# Future Communications and Energy Management in the Internet of Vehicles: Toward Intelligent Energy-Harvesting

Xiaojie Wang, Zhaolong Ning, Xiping Hu, Lei Wang, Lei Guo, Bin Hu, and Xinyu Wu

## Abstract

As an emerging communication platform in the Internet of Things, IoV is promising to pave the way for the establishment of smart cities and provide support for various kinds of applications and services. Energy management in IoV has been attracting an upsurge of interest in both academia and industry. Currently, green IoV mainly focuses on two aspects: energy management of battery-enabled RSUs and EVs. However, these two issues are always resolved separately while ignoring their interactions. This standalone design may cause energy underutilization, a mismatch between traffic demands and energy supplies, as well as high deployment and sustainable costs for RSUs. Therefore, the integration of energy management between battery-enabled RSUs and EVs calls for comprehensive investigation. This article first provides an overview of several promising research fields for energy management in green IoV systems. Given the significance of efficient communications and energy management, we construct an intelligent energy-harvesting framework based on V2I communications in green IoV communication systems. Specifically, we develop a three-stage Stackelberg game to maximize the utilities of both RSUs and EVs in V2I communications. After that, a real-world trajectory-based performance evaluation is provided to demonstrate the effectiveness of our scheme. Finally, we identify and discuss some research challenges and open issues for energy management in green IoV systems.

## Introduction

With the increasing number of intelligent vehicles and the integration of sensors, the Internet of Vehicles (IoV) has become a promising communication platform of the Internet of Things, and is acknowledged as the fundamental technology to construct intelligent transportation systems for smart cities. Modern transportation systems are promising to bring convenience to citizens' daily life through services and applications of enhanced mobility and improved safety on roads. According to the results published by Juniper Research UK 2018, smart cities can help citizens save 125 hours per year on average, among which mobility and public safety can save 60 and 35 hours, respectively. IoV supports several types of communication patterns, such as vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-sensor (V2S), and vehicle-to-pedestrian (V2P). Currently, automobile exhaust emission is a major factor affecting human environments and air conditions. As early as 1970, a Los Angeles photochemical smog episode occurred, caused by the exhaust emission of more than 2.5 billion vehicles. After that, many countries have issued and implemented relevant laws as well as regulations to strengthen the management of automobile exhaust emission. For example, Europe has enforced the regulation of Euro I-VI, with the purpose of limiting emissions of NOx, HC, and CO. For $CO_2$ emissions, a target of 130 g/km was realized in 2015 by the European Commission, and 95 g/km will be reached in 2021 [1]. Other countries, including China, Japan, and the United States, have also made similar policies in their automotive markets. Therefore, an upsurge of interest has arisen in the establishment of green IoV systems all over the world, aiming to relieve the environmental pollution by taking advantage of electric vehicles (EVs) and renewable energy sources.

Since IoV systems can provide drivers and passengers with various kinds of vehicular applications, such as location-aware road services, autonomous driving, and in-car entertainment, wireless traffic demands from vehicles to the Internet are increasing rapidly. A number of battery-enabled roadside units (RSUs) have been deployed along main roads to boost network capacity. For example, some RSUs can cache contents in their local buffers and deliver the required contents to passing vehicles without fetching through backhauls. Due to the disconnection between smart grid and RSUs in some rural areas, energy harvesting policies need to be designed for RSUs to serve the huge service requests from vehicles. A promising solution is to enable wind or solar-powered RSUs in an energy-constrained vehicular environment. The Department of Transportation of the United States has predicted that solar-powered RSUs will dominate 40 percent of all rural freeway RSUs by 2050 [2].

