Networked Electric Vehicles for Green Intelligent Transportation

Lin Cai, Jianping Pan, Lian Zhao, and Xuemin Shen

Abstract

Electric vehicles (EVs) are a key to future clean transportation systems. With the ubiquitous Internet-of-the-Things technologies including vehicle-to-vehicle and vehicle-to-infrastructure communication technologies, the nexus of the Internet, EVs, charging stations, and smart grid forms a perfect storm of opportunities for future green and intelligent transportation systems. In this new paradigm, reliable and efficient information exchanges between EVs, meters, charging stations and the power grid, as well as intelligent charging services, are key issues. To address these issues, this article promotes a hybrid vehicle-to-infrastructure and vehicle-to-vehicle communication network design. Facilitated by ubiquitous communication systems, how to efficiently and effectively manage EV charging services in both the charging station scenario and the distributed home charging scenario is discussed. Then, open research issues related to the communication technologies and charging services for networked EVs are summarized. Ultimately, networked EVs may not only revolutionize how people and goods move, but also how energy flows, leading to future green and intelligent transportation systems of both *things* and *energy*.

Introduction

Climate change and extreme weather, a by-product of greenhouse gas emissions, has been a critical issue facing the entire world. Electric vehicles (EVs) are a key to clean transportation, promoting sustainable energy development and addressing air quality and climate change issues. They are especially beneficial when a growing portion of the electricity is generated from renewable and low-emission sources. Despite various incentives from governments worldwide, the rollout of EVs has been slow. Limited cruising range and lack of convenient charging services are among the major obstacles. Furthermore, the aggregated charging demand of a large number of EVs may create a peak load which can affect the power grid.

The good news is that EVs are now hitting a critical mass on the market at the same time as vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication technologies are maturing, and electric utilities around the globe are racing to make their power grids more intelligent by adopting information and communication technologies (ICT). In addition to solving the above range and charging problems, the nexus of the Internet, EVs, charging stations, and smart grid forms a perfect storm of opportunities for future green and intelligent transportation systems. For instance, when EVs are connected and their charging and discharging are coordinated, their batteries can serve as mobile storage for power systems to provide demand response services. Real-time EV information can also help charging stations and power grids optimize their operations and be well prepared for future demand. Real-time road and power grid information can be used to optimize EVs' travel paths to reduce energy consumption and travel time, ease congestion, and also guide EVs to the most desirable places for charging or exchanging batteries. Mobile charging services provide another viable option for EV owners, when moving smart EVs can dock and form a platoon to charge each other.

In this new paradigm as shown in Fig. 1, reliable and efficient information exchanges between EVs, meters, charging stations and the power grid, as well as intelligent EV charging management, are the key issues. In this article, we introduce a scalable and efficient EV communication network design, and smart EV charging services providing demand response, which are key enablers and services for networked EVs, respectively. We first briefly introduce the background. Then we present an efficient EV communication network design and smart EV charging management, followed by future research issues and concluding remarks.

Background

In the past decade we have witnessed the emergence of Internet-of-the-Things (IoT) technologies facilitated by M2M communications, bringing disruptive changes to traditional industry sectors and transforming their landscapes. Two of the most noticeable machine-to-machine (M2M) applications are V2V/V2I communication networks, and smart grid enabled by the communication systems connecting smart meters, distribution, transmission and generation systems. Currently, these two systems are still under development, and we anticipate the tremendous benefits they will bring to the traditional transportation system and power grid. This article considers one step further. Given the growing population of EVs and their high energy demand and large battery capacity, connecting EVs will bring many new opportunities for future green and intelligent transportation systems, as discussed in the Introduction.

To exploit these new opportunities, ICT plays a critical role. Although the availability of Internet

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To exploit these new opportunities, ICT plays a critical role. Although the availability of Internet services for human beings has become ubiquitous thanks to all-IP cellular systems, it is technically challenging to develop an advanced information, communication and control system in the context of connecting EVs, charging stations, and power grids.

