Software Defined Machine-to-Machine Communication for Smart Energy Management

Zhenyu Zhou, Jie Gong, Yejun He, and Yan Zhang

The authors provide a comprehensive review of the state-of-the-art contributions from the perspective of SDN and M2M integration. The overall design of the proposed software-defined M2M (SD-M2M) framework is presented, with an emphasis on its technical contributions to cost reduction, fine granularity resource allocation, and end-to-end quality of service guarantee.

ABSTRACT

The successful realization of smart energy management relies on ubiquitous and reliable information exchange among millions of sensors and actuators deployed in the field with little or no human intervention. This motivates us to propose a unified communication framework for smart energy management by exploring the integration of software-defined networking with machine-to-machine communication. In this article, first we provide a comprehensive review of the state-of-the-art contributions from the perspective of software defined networking and machine-to-machine integration. Second, the overall design of the proposed software-defined machine-to-machine (SD-M2M) framework is presented, with an emphasis on its technical contributions to cost reduction, fine granularity resource allocation, and end-to-end quality of service guarantee. Then a case study is conducted for an electric vehicle energy management system to validate the proposed SD-M2M framework. Finally, we identify several open issues and present key research opportunities.

INTRODUCTION

Despite the unprecedented development in the energy industry, the conventional energy system with centralized energy generation and unidirectional energy flows has become a bottleneck for facilitating the large-scale penetration of distributed and diversified renewable energy sources. Considering the intermittent and fluctuating characteristics of renewable energy and the stochastic charging/discharging behaviors and load profiles of electric vehicles, the high-level integration of uncontrolled and uncoordinated renewable generators and electric vehicles with the distribution networks will dramatically increase system volatility and disturbances, which often lead to power blackouts and brownouts due to cascading failures. Hence, smart energy management is urgently required to harness the huge potential of widespread renewable energy sources by dynamically optimizing the balance between energy supply and demand.

The successful realization of smart energy management lies in the real-time information of load-supply profiles and system operating conditions. By integrating every piece of the energy system with novel information and communication technologies (ICT), frequently updated measurements and samples of energy generation, transmission, distribution, storage, and consumption statuses can be retrieved via millions of sensors and actuators in the field. In particular, high-level syntactic and semantic interoperability among heterogeneous systems is enabled through open plug-and-play communication interfaces, which also provide the flexible control and self-deployment of standard and modular autonomous energy sources while hiding the diversity of underlying technologies. However, the communication network required by smart energy management is very different from conventional human-to-human-oriented telecommunication networks. This type of communication, which is characterized by ubiquitous information exchange among a large number of intelligent machines such as sensors, actuators, intelligent electronic devices (IEDs), smart meters, and so on, with little or no human intervention, is commonly known as machine-to-machine (M2M) communication [1].

Cellular technologies have become major driving forces for M2M due to the ubiquitous presence of cellular infrastructures and the availability of large-capacity long-range wide access. The Third Generation Partnership Project (3GPP) has specified several methods to support M2M communication in the current Long Term Evolution-Advanced (LTE-A) systems [2]. M2M devices are allowed to coexist with human-to-human communications in the same network and use random access channel (RACH) to build connections with centralized base stations (BSs). As a result, M2M communication, with self-organization, self-configuration, and self-healing capabilities, is expected to be a key enabler for the reliable operation of smart energy management.

Nevertheless, the seamless integration of M2M communication with smart energy management is still nontrivial. First of all, the conventional application-oriented method requires complete customization of M2M platforms for the specific application scenario, which has little flexibility in adapting to rapidly changing demand. It is extremely inefficient to manage the massive

---

This work was partially supported by the National Science Foundation of China (NSFC) under Grant Numbers 61601181 and 61372077; the Fundamental Research Funds for the Central Universities under Grant Number 2017MS13; the Beijing Natural Science Foundation (4174104); Beijing Outstanding Young Talent under Grant Number 2016000020124G081. This work is also partially supported by the projects 240079/F20 funded by the Research Council of Norway.

Digital Object Identifier: 10.1109/MCOM.2017.1700169

Zhenyu Zhou is with North China Electric Power University; Jie Gong is with Sun Yat-sen University; Yejun He is with Shenzhen University; Yan Zhang is with University of Oslo.