Some studies have investigated downlink traffic scheduling and service request routing strategies

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EVs will play a dominant role in the next-generation vehicular system for smart and green city construction. Charging management for EVs is important to achieve efficient energy management. Its challenges mainly contain two aspects: selecting a charging station to design a reasonable charging plan, and constructing an efficient communication framework between EVs and the power grid.

to reduce energy consumption of RSUs. However, these schemes merely consider the situation in which RSUs are a unique kind of energy consumption components in the whole network, regardless of other energy consumption terminals, such as EVs and sensors. The highly dynamic traffic demands and intermittent renewable energy supplies may cause energy underutilization, a mismatch between traffic demands and energy supplies, as well as high deployment and sustainable costs for RSUs [3]. Therefore, the combined energy management policy for various energy-consumption components in IoV systems calls for deep investigation.

This article mainly focuses on two energy consumption components in IoV systems: battery-enabled RSUs and EVs. To the best of our knowledge, this is the first work to provide a comprehensive energy management strategy by jointly integrating these two network components. Specifically, an energy-harvesting framework is constructed to support green IoV systems. We first provide an overview of several promising research aspects for energy management in IoV systems, and classify them into four categories. Following that, we establish an energy-harvesting framework based on V2I communications in IoV systems, by which RSUs can make intelligent decisions on energy harvesting to satisfy the required services. In order to satisfy the utilities of both EVs and RSUs, we further design an energy-harvesting strategy between EVs and RSUs based on a three-stage Stackelberg game to balance the benefits among participants. A real-world trajectory-based case study is performed to evaluate the effectiveness of our framework. Finally, we discuss some open issues and directions for energy management in green IoV systems to provide a guideline for future studies.

## Overview of Energy Management in Green IoV Systems

Energy management in IoV systems contains various technologies, for example, power plants, energy storage systems, efficient communication protocols, and flexible power management. In the following, we mainly discuss four promising research aspects for energy management in green IoV systems.

### Energy-Saving in RSU Scheduling

RSUs are fundamental infrastructures in vehicular networks because they can provide network access for vehicles in both highway and urban environments. Currently, battery-enabled RSUs are deployed along roads in many countries. With the limited number of RSUs and continuous traffic requirements of vehicles, how to make RSUs conserve their battery power until the next charging cycle to serve vehicular communication requirements deserves investigation. For battery-enabled RSUs, downlink traffic scheduling is promising to reduce energy consumption [4]. The energy consumption can be significantly lowered if an RSU communicates with a nearby vehicle instead of one far away. Therefore, efficient task scheduling is important to serve vehicular communication requirements by making the RSU always communicate with a nearby vehicle [5]. In addition, the overall energy consumption optimization by scheduling the requirements among different RSUs is necessary when a set of RSUs coexist. Another promising solution is to make RSUs turn on and off in a periodic manner so that the overall energy consumption can be reduced. However, a minimum number of active RSUs should be set to maintain the network operation and connectivity.

### Energy Harvesting for RSUs

Since smart grid cannot be connected with RSUs in some rural areas, taking advantage of renewable energy sources is an attractive approach to support the operation of RSUs. Specifically, wind and solar energy can be commonly used for electronic power generation. Solar-powered batteries can be embedded in RSUs to convert solar energy to electricity [6]. A rechargeable large battery is necessary since solar panels cannot directly provide energy for RSUs. In the discharge circle, a downlink scheduling scheme is carried out to control the energy consumption for communications between RSUs and vehicles. Wind-powered RSUs are utilized in [7], and the minimum size of storage battery is analyzed based on a power consumption model. When the energy is insufficient, some RSUs will go into a sleep cycle. In addition, it is cost-effective to leverage radio frequency (RF) energy transfer technology to transfer energy from passing vehicles to RSUs [2].

### EV Charging Based on Vehicle-Grid Technology

EVs will play a dominant role in the next-generation vehicular system for smart and green city construction. Charging management for EVs is important to achieve efficient energy management. Its challenges mainly contain two aspects: selecting a charging station to design a reasonable charging plan, and constructing an efficient communication framework between EVs and the power grid. A communication framework based on a publish/subscribe mode is designed in [8]. Considering traffic conditions and drivers' preferences, charging stations periodically broadcast their conditions (e.g., the number of charging EVs and residual electric power) to RSUs. EVs can obtain the published information when traveling into the communication range of an RSU and choose a suitable charging station. An optimization problem is formulated to configure electric power capacities for both EVs and the smart grid in [9], where EVs can not only purchase energy from the power grid, but also sell energy in turn. A cooperative optimization scheme based on improved particle swarm optimization is proposed to balance the benefits of EVs and the power grid, considering different prices of electric power in different space and time.