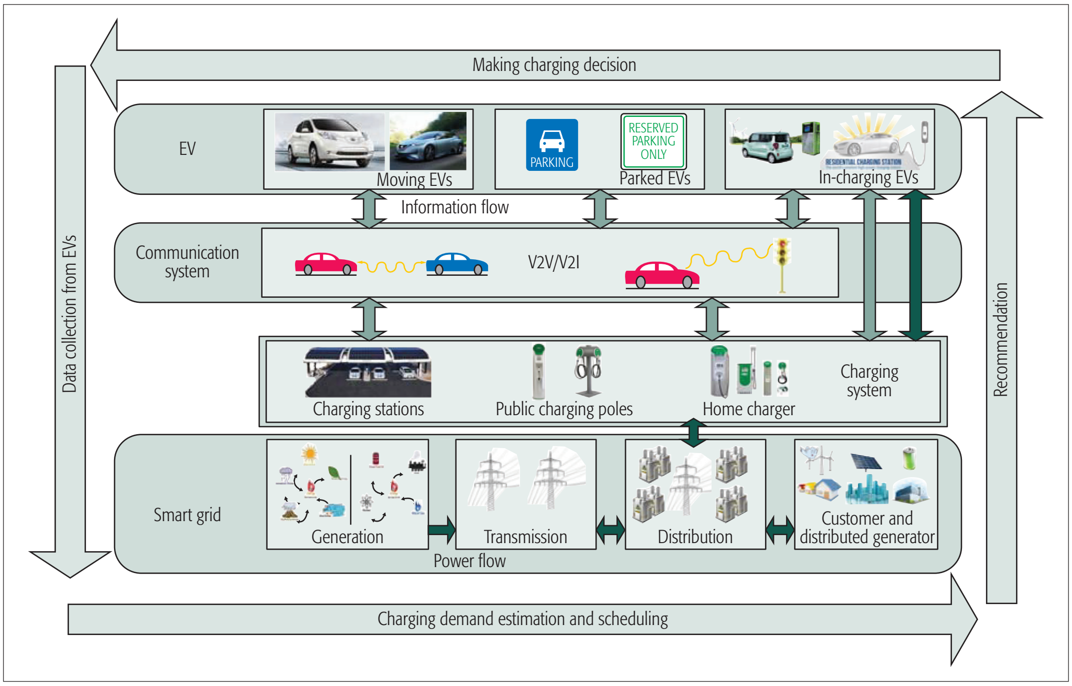

Figure 1. Hybrid V2V/V2I communication networks.

services for human beings has become ubiquitous thanks to all-IP cellular systems, it is technically challenging to develop an advanced information, communication and control system in the context of connecting EVs, charging stations, and power grids due to the following major issues:

•Vehicle density may change drastically over time (during off/peak hours) and location (main vs. side streets), and wireless communications may suffer severe fast fading and shadowing due to mobility or indoor/underground parking.

•Real-time safety, charging and trip planning, and other location-related messages have stringent delay constraints, while other infotainment applications can be delay tolerant. The scalability and availability of always-on services with heterogeneous delay requirements to EVs are difficult to guarantee using the current cellular systems.

•EVs have limited cruising ranges, and different EV charging options may vary substantially in charging speed, energy cost, and EV's battery lifetime and cost.

•Given the distributed and relatively large battery capacity, EVs may provide various charge-back services to the grid in different time granularity [1]. However, the high mobility of EVs makes it difficult to fully utilize their batteries for demand response services. Also, how to ensure reliable and timely information and control message delivery for these services and optimize the charging schedule based on real-time information are open issues.

Networked EVs can rely on V2V communications, V2I communications, or both. Most existing research on V2V and V2I communications focused on safety message broadcast or infotainment services, while the new applications from EVs have new QoS constraints and features. For instance, the delay, reliability, and availability requirements for EV status updating can be more stringent than infotainment services, while the messages may need to propagate over longer distances rather than simply being broadcast to neighboring vehicles only. Software-defined radio and software-defined networks are promising approaches to efficiently and flexibly manage wireless transmissions and allow networks to keep up with the pace of changing requirements [2]. However, they have been investigated mainly for stationary networks, and the high-mobility vehicle networks are much more challenging, due to dynamic topology, time-varying communication channels, and heterogeneous V2V and V2I communication technologies.