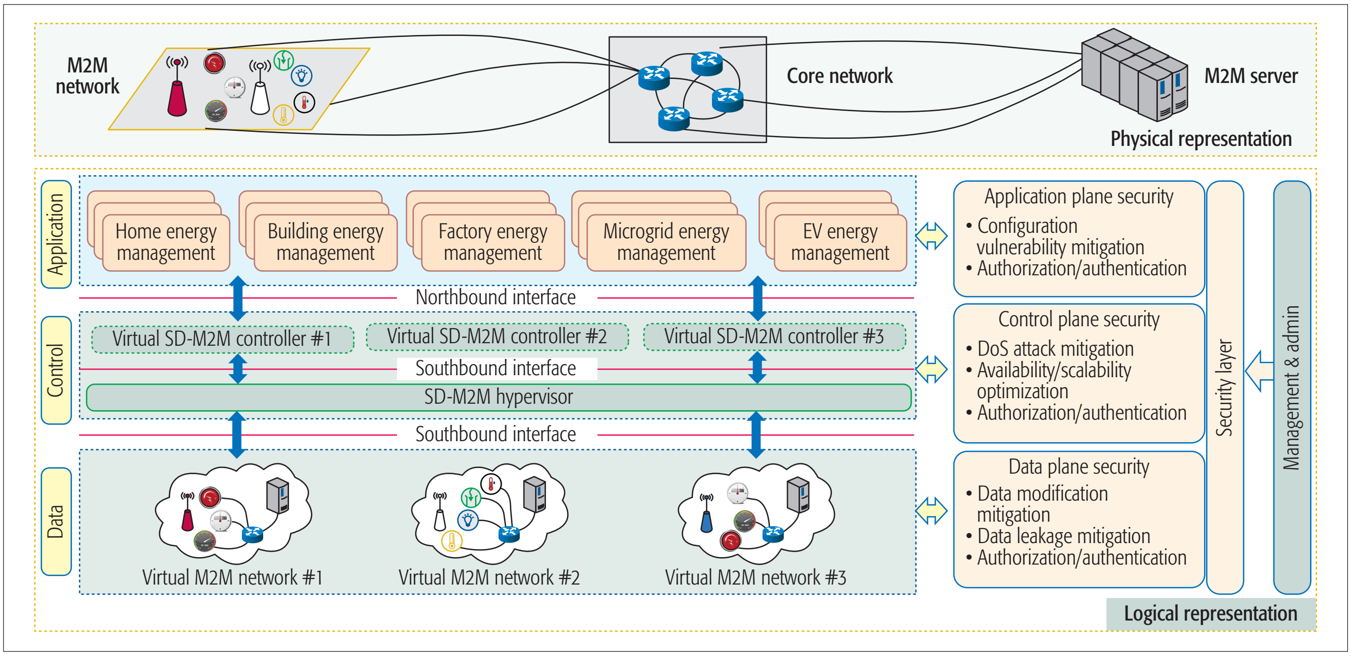

Figure 1. The conceptual architecture of software-defined M2M communication.

number of M2M devices in this way due to the increasing system complexity, and the extensive heterogeneity across hardware, interconnectivity, and deployment scenarios. Second, the tight coupling between applications and the task-oriented hardware provides little possibility of reusing existing physical M2M infrastructure for novel applications. Redundant hardware deployments are required for different applications or even the same application of different operators, which leads to excessively high capital and maintenance costs. Last but not least, power grid applications have diverse quality of service (QoS) requirements in terms of latency, burst size, throughput, and packet arrival rate. The coexistence of protection, control, monitoring, and billing traffic in the same communication network poses new challenges for efficient resource allocation design in M2M communication [3]. It is infeasible to realize intelligent resource allocation if the applied control logic is embedded into hardware devices.

Software-defined networking (SDN) provides an open architecture for enabling centralized control and automatic management of networks through the decoupling of the control plane and data plane, and the incorporation of network programmable capability. The design, deployment, management, and maintenance of networks can easily be implemented on an open-standard-based centralized controller rather than directly configuring a massive number of heterogeneous devices. There are some works attempting to integrate M2M with SDN. A virtual resource allocation algorithm was proposed for M2M communication underlaying software-defined cellular networks in [4]. Vukobratovic *et al.* presented a reconfigurable architecture for adapting Internet of Things (IoT) data transfer to subsequent data analysis based on the concept of network function computation [5]. Ameigeiras *et al.* designed an SDN-based M2M access cloud architecture to improve transmission latency, network scalability, and mobility support [6]. A software-defined dynamic M2M server selection and traffic redirection algorithm was proposed in [7] for a virtual home gateway. Hasegawa *et al.* proposed a joint bearer aggregation and control-data plane separation scheme to increase capacity of an M2M core network in [8]. There are some surveys [9, 10] that cover software-defined IoT at large. However, the above works mainly focus on conventional M2M networks. The specific technological characteristics and application scenarios when deploying SDN-based M2M for smart energy management have been largely neglected.

In this article, we present our visions on software-defined M2M (SD-M2M) communication, and study its potential in smart energy management. We start by introducing the overall design of the proposed SD-M2M architecture, with an emphasis on its technical contributions to intelligent service orchestration and resource allocation. Then the proposed SD-M2M framework is able to significantly reduce service, providing low cost, guaranteed end-to-end QoS delivery, and fine-granularity resource allocation by separating the data and control planes and decoupling service provision from physical infrastructures. We discuss how to integrate SD-M2M with different applications of smart energy management, and present a case study to evaluate the performance gains in both data delivery and energy management. Finally, we conclude the article and present major research open issues.

The Proposed Software-Defined M2M Framework

This section provides a detailed illustration of the proposed SD-M2M architecture, with a particular emphasis on its technical contributions to complexity reduction, fine-granularity resource allocation, and end-to-end QoS guarantee.

Figure 1 shows the SD-M2M architecture, which can be divided into four different planes: the data plane, the control plane, the applica-

The centralized SD-M2M controller makes decisions on an up-to-date global view of the network state, and enables vendor-independent control over the corresponding virtual M2M network from a single logical point. This allows the implementation of fine-granularity control policies with enhanced network resource utilization efficiency and QoS provisioning capabilities.

tion plane, and the management and administration plane. The data plane is composed of all of the programable field equipment and network elements involved in M2M communication, including sensors, actuators, IEDs, smart meters, gateways, BSs, switches, routers, and so on. These are essential to support autonomous data acquisition and transmission in smart energy management. With the data-control decoupling, the data plane devices are greatly simplified without the need to understand hundreds of communication protocols.

The control plane consists of an SD-M2M hypervisor and multiple heterogeneous or homogeneous SD-M2M controllers. The virtualization of the physical M2M network is enabled by inserting a hypervisor between the data-plane devices and the controllers. The hypervisor views and interacts with the data-plane devices through the standard-based southbound interface and slices the abstracted physical infrastructures into multiple isolated virtual M2M networks that are controlled by their respective controllers. The hypervisor also sends the abstraction information to the controllers through the southbound interface. The centralized SD-M2M controller makes decisions on an up-to-date global view of the network state, and enables vendor-independent control over the corresponding virtual M2M network from a single logical point. This allows the implementation of fine-granularity control policies with enhanced network resource utilization efficiency and QoS provisioning capabilities.