### Wireless Power Transfer for EVs

Traditional power transfer stations are based on wired charging technologies, making drivers stop their EVs and spend several hours to charge. Many drivers cannot tolerate the long charging time, and desire to find other possible charging modes. Wireless power transfer technologies are promising to overcome this drawback and allow EVs to charge in a wireless manner even while moving. The energy conversion efficiency of RF energy transfer can reach up to 85 percent prac-

| Definition | Description |
|---|---|
| $S_t^r, S_t^v$ | Electric power prices of an RSU and an EV at time $t$, respectively |
| $P_i, P_r$ | The amount of energy sold to an EV and an RSU, respectively |
| $C_i^d, C_i^m$ | Deployment and maintain costs for an RSU, respectively |
| $S_{t+t_0}^g, S_{t-t_1}^g$ | The electric power price of smart grid after $t_0$ time and before $t_1$ time, respectively |
| α, β | Charging efficiency for RSUs and smart grid, respectively |
| $U_r$, $Uv$ | Utilties of an RSU and an EV, respectively |

**TABLE 1**. Main notations.

tically [2]. Currently, the design of wireless power transfer systems has drawn great attention. An efficient wireless power transfer system is constructed in [10], including four coils for wireless charging. A source coil and two transmitter coils are installed to create and boost an electromagnetic field on the power supply equipment. An induction coil is installed in the EV to receive electric power from the electromagnetic field. One key challenge for wireless power transfer is how to improve the charging efficiency for EVs.

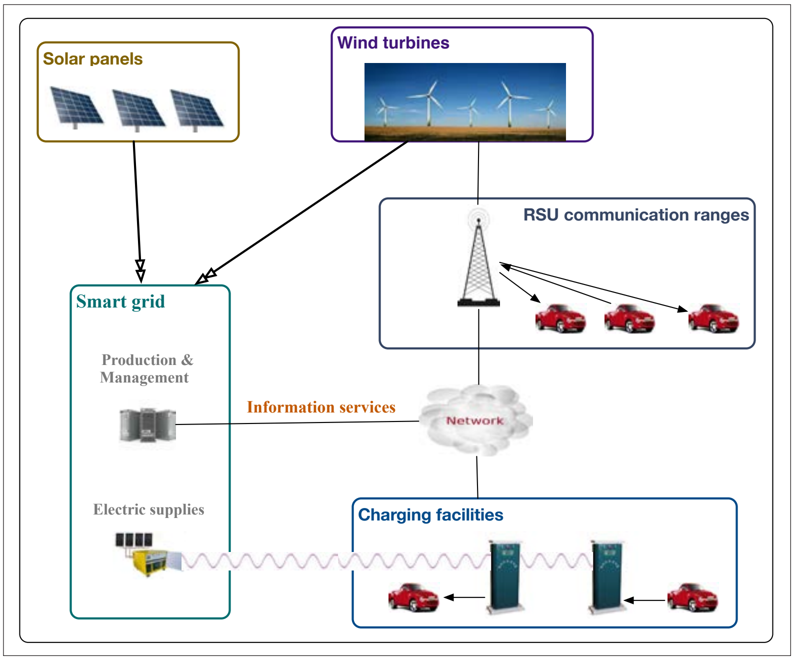


**FIGURE 1**. A communication sketch for green IoV systems.

## Green IoV Framework

To the best of our knowledge, the study on joint optimization of energy management between battery-enabled RSUs and EVs is still vacant. With the objective of both satisfying the required service requirements of EVs and reaching Nash equilibrium on the benefits of both EVs and RSUs, we design an intelligent energy-harvesting framework, named IEAF, based on V2I communications.

