy harvesting, where energy transmitters can be scheduled for RF power transfer based on the harvesting requirements of the IoT devices. This requires a certain level of coverage and sufficient time to harvest. Therefore, scheduling of energy transmitters with guaranteed coverage and duration is vital for the energy efficiency of dedicated energy harvesting.
- Multi-path Energy Routing: Multi-path energy routing collects the scattered RF energy from different sources with the help of RF energy routers. Then these energy routers can transfer energy via an alternative path to IoT devices. Multi-path energy routing is based on the idea of multi-hop energy transfer in which relay nodes are deployed near to the IoT devices. This will help to reduce path loss between the relay node and the IoT devices, and also improve the RF-to-DC conversion efficiency.

A. Case Study: Scheduling of Energy Sources in Dedicated Energy Harvesting for IoT devices

We consider a network in smart cities with dedicated RF energy transmitters that consists of $N_I$ number of IoT devices (each device is equipped with harvesting circuit) and $N_E$ number of energy transmitters as shown in Fig. 5. It is assumed that energy transmitters have continuous power supply and they can satisfy requirements of all IoT devices in the area. The IoT devices can request for power transfer to harvesting controller which is considered as a task $k$. The harvesting controller is considered as cloudlet controller which is a centralized resource pool with information about the location
of IoT devices and energy transmitters. The controller can assign multiple tasks from $K$ ($K$ is set of tasks) to the energy transmitters. The transmit power of $e$-th energy transmitter is denoted by $P_e$. The energy transmitter $e$ can transfer power to a task $k \in K$ if the requesting IoT device is in the harvesting range of $e$. The harvesting range is denoted by $\phi_{e,t}$ which is 1 if the task $k$ is in the harvesting range of $e$ and 0 otherwise. Let the energy consumption by $e$-th energy transmitter in active mode be $\xi_{e,A}$ and in sleep mode $\xi_{e,S}$.

We propose a scheduling scheme for energy transmitters in dedicated energy harvesting for IoT devices as shown in Fig. 5. IoT devices request the controller for power transfer by sending a request if their residual energy is less than a pre-set threshold $\xi_{Th}$. The threshold is set while considering that the node has sufficient energy for critical operations. The request packet contains the requesting node’s identity (ID), controller’s ID, and energy harvesting requirements. Here, we adopt RF-MAC protocol proposed in [15]. The sensor node with residual energy less than a pre-set threshold can send RFP for instant charging through access priority mechanism (for details about this mechanism, see [15]) which ensures that the node with residual energy $\leq \xi_{Th}$ gets channel access before data transmission by other sensor nodes. The nodes which have data to transmit are forced to freeze their back-off timers as data transmission is not possible at this time. The controller receives this request packet and processes it to activate the energy transmitter(s). The harvesting controller receives this request for task $k$ and calculate $\phi_{et}$ for all energy transmitters. An energy transmitter can be activated for harvesting the target IoT device(s) if and only if 1) task $k$ is within the harvesting range of $e$, i.e., $\phi_{et} = 1$, and 2) task $k$ is scheduled/activated on $e$. We define a binary variable $\psi_e$ which is 1 if the energy transmitter $e$ is scheduled / activated and 0 otherwise.

The objective here is to activate minimum number of energy transmitters to minimize the energy consumed by dedicated energy transmitters, i.e., $\psi_e \xi_{e,A} + (1 - \psi_e) \xi_{e,S}$. This is subject to constraints on coverage $\phi_{et}$, duration of energy harvesting $\delta_e$, and target harvesting energy $E_{TC}$. One way to get an optimal solution is to enumerate over all possible combinations of $\psi_e$, which is computationally expensive and unrealistic for a large number of energy transmitters and tasks. Therefore, we consider branch and bound algorithm for the scheduling of dedicated RF energy sources. Once the activation of energy sources is optimized at the controller, then a grant for power transfer packet is sent to the energy transmitters which are selected for RF power transfer. Finally, the energy source(s) send the acknowledgment packet to IoT device(s) which requested the power transfer. This packet has the information of central frequency of energy transmitter and the duration of energy charging.