The application plane covers an array of smart energy management applications such as home energy management (HEM), factory energy management (FEM), building energy management (BEM), microgrid energy management (MEM), and electric vehicle energy management (EVEM). With standard-based application programming interfaces (APIs) between the control and application planes, smart energy management applications can explicitly and programmatically communicate their requirements to the respective controllers via the northbound interface, and can thus operate on an abstraction of the M2M networks without being tied to the details of physical infrastructures.

The management and administration plane provides management and access control functions to all the other three planes (i.e., the data plane, the control plane, and the application plane). It covers static tasks including device setup and management, privacy and security policy configuration, firmware and software updates, performance monitoring, and so on. The security layer protects the data plane from various security threats such as flow rule modification, unauthorized access control, and side channel attack. In the control plane, the security layer provides solutions for controller access authorization and authentication, denial of service (DoS) or distributed DoS (DDoS) attack mitigation, controller availability and scalability optimization, and so on. Furthermore, security enforcement mechanisms can be implemented to secure the application plane from unauthorized and unauthenticated applications, fraudulent rule insertion, configuration vulnerabilities, and other application-specific security threats.

The main benefits of SD-M2M are summarized as follows.

Reduced complexity and accelerated innovation. In the SD-M2M communication framework, the underlying physical infrastructures are abstracted from smart energy management applications, and the complicated decision-making functions are left to the centralized controller. The controller is designed to hide the hardware details from service orchestration and provisioning, and to manage the data-plane devices automatically and intelligently via common APIs. We focus on how to realize seamless integration between SDN and M2M for smart energy management by exploring existing SDN controllers rather than trying to reinvent the wheel. As a result, SD-M2M provides unprecedented flexibility, programmability, and controllability for vendors and operators to build highly scalable and reliable M2M networks that can swiftly adapt to evolving applications of smart energy management. Rapid innovation is also enabled through the ability to tailor the behavior of the network and to deliver new applications and service differentiation in real time without the need to deploy and configure individual hardware devices.

End-to-end QoS guarantee in heterogeneous networks. Smart energy management functionalities such as real-time supervisory control and data acquisition, generation dispatch and control, and energy scheduling and accounting have diverse QoS requirements and different operation domains [11]. Thus, the most important challenge for conventional M2M communication is how to guarantee end-to-end QoS for different applications in heterogeneous networks. To provide a solution, SD-M2M creates a unified QoS delivery platform by decoupling the service provision functions from physical infrastructure domains. In this platform, the network resources and control functionalities are abstracted and sliced into distinct virtual networks, which are provided for respective applications via standard APIs. To guarantee reliable service delivery, the most appropriate virtual network is selected to meet the end-to-end QoS requirement. In this way, multiple virtual networks can be constructed on the same platform to meet the diverse QoS requirements of different system functions. The capability of inter-domain service delivery is significantly enhanced through the ability to coordinate network control and orchestrate resource allocation among controllers in different domains.

Fine-granularity resource allocation in a multitenant environment. In SD-M2M, physical infrastructures are abstracted from three dimensions of attributes: topology, physical device resources, and physical link resources. We focus on how to realize M2M infrastructure abstraction for intelligent service orchestration and resource allocation rather than redesign the concept of network functions virtualization. The degree of abstraction for each dimensional attribute can be flexibly controlled by the adjustment of physical resources. First, in the abstraction of network topology, the degree of abstraction relies on the virtual nodes and links. For instance, a physical topology that represents the layout of connected devices can be either abstracted as an identical virtual topology in the lowest degree of abstraction, or as a