### Framework Overview

As shown in Fig. 1, solar panels and wind turbines are two major renewable energy sources to generate energy for smart grid. RSUs are equipped with wind turbines, and generally go through three stages in one battery cycle, that is, electric powers at high level, mid level and low level, respectively. When they are in a high-level situation, the energy generation speed of wind turbines is higher than the energy consumption speed of RSUs. Under this circumstance, RSUs have sufficient electricity and can sell redundant energy to passing EVs through RF energy transfer technology. In other words, EVs can not only obtain electric power from charging facilities, but also purchase electric power from RSUs on their routes. When RSUs are in mid-level and low-level situations, the energy generation speed of wind turbines is lower than the energy consumption speed of RSUs, and they can purchase energy from nearby EVs to support their operations. Both in high-level and mid-level situations, RSUs serve all the requirements of EVs. When the electricity of RSUs is in a low-level situation, they will only serve the requirements of EVs.

On one hand, RSUs intend to maximize their benefits through selling redundant energy to passing EVs, and minimize their costs by purchasing energy from EVs when their energy is in shortage; on the other hand, EVs prefer to maximize their cost savings when purchasing energy from RSUs, and maximize their benefits by selling energy to RSUs. To resolve the contradiction of utility between RSUs and EVs as well as balance their energy, an energy-harvesting strategy, leveraging a three-stage Stackerberg game, is designed based on V2I communications.

### System Model

The vehicular communication requirement flow arriving at an RSU is considered to follow a Poisson process [4]. The RSU can be viewed as a server processing requirements from EVs, and modeled as an $M/G/1/n$ queueing system. The queueing and processing time for a service requirement from EVs can be obtained by queueing theory. In addition, each RSU is equipped with a wind turbine to provide energy. Therefore, the harvested energy via wind turbines can be determined by the wind speed, air density, and circular turbine cross-section [7]. The harvested power of the RF energy transfer can be obtained based on RF energy propagation models [11]. The main notations of our framework are summarized in Table 1.

When the electric power of an RSU is in high-level, it has sufficient electricity to support its operations. When a traffic requirement arrives, it is stored in the waiting queue of RSUs for processing regardless of the electric power consumption. In addition, RSUs can sell redundant electric currency to passing EVs through RF energy transfer. Therefore, RSUs' utilities in this stage can be leveraged to minimize their maintenance costs, equivalent to maximizing their benefits, that is, $U_r = S_t^r \times P_i - C_i^d - C_i^m$. Herein, $S_t^r$ is the RSU's energy price at time $t$. The amount of energy sold to an EV is $P_i$, which should be less than the remaining energy provided by the RSU's battery. Variable $C_i^d$ is the deployment cost equally apportioned for a deal,