EV charging is a key issue for the massive rollout of EVs. Existing works dealing with the EV charging scheduling often simplified the problem by assuming a first-come-first-serve (FCFS) queue and constant charging rate. In some cases, such as charging in a parking lot or at home, so long as the charging can be finished before the deadline, it is preferable to schedule the charging flexibly and not necessarily FCFS. The battery charging rate is also a varying parameter related to its state of charge (SoC), which brings new challenges and opportunities to optimize the scheduling and to provide demand-side management services. Given the possibility of EV-to-EV charging, mobile charging services will emerge and be highly demanded, and how to optimize the scheduling of mobile charging services is a challenging issue.

A few recent advances, including some of ours, have shed new light on addressing the above challenges, which will be discussed in the following sections.

Scalable and Efficient EV Communication Networks

Considering the two-way communication flows among EVs, charging stations, communication systems, and smart grid (SG), and the two-way power flows between the grid and EVs as shown in Fig. 1, the first key research issue is to develop advanced always-on communication systems.

Hybrid V2V/V2I Communication Network Architecture

The massive rollout of EVs relies on smart charging and other services, which require anytime, anywhere wireless connectivity, scalable to any network size and diameter. Compared with setting up a new dedicated wireless network, reusing the existing cellular infrastructure can reduce the technology development cycle, and leverage many existing state-of-the-art technical solutions and business models, and thus is appealing. Furthermore, integrated EV charging stations and cellular units can be deployed together to provide both smart charging and communication services simultaneously, e.g., the pilot EV+cellular infrastructure project in English Bay Parks, Vancouver, Canada. However, there are many new challenges to support EV network applications using current cellular systems such as LTE/LTE-A.

To optimize the travel plan and charging, an EV needs to report its status periodically, such as location and the EV's battery SoC, and to receive the charging stations' capacity, current load, price, and other advertisements in a timely manner. These messages feature small data sizes, sometimes even smaller than what can be carried in one single minimum scheduling time-frequency unit of current LTE/LTE-A systems, resulting in low-efficient cellular transmissions [3]. Considering the complicated mobile environment or indoor/underground parking lot situations, the wireless channel condition can be very poor, further reducing spectrum efficiency. Thus, a key design objective is to improve spectrum and energy efficiency for supporting these large-volume, small-size data packets. Furthermore, the high mobility of EVs leads to a fast-fading channel environment, and how to maximize system throughput by taking advantage of the diversity gain in a realistic setting is also critically important.

On the other hand, EVs may travel across many locations and even countries with different service providers, spectrum allocations, and standards. It is desirable to ensure the compatibility of the on-board unit (OBU) and nearby infrastructures, base station (BS) or road side units (RSU). Although cellular systems can support many applications in both intelligent transportation systems (ITS) and SG, vehicles often need to exchange location-sensitive information with nearby vehicles. Using cellular systems may not be desirable due to the longer distance and delay between the vehicles and the base station, and the higher spectrum cost. Furthermore, in remote areas, providing ubiquitous and always-on coverage using cellular infrastructures may be too expensive. In addition, in the presence of natural disasters, the communication infrastructure may be damaged when it is most needed. Thus, V2V ad-hoc communications using low-cost, dedicated short-range communications (DSRC) or other short-distance wireless technologies (such as WLAN) complementary to V2I communications will be indispensable for connecting vehicles. In December 2016, the U.S. Department of Transportation proposed to mandate V2V communications on all lightweight vehicles. From the above aspects, it is anticipated that future vehicle communication systems will be hybrid, combining both V2I and V2V networks, as shown in Fig. 2.