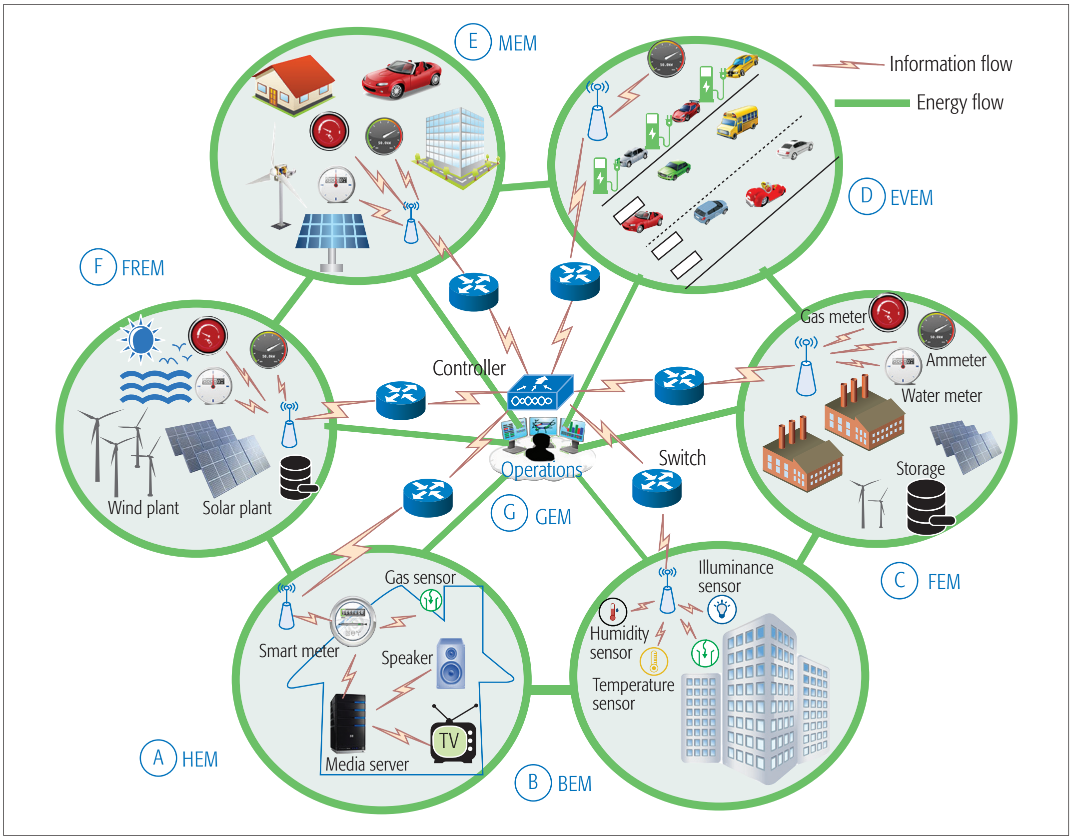

Figure 2. The scenario of deploying SD-M2M for smart energy management applications.

Smart BEM is realized by dynamically optimizing the energy consumption related to heating, cooling, ventilation, and lighting. SD-M2M provides a comprehensive platform to interact with M2M devices deployed in various building monitoring, control and automation systems, which are usually developed based on different communication protocols.

single virtual node or link in the highest degree of abstraction. Second, the degree of abstraction for physical device resources is dependent on CPU, memory, storage, and other computing resources. Third, in the abstraction of physical link resources, the ability to choose different levels of abstraction is determined by the allocation of link bandwidth, buffers, queues, and so on. Hence, SD-M2M offers a granular level of resource allocation in a highly abstracted and automated fashion, and allows the same physical infrastructures to be shared among multiple tenants.

Software-Defined M2M Communication for Smart Energy Management Applications

Figure 2 presents the scenario of deploying SD-M2M for smart energy management applications. We focus on several sub-areas where SD-M2M will play a key role and present how to integrate SD-M2M with different applications in a bottom-up approach. A comprehensive summary of the communication features and critical aspects for smart energy management applications is provided in Table 1.

Home Energy Management

HEM enables residential energy consumers to be actively involved in the grid operation through intelligent interaction with the external environment. Intelligent machines are embedded to collect home appliance operation status, energy consumption, home environment, and home user behaviors for smart HEM. SD-M2M will play a key role in facilitating HEM by shielding vendor-specific details and features of home appliances from application development and system operation. All of the registered M2M devices in a home can be divided into virtual networks with abstracted network, storage, and computing capability, and be managed through standard APIs to deliver home user demand-oriented services in a short time.

Building Energy Management

Residential and commercial buildings have been estimated to represent approximately half of the total world energy consumption. M2M communications are critical to collect real-time data of temperature, occupancy behavior, outdoor environment, humidity, illuminance, electricity price, and more. Smart BEM is realized by dynamically optimizing the energy consumption related to heating, cooling, ventilation, and lighting. SD-M2M provides a comprehensive platform to interact with M2M devices deployed in various building monitoring, control, and automation systems, which are usually developed based on different communication protocols. M2M networks in different buildings and systems can be abstracted and integrated into the same virtual network, which provides the benefit of allowing multiple buildings to be remotely managed by a centralized controller.

Factory Energy Management

Smart FEM will be a key enabler for the upcoming fourth industrial revolution. M2M devices are installed in a factory not only to collect energy generation, storage, and consumption data, but also to monitor real-time status of manufacturing lines. SD-M2M enables FEM operators to build

Application	Communication features	Critical aspects	Benefits of SD-M2M
Home energy management	• Delay-tolerant • Periodic/event-based • Short range • Low-level priority	• Diverse communication protocols • Massive connection • High random access loads • Small burst traffic	• Reduced cost and complexity • Accelerated innovation • Vendor-independent control
Building energy management	• Delay-tolerant • Periodic/event-based • Short range • Low-level priority	• Diverse communication protocols • Massive connection • Small burst traffic	• Reduced cost and complexity • Accelerated innovation • Coordinated management • Vendor-independent control
Factory energy management	• Delay-sensitive • Periodic/event-based • Middle-level priority • Middle range	• Diverse communication protocols • High reliability • Middle-level QoS requirement	• Reduced cost and complexity • Accelerated innovation • Coordinated management • Vendor-independent control
EV energy management	• Delay-sensitive • Semi-periodic/event-based • Middle-level priority • Middle range	• Mobility management • Random charging/discharing behaviors • High reliability • Middle-level QoS requirement	• Reduced cost and complexity • Coordinated mobility management • Fine-granularity resource allocation
Microgrid energy management	• Delay-sensitive • Semi-periodic/event-based • High-level priority • Middle range	• High reliability • High-level QoS requirement • Multi-tenant environment • Massive connection	• End-to-end QoS guarantee • Fine-granularity resource allocation • Coordinated management
Field renewable energy management	• Delay-sensitive • Periodic/event-based • Long range	• Fault-tolerant capability • High reliability • High-level QoS requirement	• End-to-end QoS guarantee • Low maintenance cost • Fine-granularity resource allocation
Grid energy management	• Extremely delay-sensitive • Periodic/event-based • No/limited retransmission • Long range	• Mission-critical • High reliability • Continuous transmission • High-level QoS requirement	• End-to-end QoS guarantee • Fine-granularity resource allocation • Coordinated management

Table 1. A comprehensive summary of the communication features and critical aspects for smart energy management applications.

highly reliable and programmable communication networks for integrating distributed renewable energy sources and energy-saving equipment such as motors and inverters. With the decoupling of data and control planes, the coexistence of energy and manufacturing traffic in the same communication network is supported through physical infrastructure abstraction and centralized resource coordination. Energy consumption improvement points and deterioration factors can easily be identified by interrelating product information with energy information through open and programmable APIs.