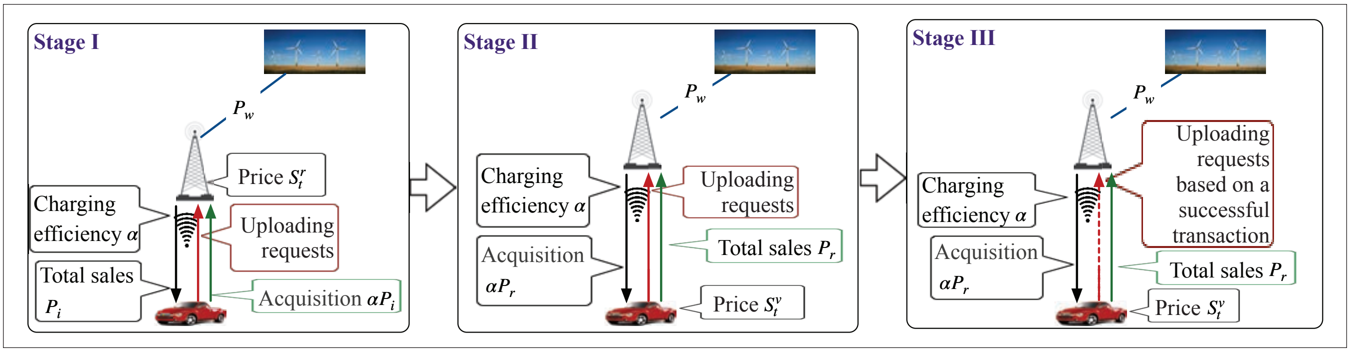


**FIGURE 2**. Interactions based on V2I communications: An RSU sells energy to an EV in Stage I; the RSU purchases energy from an EV in Stage II; an EV provides energy to enable the RSU to process its service requests in Stage III.

while $C_i^m$ is the maintenance cost for the deal. The unit deployment cost can be calculated by the total deployment cost divided by the battery life of RSUs. The deployment cost for a deal can be computed by the unit deployment cost times the duration from the last deal to this deal in the current stage. Similarly, the maintenance cost for the deal can be obtained.

For an EV, it can purchase energy from an RSU. Its utility function is to maximize cost saving, that is, $U_v = (S^g_{t+t_0} \times P_i \times \alpha/\beta - S^r_t \times P_i$, where $S^g_{t+t_0}$ is the charging price set by the smart grid when the EV prepares to charge after time interval $t_0$. The charging efficiencies of an EV charging from an RSU and the smart gird are denoted by $\alpha$ and $\beta$, respectively.

When the electric power of an RSU is in mid-level, it stops selling its electric currency and begins to purchase electric power from passing EVs to store energy for service management. Under this situation, it serves all the requirements submitted by the passing EVs and purchases energy from them if possible. The corresponding utility is $U_r = S^v_t \times P_r - C^d_j - C^m_j$, where $S^v_t$ is the price for electric power sold by an EV at time $t$, and $P_r$ is the amount of electricity sold to the RSU. The installation cost for this deal is denoted by $C^d_j$, and can be calculated by the accumulation of the installation cost for each unit based on the time for generating $\gamma P_r$ energy by wind turbines. Similarly, $C^m_j$ is the maintenance cost for this transaction.

For an EV, if its electric power is sufficient to support the corresponding operations until arriving at its destination, it can sell an amount of energy to RSUs. Therefore, the objective of the EV becomes to maximize its benefits: $U_v = S^v_t \times P_r - S^g_{t-t_1} \times P_r/\beta$, where $S^g_{t-t_1}$ is the price of the electric power when the EV purchases from a charging facility of smart grid.

When the electric power of an RSU is in low-level, it lacks energy. In order to maintain its fundamental functions, the RSU merely serves the requirements from EVs, which can supply enough energy to process the uploaded requirements. The utility of the RSU is the same as that in the mid-level situation. For the EV, whether its requirements can be served or not depends on the energy supply. If not enough energy can be supplied for the RSU to process its requirements, another RSU needs to be selected, causing a large delay for the response of its requirements. Therefore, the utility of EV in this stage is to minimize the response delay for the corresponding requirements.

## Intelligent Energy Harvesting

According to the analysis above, we notice that the utilities of RSUs and EVs always conflict with each other. In order to balance their benefits, we propose an intelligent energy-harvesting strategy based on a three-stage Stackerberg game, and their interaction is shown in Fig. 2. The corresponding process can be described as follows:

Stage I illustrates the electric power of an RSU in high-level, and the RSU is the leader in the Stackerberg game that offers a price to EVs. If the price is lower than that of the smart grid, EVs can purchase electric power from the RSU. We can obtain the corresponding Nash equilibrium condition $A \le S^{r*}_t \le B$, where $A = (C^d_i + C^m_i)/P_i$ and $B = \alpha S^g_{t+t_0}/\beta$.

Stage II shows the electric power of the RSU in mid-level, in which an EV plays the role of leader in the Stackerberg game and offers a price to the RSU. If price $S^{v*}_t$ satisfies $D \le S^{v*}_t \le E$, where $D = S^g_{t-t_1}/\beta$ and $E = (C^d_j + C^m_j)/P_r$, a Nash equilibrium can be reached, and the RSU buys the electric power from the EV.