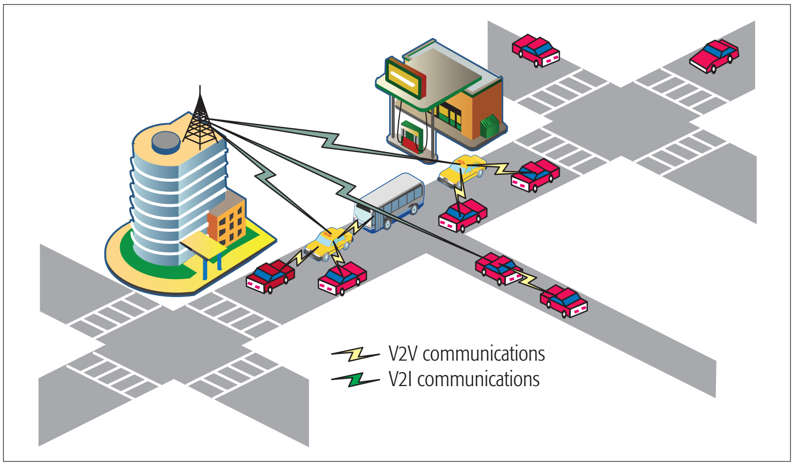

Figure 2. Hybrid V2V/V2I communication networks.

Throughput-Optimal Scheduling for V2I Communications

To support anytime, anywhere charging for EVs, frequent V2I message exchanges are needed, where the infrastructure can be BS or RSU. Throughput-optimal scheduling can maximize the throughput in a dynamic environment, which is particularly desirable for wireless communication systems given the limited wireless spectrum. In a multi-user system with a fixed number of flows and a dedicated queue for packets from each flow, the classic Queue-MaxWeight (Q-MW)-based throughput-optimal scheduling will select the flow with the largest product of the channel rate and queue length to transmit, so flows with better channel conditions have a higher chance to transmit. This opportunistic scheduling can thus take advantage of channel diversity to maximize the total throughput. However, the classic Q-MW scheduling cannot be applied to systems with flow-level dynamics and cannot co-exist well with TCP [4]. A few delay-driven MaxWeight throughput-optimal solutions have been proposed, which can deal with flow-level dynamics [5] but are not desirable for applications with small-latency requirements, as they give a higher priority to older flows and a new flow may have to wait for a long start-up time before being scheduled to transmit.

Recently, Head-of-line Access Delay (HAD) based scheduling has been proposed, which can achieve throughput optimality and provide good support for TCP flows [6]. HAD delay is the access delay of a flow, that is, the time duration for the first packet in a queue being in the head-of-line status while waiting for transmission. Using the HAD scheduler, a flow with the maximal product of the channel rate and HAD delay will have the highest priority to transmit. This solution can also take advantage of time-varying channel conditions to achieve throughput optimality. Furthermore, since the priority of each flow grows w.r.t. its HAD delay, similar to round-robin, TCP-compatibility and a certain level of fairness can be ensured. Consequently, a new flow can quickly gain the transmission opportunity to avoid the high startup latency problem associated with the other delay-driven MaxWeight schedulers.

The hybrid V2V/V2I communication network paves the way to overcoming the major barriers to the large-scale adoption of EVs, including the charging and range anxiety problems. With hybrid vehicle communication networks, EVs can easily find suitable charging stations, and select the best one based on the travel cost to/from the charging station, the expected waiting time, charging cost, and charging speed.

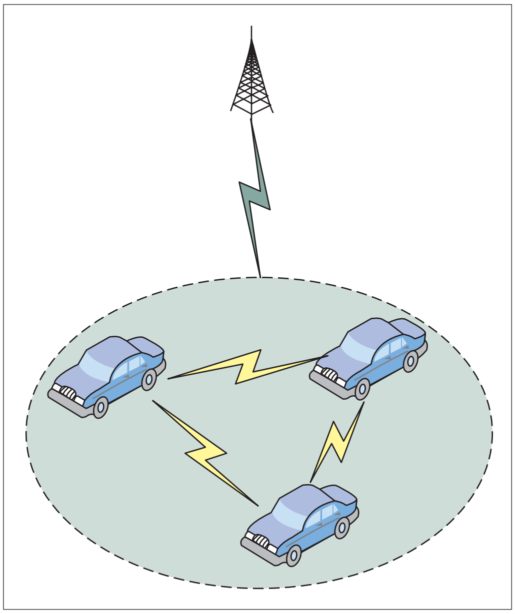

Figure 3. Using V2V to reduce V2I transmission cost.