ELECTRIC VEHICLE ENERGY MANAGEMENT

The massive amounts of data in every aspect of electric vehicles including locations, travel patterns, driver behaviors, battery states, and historical profiles are routinely collected for realizing smart EVEM, which reduces the energy demand-supply imbalance by absorbing excess energy during off-peak hours and discharging the batteries into the grid when needed [12]. SD-M2M with centralized intelligence provides an flexible communication network for coordinated charging and discharging different types of electric vehicles at distributed locations such as residential community, workplaces, parking lots, and charging stations. For mobility management, seamless handover of electric vehicles from one BS to another can be realized by coordinating network control and orchestrating resource allocation among multiple controllers.

MICROGRID ENERGY MANAGEMENT

A microgrid is a small-scale electric power system with co-located distributed energy sources and loads. It can either synchronize to the main grid and operate in grid-connected mode, or operate in island mode by disconnecting both loads and energy sources from the main grid [13]. Hence, MEM provides the benefits of relieving the stress of load-supply imbalance through local consumption of distributed renewable energy sources. In SD-M2M, the physical M2M infrastructure can be abstracted and sliced into distinct virtual networks to support a variety of microgrid energy management functions with diverse communication requirements. Sufficient communication and computing resources should be allocated for the monitoring and control of critical interconnection points (i.e., the points of load connection, common coupling, and distributed energy source connection) in order to support seamless dispatch, scheduling, and control of distributed energy sources. Various stakeholders such as microgrid operator, distributed energy source operator and aggregator, and load aggregator are allowed to exchange key operating parameters in real time with the supported coordination among heterogeneous controllers.

REMOTE FIELD RENEWABLE ENERGY MANAGEMENT

Large-scale solar and wind plants are normally deployed in remote and isolated renewable-rich areas such as deserts and offshore. M2M communication, which enables the reliable acquisition of field monitoring data over a long transmission range, serves as the basis for smart FREM. The data of temperature, pressure, humidity, solar position, and wind speed, as well as power quality-related parameters are collected and transmitted back to a control center for power output forecasting and energy management optimization. In remote harsh and hazardous locations, SD-M2M with fault-tolerant capability becomes an ideal choice. The decoupling of services and physical infrastructure makes it possible to reuse existing redundant devices during system malfunction. Furthermore, the centralized controller with a global view can easily detect device breakdowns and network disconnections to guarantee automatic acquisition of data with minimum interruptions.

GRID ENERGY MANAGEMENT

M2M devices such as phase measurement units are embedded into generation and transmission domain equipment to continuously collect critical data of power grid such as voltage, current, harmonics, and frequency [14]. These data are utilized by smart GEM to improve the flexibility and reliability performance of the overall power system. SD-M2M can support the real-time delivery of the strictly delay-sensitive system state measurements and high-resolution phase information. For instance, the integrated fiber-wireless communication infrastructures based on low-latency Ethernet passive optical networks and highly scalable cellular networks can be abstracted into different slices and then allocated at a fine-grained level to meet the end-to-end QoS requirements.

CASE STUDY AND ANALYSIS

To validate the benefits of SD-M2M, we consider the application scenario of EVEM as shown in Fig. 2, which is composed of one gas generator, four wind turbines, and 100 electric vehicles. Important data such as charging time, location, battery state, and load profile are monitored by SD-M2M devices and sent back to M2M servers through cellular links. The case study is divided into two parts. In the first part, we evaluate the capability of SD-M2M for supporting real-time delivery of strictly delay-sensitive data. In the second part, we demonstrate the relationship between SD-M2M penetration rate and performance gain of smart energy management.

When an M2M device attempts to connect to a BS, it has to randomly select a preamble and send it to the BS via a time-frequency resource block. The BS decodes the received preamble and sends back a response message. A random access collision occurs if two or more M2M devices happen to select the same resource block, and then each M2M device has to wait for a random period and repeat random access again. Thus, the operation of smart energy management is in danger since critical data cannot be delivered immediately without delay. In particular, the probability of collision increases dramatically when a massive number of M2M devices attempt to access the network simultaneously.

SD-M2M provides a promising solution to the above challenge through an advanced level of resource abstraction and fine-granularity resource allocation. The hypervisor slices the physical infrastructure into K distinct virtual M2M networks based on QoS requirements. Without loss of generality, we focus on the kth ($k = 1, \ldots, K$) virtual network with N_k M2M devices. Assuming that M_k resource blocks are allocated by the controller, the total number of resource blocks is calculated as $\sum_{k=1}^{K} M_k$. Given $K = 20$ and $M_k = 10$ for $k = 1, 2, \ldots, K$, the total number of required resource blocks is 200. Each M2M device only needs to be aware of the resource blocks allocated to the corresponding virtual network instead of sensing the whole physical network. If the achieved spectrum efficiency cannot meet the specified QoS requirement, more resources can be allocated to this virtual network for improving performance by coordinating resource allocation with other virtual networks. The study of inter-virtual network coordination is left for future study.

The strategy of each M2M device is to decide when to access the network and which resource block to choose. Since random access will be successful if and only if the resource block is idle and is not requested by others, the achievable spectrum efficiency is jointly determined by the number of available resource blocks, the actions of other M2M devices, and the channel quality of the requested resource block. As a result, each M2M device needs to decide whether or not to access the network at each time slot based on the state of resource blocks. A Markov decision process (MDP) provides an effective mathematical framework to formulate this category of decision making problems with a stochastic process. A standard MDP formulation involves the following elements: state, action, cost function, and state transmission. The system state S is defined as the set of all resource block states. The state transition probability can be modeled as a Poission process. The action is defined as the probability to access the network, which is relative to the system state. The optimization objective is to maximize the average transmission rate per device over the infinite time horizon. The MDP problem can be broken down into a collection of simpler subproblems and solved one by one via dynamic programming [15]. The proposed algorithm is guaranteed to obtain the optimal performance upon termination. The relative proof can be found in [15, references therein].