Stage III is in a low-level situation, and the RSU merely serves EVs that can provide enough energy to process their requirements. Therefore, when an EV has a request to process, it should make a tradeoff between its benefit and the response delay. If a request is delay-tolerant, the EV can choose other RSUs to process its requests later if its benefit cannot be satisfied. In this situation, the Nash equilibrium condition is the same as that in Stage II if a deal can be made between the EV and the RSU. If the request is delay-sensitive, the EV needs to satisfy the request regardless of its benefits. Therefore, the Nash equilibrium condition is $S^{v*}_t \le E$.

## Performance Evaluation

We utilize a real-world trajectory of taxies in Shanghai, China, from April 1, 2015 to April 30, 2015 for performance evaluation. We randomly place RSUs in Jingan district and obtain the average performance by the Monte Carlo method. We obtain the information of wind speeds in Shanghai from [12], and model the hourly energy generated by winds according to Gaussian distribution similar to [7]. We also set the average packet size as 867.4 bytes, the energy consumption per bit as $2.92 \times 10^{-6}$) J, and the energy capacity of an RSU battery as 262 kJ as in [13]. We consider the signal-to-interference-plus-noise ratio (SINR)-based channel model, where the cross gain is related to the Euclidean distance and channel fluctuations.

The packet blocking probabilities of our solution and the sleep-based solution are demonstrated in Fig. 3a. Packet blocking probability is defined as the number of requirements dropped by the RSU when its waiting queue is full compared to the number of total requirements uploaded by EVs. The sleep-based solution [7] is an energy-harvesting scheme based on wind turbines and allows RSUs to sleep at points when the energy generation speed is lower than the energy consumption speed. We can observe that the packet blocking probability of our scheme is lower than that of the sleep-based solution, especially during the peak time, that is, 8:00–9:00 and 17:00–18:00. The reason is that our solution allows RSUs to purchase energy from EVs when they have insufficient energy, while RSUs go into sleep cycles when they are lacking energy in the sleep-based solution.

Average residual energy of RSUs is compared in Fig. 3b. We can observe that the performance of our scheme is better since it can balance energy between EVs and RSUs. However, RSUs are forced to sleep when they have insufficient energy in the sleep-based solution. During peak time, the sleep-based solution allows the RSU to go to sleep while our algorithm serves passing EVs with its best efforts. Consequently, more requirements can be satisfied by our algorithm, and more energy is consumed compared to the sleep-based solution.

Figure 4 shows the benefits of RSUs and EVs. The benefit of RSUs is defined as the total earning minus the total maintenance and deployment costs during a time period. The benefit of EVs illustrates the total cost savings plus the total earning. The normalized benefits of vehicles and RSUs are unified values, reflecting the gaps of their achieved results. We notice that the benefit of RSUs is high when the time is between 12:00 and 15:00, since the wind energy is sufficient and the service demands of EVs are low. RSUs can harvest sufficient energy and sell redundant energy to EVs.

For EVs, their benefits are high when the energy of RSUs is insufficient, since EVs can sell their energy to RSUs with the purpose of supporting their normal operations. In addition, when the energy generation speed is higher than the energy consumption speed between 13:00 and 15:00, RSUs can sell energy to EVs at a low price, increasing vehicular cost savings. However, the sleep-based solution cannot increase benefits of RSUs and EVs, since it does not consider an energy-harvesting scheme between EVs and RSUs.