Efficient V2I Transmissions Using V2V and Network Coding

The frequent EV and charging station control and status update messages feature small-size data, resulting in low-efficient cellular transmissions. To ensure that sufficient data is being transmitted within each scheduled resource block, we can apply both V2V and network coding (NC) to solve the small-packet problem. V2V communications can either use the D2D technologies that are supported by LTE and LTE-A cellular systems, or DSRC communication technologies.

As shown in Fig. 3, in the downlink, for the unicast scenario, where control/information messages are sent to individual EVs, a BS can use NC to combine packets targeting a group of vehicles to generate a number of linear combinations and broadcast them to the group. When any vehicle in the group is *mature*, (i.e., it receives sufficient linear combinations to decode all the packets to the group), it can be responsible for the data delivery within the group. Consequently, the needed BS downlink transmission resources can be reduced. After decoding all the packets to the group, the mature vehicle can generate new linear combinations and forward them to others using V2V. This approach can explore the spatial diversity of V2V/V2I transmissions to achieve a much higher spectrum efficiency. Using NC can limit the control and feedback overheads in the cellular system, as the BS does not need to know whether each linear combination has been received successfully or not, and it only needs to ensure that at least one vehicle in the group receives a sufficient number of linear combinations.

The application of NC and V2V in the uplink scenario is more challenging, as packets are initiated from different vehicles. Similar to the downlink scenario, neighboring vehicles can form a group. Then, one EV in the group can serve as the group head. The group head will collect the packets from the group using V2V, and then aggregate the small packets and forward them to the BS using the V2I uplink. Combining small packets in a group to transmit and using V2V for message exchange within the group can substantially reduce the downlink/uplink transmission cost in the cellular system. Preliminary results in [7] have demonstrated the benefit of this approach.

Optimal Data Forwarding with V2V

When EVs and charging stations are far away from each other and outside the infrastructure's coverage of communication, we can rely on multi-hop V2V communications. To enhance reliability, messages can be duplicated and forwarded through different paths to reach the destination. As the vehicle density may change dramatically w.r.t. time and location, we need to treat dense and sparse networks differently.

For a dense two-dimensional vehicular ad-hoc network (VANET), so long as the vehicle density exceeds a certain critical value, the probability that vehicles at two locations are connected can be high enough. Based on the closed-form connectivity analysis tool for two-dimensional VANETs [8], we can minimize the number of duplicated copies by limiting the number of forwarding paths to reach the destination and still ensure a high message delivery ratio.

For sparse networks, the connectivity between two locations can be very low. In this case, we can use vehicles as message carriers when disconnections occur. That is, if no other vehicles are found to forward the data, a vehicle can carry the message until it encounters a more suitable vehicle or enters the coverage of an infrastructure to forward the data. Based on the analytical framework in quantifying the end-to-end delay performance for the store-carry-and-forward solution, we can design the optimal data forwarding strategy and routing protocol to minimize the expected end-to-end delay and ensure the data delivery ratio [9].

Intelligent Charging Management

The hybrid V2V/V2I communication network paves the way to overcoming the major barriers to the large-scale adoption of EVs, including the charging and range anxiety problems. With hybrid vehicle communication networks, EVs can easily find suitable charging stations, and select the best station based on the travel cost to/from the charging station, the expected waiting time, charging cost, and charging speed. On the other hand, how to manage EV charging in different scenarios is a pressing issue.

Charging management at Charging Stations

Given the popularity of EVs, future garages, such as parking lots in business districts or office buildings, should also provide EV charging services and function as charging stations. Ubiquitous V2V/V2I communication networks make it possible to coordinate the incoming charging requests to guarantee profit for the operator and a good satisfaction for the customers.