We compare the proposed algorithm with a baseline greedy algorithm in which each device always requests the resource block with the best channel quality. The results are shown in Figs. 3a and 3b. We consider a virtual network with $N_k = 100$ M2M devices. Figure 3a shows the average transmission rate per device with different numbers of resource blocks M_k. The proposed algorithm outperforms the greedy algorithm by more than 300 percent when $M_k = 10$. The reason is that the reuse gain of resource blocks is fully exploited. In Fig. 3b, we fix the total number of resource blocks $M_k = 6$, and change the maximum probability of accessing the network from 12 to 20 percent. It is shown that with the increase of maximum access probability, the performance degrades dramatically. The reason is that the collision probability increases exponentially as more devices attempt to access the network simultaneously. Nevertheless, the proposed algorithm still outperforms the greedy algorithm under all scenarios.

> The decoupling of services and physical infrastructure makes it possible to reuse existing redundant devices during system malfunction. Furthermore, the centralized controller with a global view can easily detect device breakdowns and network disconnections to guarantee automatic acquisition of data with minimum interruptions.

SD-M2M provides great potential to achieve energy-efficient resource allocation through advanced level of physical resource abstraction and centralized control. However, such a benefit has yet to be fully harnessed due to the tradeoff between energy efficiency and other performance benchmarks such as spectrum efficiency and transmission latency.

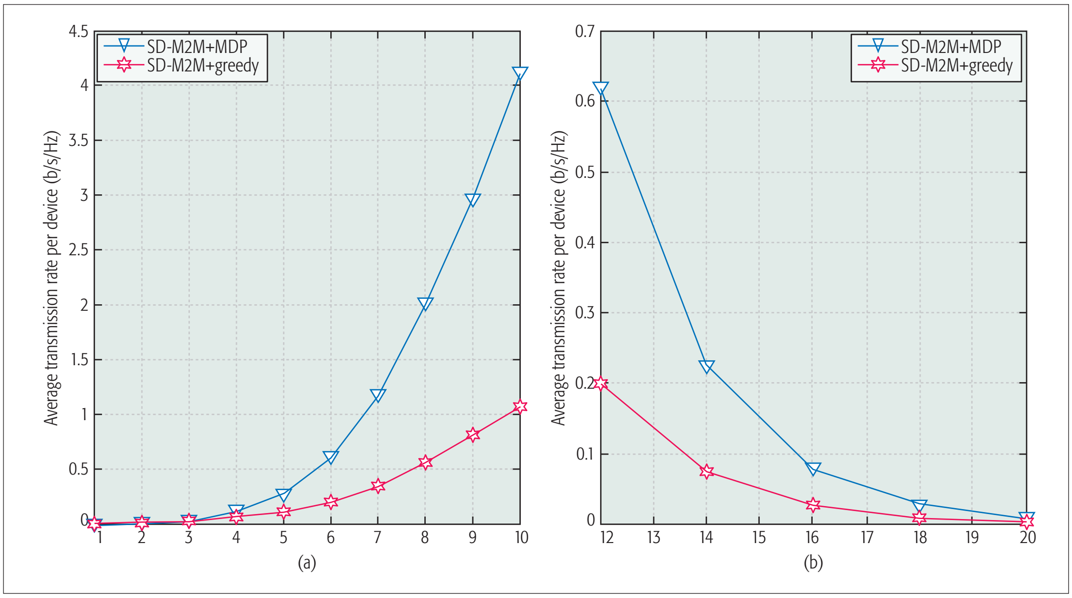

Figure 3. Spectral efficiency performance: a) average transmission rate per device vs. the number of total RBs; b) average transmission rate per device vs. the probability of accessing the network.

To evaluate the smart energy management performance, a robust energy scheduling approach proposed in our previous work [12] is employed. Robust energy scheduling allows a distribution-free model of uncertainties, and can efficiently alleviate the negative effect of data uncertainty. The goal is to minimize the generation cost of the gas generator under the constraints of active power balance, active power generation limits, charging and discharging power boundaries, charging demand balance, and spinning reserve. The optimization variables are when to charge and discharge electric vehicles, and the energy output of the gas generator. More details of the robust energy scheduling solution can be found in [12, references therein]. An electric vehicle cannot be scheduled if the critical data are not delivered on time, which occurs when either SD-M2M devices are not deployed or a QoS requirement is violated due to collision. We define the SD-M2M penetration rate as the ratio of electric vehicles that can be scheduled to the total number of electric vehicles.

Figure 4a shows the energy supply and demand profiles of electric vehicles, wind turbines, and local residents for a duration of 24 minutes. It is noted that the peak load starts at the sixth minute when the wind power output is low and the charging demand of electric vehicles is high. Figure 4b shows the total energy generation cost vs. the SD-M2M penetration rate. It is obvious that there is a positive correlation between cost reduction and penetration rate. For instance, the cost is reduced by 65 percent when the SD-M2M penetration rate is increased from 20 to 100 percent. It is interesting to note that the increment of SD-M2M penetration rate converts the exponential growth pattern of cost into a linear grown pattern. Based on the delay-sensitive mission-critical data delivered by SD-M2M, the peak load can be efficiently shifted by charging electric vehicles to absorb renewable energy during off-peak hours and discharging to produce energy during peak hours.