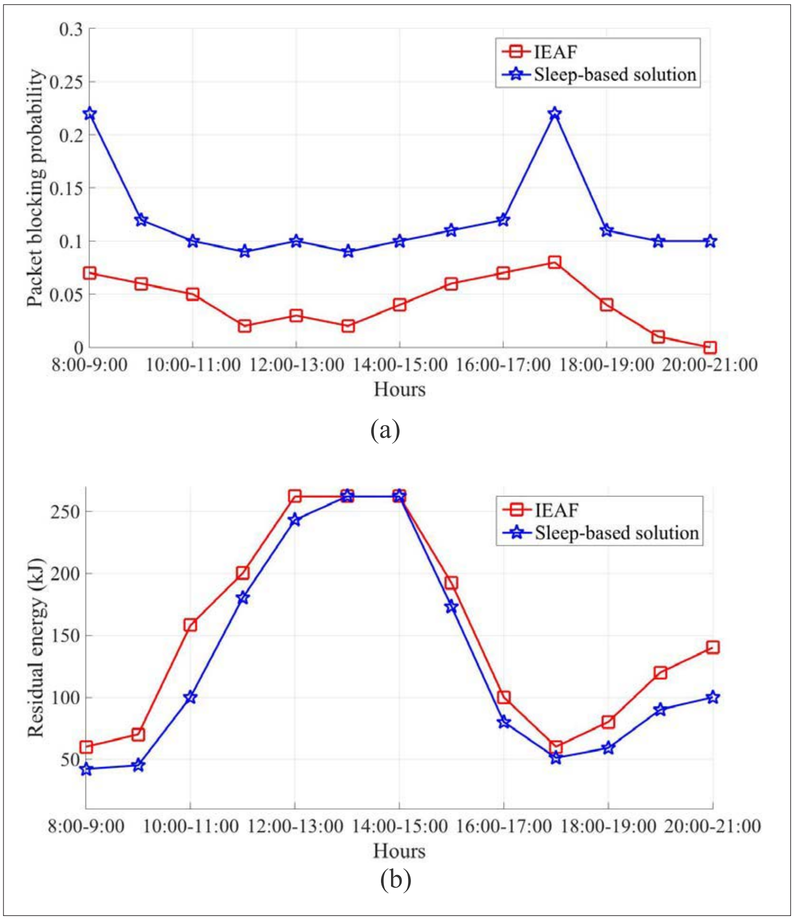


**FIGURE 3**. Performance evaluation: a) packet blocking probability; b) residual energy.

## Research Challenges and Open Issues

Many challenges and open issues still exist for energy management in green IoV systems. In the following, we discuss them from several aspects.

### Energy-Aware Security Protocol

Security protocols are necessary for communications in IoV systems to protect individual privacy. Generally, a high-level security mechanism requires high computational complexity and consumes much energy, which challenges energy-constrained devices. Therefore, energy-efficient security protocols call for investigation. However, the design of energy-aware security protocols for green IoV systems is still in its initial phase. Currently, many researchers have focused on encoding compression cost and reducing energy consumption to support energy-constrained devices. However, the encryption and compression technologies always increase the computational overhead and consume a lot of energy. Therefore, low-complexity cryptographic algorithms need to be designed to reduce the encryption overhead and energy consumption of devices [14]. In addition, a trade-off is required between the algorithm complexity and security to satisfy various network requirements.

### Dynamic Power Transfer

For a stationary charging system, drivers generally park their cars at a charging facility and leave. With the increasing number of EVs and the long time consumed for charging, dynamic power transfer is a promising technology to cope with the above-mentioned problems. It allows EVs to charge during their travels regardless of their movements. Currently, dynamic power transfer faces the following challenges:

- How to develop high-efficiency power transfer technologies to improve the transmission efficiency, such as innovative system designs and circuits, deserves to be well studied.
- How to reduce the cost for the establishment of the dynamic power transfer system also needs to be investigated, because the high cost may pose a constraint on the popularization among drivers.