1) Performance Analysis: We evaluate the performance of energy-efficient scheduling of energy transmitters. We consider omnidirectional energy transmitters which radiate waves with power 46 dBm. The proposed schemes can be modified to use with directional energy transmitters to overcome path


losses which can certainly help to improve the charging efficiency. The transmit and receive energy for IoT devices are considered from MICA2 specifications. We consider $N_I = 200$ IoT devices, which are randomly distributed in a rectangular field of $100\times100 \text{ m}$.  

Figs. 6 (a) and 6 (b) illustrate the impact of a number of tasks and energy transmitters on energy consumption, respectively for energy-efficient scheduling scheme (branch and bound, and exhaustive search, and traditional WSN. Fig. 6 (a) shows that the energy consumption is increased slowly with the increase in a number of tasks in case of energy-efficient scheduling scheme (for given number of energy transmitters, i.e., $N_E = 10$ and 20). This is because of the fact that energy transmitters are activated based on the number of tasks and their location instead of a total number of energy transmitters. We may need a different number of active energy transmitters if requesting devices are far or close from each other. The energy consumption in case of traditional WSNs is constant regardless of the number of tasks, i.e., all the energy transmitters are activated all the time. Thus the energy consumption is doubled when $N_E = 20$ compared to the case when $N_E = 10$. The energy consumption in the proposed scheme is reduced at the cost of overhead and delay caused due to the exchange of packets among IoT devices, controller, and energy transmitters. From Fig. 6 (b), it can be noticed that the energy consumption for efficient scheduling schemes is not much affected by the increase on energy transmitters $N_E$ for given number of tasks ($K = 5$ and $K = 15$). We consider a small network size for which the probability that tasks are spatially nearby is high. Thus, for different number of tasks, we may need to activate the same number of energy transmitters based on their location. Therefore, curves are superimposed. In contrast, traditional WSNs in IoT-enabled smart cities activate all the energy transmitters regardless of the number of tasks which result in a linear increase in energy consumption. Moreover, results of the branch and bound algorithm are very similar to exhaustive search case with less complexity.

V. CONCLUSIONS AND FUTURE WORK

Energy management in smart cities is an indispensable challenge to address due to the rapid urbanization. In this article, we first presented an overview of energy management in smart cities, and then presented a unifying framework for IoT in smart cities. Energy management has been classified into two levels: energy-efficient solutions and energy harvesting operations. We covered various directions to investigate energy-efficient solutions and energy harvesting for IoT devices in smart cities. Furthermore, two case studies have been presented to illustrate the significance of energy management. The first case study presented appliance scheduling optimization in smart home networks where the objective was to reduce the electricity cost. The second case study covered efficient scheduling of dedicated energy sources for IoT devices in smart cities. Simulation results were presented to show the advantage of energy management in IoT for smart cities. Possible future directions for energy management in smart cities are 1) energy-efficient mechanisms for software-defined IoT solutions which can provide scalable and context-aware data and services, 2) directional energy transmission from dedicated energy sources for wireless power transfer, 3) energy efficiency and complexity of security protocols are crucial aspects for their practical implementation in IoT; thus, it is important to investigate robust security protocols for energy constraint IoT devices, 4) fog computing can lead to energy saving for most of the IoT applications, therefore, it is important to study energy consumption of fog devices for IoT applications.

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Fig. 1. Classification of energy management for IoT in smart cities.
Fig. 2. An illustration of smart cities with focus on smart homes.
Fig. 3. A typical optimization framework for IoT in smart cities.
Fig. 4. Load pattern (a) appliances starting and ending times with and without DSM, and (b) load pattern of appliances while minimizing total electricity cost and tariff.
Fig. 5. A mechanism for scheduling of energy transmitters.
Fig. 6. Impact of (a) number of tasks $K$ on the energy consumption and (b) energy transmitters ($N_E$) on the energy consumption for different number of tasks $K$ for different number of energy transmitters ($N_E$).