To schedule the charging requirements optimally, the battery charging characteristics, electricity price variation, and each EV's charging request and its departure time should be considered. The constant-current constant-voltage (CC-

CV) charging model is often used in the literature for EVs. Time of Use (ToU) pricing has been widely adopted, so its impact on the charging station's profit should be considered. Stochastic optimization tools can be applied to solve the charging problem considering the above requirements and tradeoff, resulting in a win-win situation for both profit maximization by operators and service satisfaction by customers [10].

Distributed Charging at Home

Another important EV charging scenario is to charge EVs at home garages. With the growing penetration ratio of EVs, distributed EV charging at home garages will exert great pressure on the power grid, both at the transmission systems and the distribution grid. Without proper coordination, the simultaneous charging of a large number of EVs will result in a peak load, which may degrade the power system's stability, reliability, and efficiency. Facilitated by the real-time information exchange between the power grid and EVs, a distributed scheduling approach for supporting a high EV penetration rate under the common grid constraints was developed in [11]. The distributed solution borrowed the idea of random access protocols in computer networks such that each EV will access the grid for charging with a probability that can be adjusted according to the grid status. By tuning the access probability considering the transmission and distribution bus load constraint and the voltage drop constraint, distributed EV charging can fully utilize the power grid resources while avoiding congestion and voltage drop problems in the transmission and distribution grids.

Further Discussion and Future Work

The connected EV paradigm is promising and leading to future green and intelligent transportation systems. There are still many key issues that need to be addressed and new opportunities that can be further explored. We list a few of them in the following.

SDR Enabled, PHY-Aware Channel Selection for V2V Communications

With different spectrum cost and QoS provisioning, V2V and V2I communications are complementary to each other and together, they can provide ubiquitous and scalable communication services for EVs. For V2V, DSRC supports one control channel and six service channels, and other V2V technologies also support multiple channels. Given the dynamic environment, selecting the appropriate channel for V2V communications is an important step to ensure high reliability, low latency, and high throughput transmissions, especially for high-dense vehicle networks. How to develop a software-defined radio (SDR)-enabled, PHY-aware channel selection algorithm for V2V communications is an important open issue.

First, for different parameters of the channel in both the PHY layer (symbol-level channel activities) and the link layer (frame-level channel activities), their relationships with the traffic load should be revealed. Then, a PHY-aware channel selection procedure should be developed to select the best channel accordingly. It is also desirable to apply machine learning algorithms to analyze the multi-dimensional PHY/MAC measurement data and to estimate the traffic load of each channel to find the best one. Experiments using SDR testbeds are needed to refine the design until achieving the design goal.

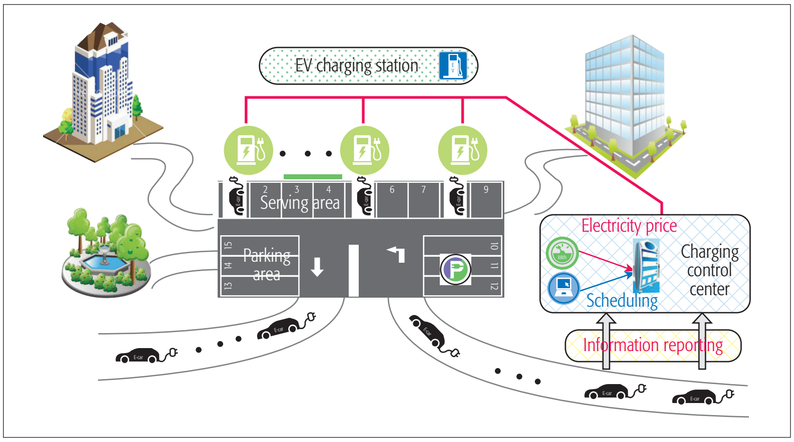

Figure 4. EV charging station [10].