CONCLUSION AND OPEN ISSUES

In this article, we propose a new software-defined M2M framework for emerging smart energy management applications. We review the current research progress on integrating SDN with M2M. Then the design principle of the proposed SD-M2M architecture is presented, and the technical contributions to cost and complexity reduction, end-to-end QoS guarantee, and fine-granularity resource allocation are elaborated in details. We also classify smart energy management applications into several classes based on operation domains, and provide a detailed treatment on how to integrate SD-M2M with each class of application. A case study is shown in an electric vehicle network to demonstrate the performance gains brought by SD-M2M in both spectral efficiency and energy management.

In the following, we point out four key research issues that call for more attention and efforts in the context of integrating SD-M2M with smart energy management.

Energy Efficiency and Energy Harvesting. Energy efficiency and energy harvesting are very important aspects of SD-M2M design due to limited battery capacity and high maintenance cost. SD-M2M provides great potential to achieve energy-efficient resource allocation through an advanced level of physical resource abstraction and centralized control. However, such a benefit has yet to be fully harnessed due to the tradeoff between energy efficiency and other performance benchmarks such as spectrum efficiency and transmission latency.

Dynamic Resource Virtualization and Sharing. The sharing of the same M2M infrastructures by multiple smart energy management operators calls for efficient resource slicing, isolation, and mapping algorithms. Due to the large number of optimization stages and scales, it is usually intractable to derive a polynomial-time solution for big instances of the formulated problem. Therefore,

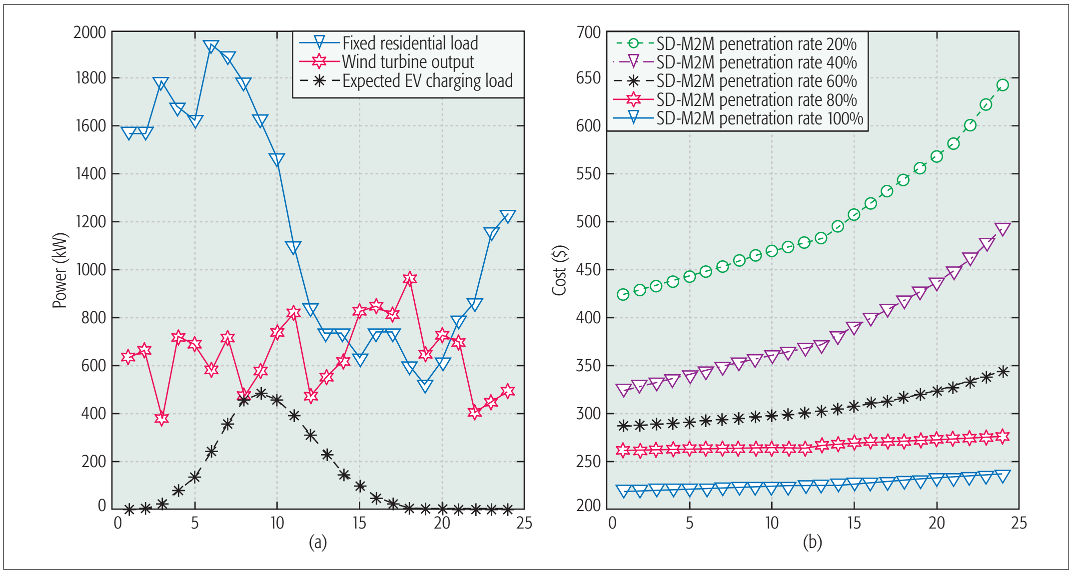

Figure 4. The smart energy management performance: a) the energy supply and demand profiles; b) the relationship between the total energy generation cost and the SD-M2M penetration rate.

The centralized SD-M2M controller is the single point of failure performance bottleneck, the promise of which leads to the collapse of both communication and energy networks. In particular, how to provide an efficient and seamless approach for privacy and trust management across a massive number of M2M devices is a valuable yet challenging issue.

alternative sub-optimal heuristic solutions should be investigated to tackle this challenge, and the corresponding optimality gap and computation complexity need to be analyzed in depth. Furthermore, considering the diverse or even conflicting objective functions of operators in multiple domains, game-theoretical or matching approaches should be incorporated to address the resource allocation problem.

Timescale Difference between Wireless Resource Allocation and Smart Energy Management. SD-M2M-based smart energy management confronts critical challenges caused by two-dimensional dynamics with different timescales. On one hand, wireless resource allocation is optimized according to dynamic channel variations on a timescale of milliseconds. On the other hand, energy utilization in smart grid is optimized based on dynamic load-supply profiles and electrical prices, which often vary on a timescale of hours, minutes, or seconds. Hence, there is lacking an efficient modeling approach to characterize the impacts of wireless resource allocation on smart energy management. The joint optimization of the two problems, which are on different timescales, requires further investigation.

Security Issues. The centralized SD-M2M controller is the single-point-of-failure performance bottleneck, the result of which leads to the collapse of both communication and energy networks. In particular, how to provide an efficient and seamless approach for privacy and trust management across a massive number of M2M devices is a valuable but challenging issue.

ACKNOWLEDGMENT

This work was supported in part by the National Science Foundation of China under Grant 61601181, in part by the Fundamental Research Funds for the Central Universities under Grant 2017MS13, in part by the Beijing Natural Science Foundation under Grant 4174104, in part by the Beijing Outstanding Young Talent under Grant Number 2016000020124G081, and in part by the projects 240079/F20 funded by the Research Council of Norway. This work was also supported in part by the National Natural Science Foundation of China under Grant 61372077, in part by the Science and Technology Innovation Commission of Shenzhen under Grant ZDSYS 201507031550105, and in part by Guangdong Provincial Science and Technology Programs under Grant 2013B090200011 and Grant 2016B090918080.