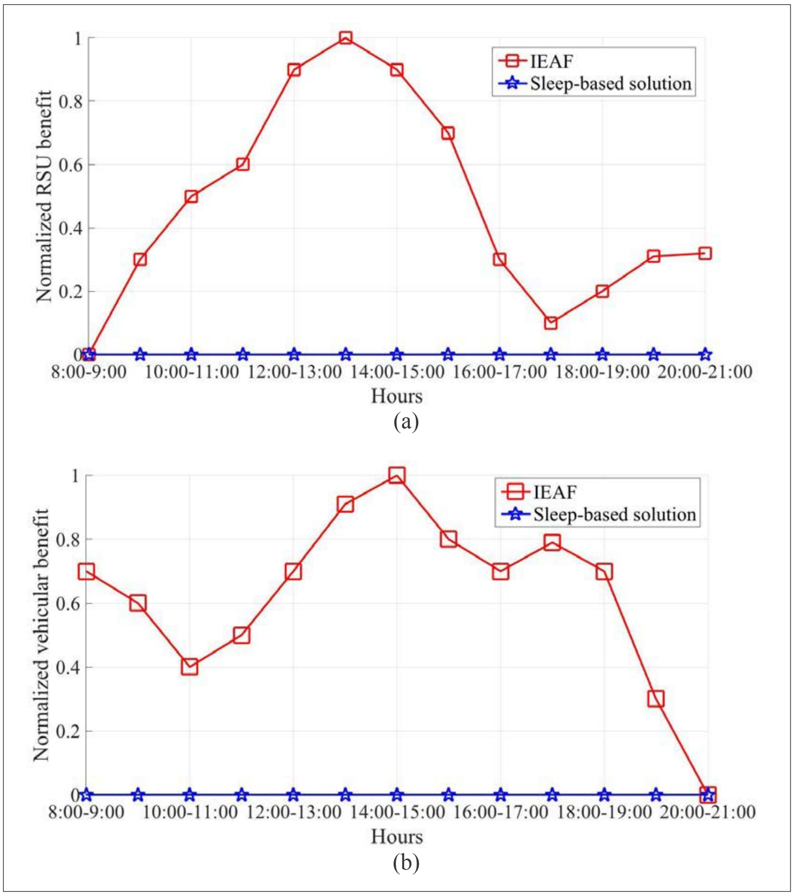


**FIGURE 4**. Performance evaluation: a) normalized RSU benefit; b) normalized vehicular benefit.

- How to reduce the mobility impact of EVs during the charging cycle is challenging, because speeds and driving directions of EVs mainly depend on traffic conditions and driving habits.
- How to seamlessly switch among different charging facilities without drivers' interactions is also challenging.

## Green Edge Computing

A significant challenge caused by connections and communications between end terminals and cloud servers is the energy efficiency of green IoV systems. One promising solution is to schedule tasks among several servers to minimize the energy consumption in the data center. Another choice is to jointly optimize radio and computational resources. However, most current solutions cannot be directly applied in vehicular networks due to the highly dynamic network topology. Therefore, energy-efficient edge computing or fog computing in vehicular networks is desired. For instance, how to offload traffic from a remote cloud to nearby fog nodes by exploiting V2I communications has a significant impact on energy management in IoV systems. In addition, how to utilize free resources of vehicles to form fog nodes and construct an energy-efficient model is also challenging [15].

## V2V Energy Swapping Strategy

Due to the increasing number of EVs and their charging demands, the power grid may be overloaded during peak times, especially in business and residential regions. V2V energy swapping is a feasible solution to relieve heavy loads on the power grid with the help of a connected aggregator. Therefore, efficient energy swapping strategies are necessary to guarantee the energy utilization. For example, how to stimulate EVs to participate in the process of energy supply to balance power demands at aggregators needs to be further investigated. In addition, online energy management protocols are desired to make a rapid match among EVs for supply and demand.

# Conclusion

This article first emphasizes research significance of energy management in green IoV communication systems and presents several promising research aspects for energy management in IoVs. Then an intelligent energy-harvesting framework based on V2I communications is constructed to both satisfy the required services of EVs and reach Nash equilibrium on the utilities of RSUs and EVs. Performance evaluation illustrates that our framework can both meet the service demands of EVs and largely increase the benefits of both EVs and RSUs. Finally, we discuss several existing research challenges and open issues to provide a guideline for further work.

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