SDN-Based Hybrid V2V/V2I Networks

Software-defined networks (SDNs) are promising to address resource and network management problems given their flexibility, adaptiveness, programmability and logically centralized knowledge and processing. Although currently SDNs are mainly used in wired networks, especially in data centers, they are very attractive for large-scale, hybrid V2V and V2I networks. The separation of the data plane and control plane is appealing for connecting EV/charging stations of large scale and high heterogeneity [12]. To apply the SDN architecture, vehicle-to-BS connections can be used for the control plane thanks to the long transmission range, and the vehicle-to-RSU and V2V connections can be used for data plane considering their lower spectrum and energy costs and higher data rates. With better knowledge of the whole network topology and traffic flows, SDN-based routing solutions are anticipated to achieve higher resource utilization and better performance. It is desirable to apply, test and fine tune the scheduling algorithm, the V2V/NC transmission schemes, and the routing protocols discussed in the previous section in both the SDN-based and the traditional network architectures, and compare their performance and control overheads.

Scheduling of Mobile Charging Stations

Ubiquitous communication networks can also facilitate the optimal arrangement of mobile EV-to-EV charging, if EVs can dock with each other and form a "platoon," e.g., the EO Smart Connecting Car 2 launched by DFKI Robotics Innovation Center in 2015 [13]. EV-to-EV charging is very appealing as EVs can be charged without spending tens of minutes to hours in charging stations. Given the time saved, it can be a highly profitable charging service. In this scenario, EVs can serve as mobile charging stations for others.

Scheduling and management of the mobile charging stations is a new, challenging problem. Given the charging requests from various locations, For EV charging, integrating a large number of EVs into the grid is both a challenge and an opportunity for power grids. If regulated wisely, EV batteries can serve as distributed energy storage to relieve the peak demand and maintain a balance of the generation and load. In other words, in SG, EV charging can be controlled to provide the demand-side management services.

their traveling paths, and the locations and capacities of available mobile charging stations, the optimal scheduling problem should be studied. That is, how to dispatch suitable mobile charging stations to serve the requests, aiming to guarantee the service requirements and minimize the cost (including the travel cost and the charging/discharging cost of the mobile charging stations). The uncertainty of real-time road traffic and traveling time makes the problem more difficult to solve.

EV Charging Providing Demand Side Management

For EV charging, integrating a large number of EVs into the grid is both a challenge and an opportunity for power grids. If regulated wisely, EV batteries can serve as distributed energy storage to relieve peak demand and maintain a balance of generation and load. In other words, in SG, EV charging can be controlled to provide demand-side management (DSM) services [14, 15]. The development of distributed, centralized or hybrid charging scheduling to achieve the DSM function of frequency regulation and load balance is an important open research issue.

Conclusions

This article pushes the frontier of wireless networking to a new paradigm, a cyber-physical system connecting EVs, stationary and mobile charging stations, power grids, and the Internet. It is anticipated that numerous new theoretical models will be developed for hybrid V2I/V2V networks, applying and further developing the tools in stochastic geometry, stochastic network optimization and queueing theory. To solve the intelligent charging problem and use EV batteries as mobile storage for power grids, new machine learning and dynamic optimization tools have been and will be applied and developed to facilitate smart stationary and mobile charging services and enable demand-side management. In conclusion, the new paradigm of connected EVs may not only revolutionize how people and goods move, but also how energy flows, leading to future green and intelligent transportation systems of both *things* and *energy*.

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Biographies

Lin Cai [S'00, M'06, SM'10] (cai@ece.uvic.ca) received her M.A.Sc. and Ph.D. degrees in electrical and computer engineering from the University of Waterloo, Waterloo, Canada, in 2002 and 2005, respectively. Since 2005, she has been with the Department of Electrical & Computer Engineering at the University of Victoria, where she is currently a professor. Her research interests span several areas in communications and networking, with a focus on network protocol and architecture design supporting emerging multimedia traffic over wireless, mobile, ad hoc, and sensor networks. She has been a recipient of the NSERC Discovery Accelerator Supplement Grants in 2010 and 2015, respectively, and the best paper awards at IEEE ICC 2008 and IEEE WCNC 2011. She has served as an associate editor for *IEEE Transactions on Wireless Communications*, *IEEE Transactions on Vehicular Technology*, *EURASIP Journal on Wireless Communications and Networking*, the *International Journal of Sensor Networks*, and the *Journal of Communications and Networks* (JCN), and a Distinguished Lecturer (DL) of the IEEE VTS society.

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