REFERENCES

[1] Y. Zhang *et al.*, "Cognitive Machine-to-Machine Communications: Visions and Potentials for the Smart Grid," *IEEE Network*, vol. 26, no. 3, May 2012, pp. 6–13.

[2] A. Rico-Alvarino *et al.*, "An Overview of 3GPP Enhancements on Machine-to-Machine Communications," *IEEE Commun. Mag.*, vol. 54, no. 6, June 2016, pp. 14–21.

[3] Y. Yan et *al.*, "A Survey on Smart Grid Communication Infrastructures: Motivations, Requirements and Challenges," *IEEE Commun. Surveys & Tutorials*, vol. 15, no. 1, Feb. 2012, pp. 5-20.

[4] M. Li *et al.*, "Random Access and Virtual Resource Allocation in Software-Defined Cellular Networks with Machine-to-Machine (M2M) Communications," *IEEE Trans. Vehic. Tech.*, Dec. 2016, pp. 1–15.

[5] D. Vukobratovic *et al.*, " Condense: A Reconfigurable Knowledge Acquisition Architecture for Future 5G IoT," *IEEE Access*, vol. 4, July 2016, pp. 3360–78.

[6] P. Ameigeiras *et al.*, " Link-Level Access Cloud Architecture Design Based on SDN for 5G Networks," *IEEE Network*, vol. 29, no. 2, Mar. 2015, pp. 24–31.

[7] A. Papageorgiou *et al.*, "Dynamic M2M Device Attachment and Redirection in Virtual Home Gateway Environments," *IEEE ICC 2016*, Kuala Lumpur, Malaysia, July 2016, pp. 1–6.

[8] G. Hasegawa and M. Murata, "Joint Bearer Aggregation and Control-Data Plane Separation in LTE EPC for Increasing M2M Communication Capacity," *IEEE GLOBECOM 2015*, San Diego, CA, Dec. 2015, pp. 1–6.

[9] K. Sood, S. Yu, and Y. Xiang, "Software-Defined Wireless Networking Opportunities and Challenges for Internet-of-Things: A Review," *IEEE Internet of Things J.*, vol. 3, no. 4, Sept. 2016, pp. 453–63.

[10] I. Khan *et al.*, "Wireless Sensor Network Virtualization: A Survey," *IEEE Commun. Surveys and Tutorials*, vol. 18, no. 1, Mar. 2015, pp. 553–76.

[11] R. Yu *et al.*, "QoS Differential Scheduling in Cognitive-Radio-Based Smart Grid Networks: An Adaptive Dynamic Programming Approach," *IEEE Trans. Neural Network Learning Systems*, vol. 27, no. 2, Apr. 2015, pp. 435–43.

[12] Z. Zhou *et al.*, "Robust Energy Scheduling in Vehicle-to-Grid Networks," *IEEE Network*, vol. 31, no. 2, Mar. 2017, pp. 30–37.

[13] Z. Zhou *et al.*, "Game-Theoretical Energy Management for Energy Internet with Big Data-Based Renewable Power Forecasting," *IEEE Access*, Feb. 2017, pp. 1-14.

[14] G. C. Madueño *et al.*, "Assessment of LTE Wireless Access for Monitoring of Energy Distribution in the Smart Grid," *IEEE JSAC*, vol. 34, no. 3, Feb. 2016, pp. 675–88.

[15] J. Gong *et al.*, "Policy Optimization for Content Push Via Energy Harvesting Small Cells in Heterogeneous Networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 2, Nov. 2016, pp. 717–29.

BIOGRAPHIES

ZHENYU ZHOU [M'11, SM'17] (zhenyu_zhou@ncepu.edu.cn) received his M.E. and Ph.D. degrees from Waseda University, Tokyo, Japan, in 2008 and 2011, respectively. Since March 2013, he has been an associate professor at North China Electric Power University. He received the Beijing Outstanding Young Talent in 2016 and the IET Premium Award in 2017. He is an Editor of *IEEE Access* and *IEEE Communications Magazine*. His research interests include green communications and smart grid.

JIE GONG [S'09, M'13] (gongj26@mail.sysu.edu.cn) received his B.S. and Ph.D. degrees in the Department of Electronic Engineering of Tsinghua University in 2008 and 2013, respectively. He visited the University of Edinburgh in 2012. During 2013–2015, he worked as a postdoctorial scholar at Tsinghua University. He is currently an associate research fellow in the School of Data and Computer Science, Sun Yat-sen University, Guangzhou, China. His research interests include cloud RAN, energy harvesting technology, and green wireless communications.

YEJUN HE (heyejun@126.com) received his Ph.D.degree in information and communication engineering from Huazhong University of Science and Technology in 2005. He is a full professor with the College of Information Engineering, Shenzhen University, China, where he is the director of the Guangdong Engineering Research Center of Base Station Antennas and Propagation, and the director of the Shenzhen Key Laboratory of Antennas and Propagation. His research interests include wireless mobile communication, antennas, and radio frequency. He is a fellow of IET.

YAN ZHANG [M'05, SM'10] (yanzhang@ieee.org) is a full professor at the Department of Informatics, University of Oslo, Norway. He is an Editor of *IEEE Communications Magazine*, *IEEE Transactions on Green Communications and Networking*, *IEEE Communications Surveys & Tutorials*, and others. His current research interests include next-generation wireless networks leading to 5G, green, and secure cyber-physical systems (e.g., smart grid, healthcare, and transport). He is an IEEE VTS Distinguished Lecturer. He is a Fellow of IET.