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Perspective

Combining Heterogeneous Vehicles to Build a Low-Cost and Real-Time Wireless Charging Sensor Network

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Abstract: A wireless charging system that supports a large sensor network not only needs to provide real-time charging services but also needs to consider the cost of construction in order to meet the actual applications and considerations. The energy transfer between mobile devices is extremely difficult, especially at large distances, while at close distances a wireless, fast-charging, automatic, and high-precision landing system would be required. However, previous studies that used wireless charging cars, wireless charging unmanned aerial vehicles (UAVs) alone, or wireless charging pads to build a large-scale wireless charging system could not meet the above two conditions at the same time. If we can make good use of the existing high-speed backbone transport, such as the vehicular ad hoc network (VANET), it can not only consider the cost of construction and the speed of movement but also support the real-time charging service required by large-scale sensor networks. In this work, we propose an integration of heterogeneous mobile and charging vehicles, including VANET and UAV net, to provide a wireless rechargeable sensor network with a low-cost and high-efficiency charging system. Moreover, reward mechanisms are also designed to encourage private cars to provide transportation and charging capabilities to UAVs in the designed system.

Keywords: VANET; WRSN; drones; wireless charging

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1. Introduction

As a key technology of the Internet of Things (IoT), wireless sensor networks cover a wide range of applications, including the transmission of war information, warehouse management, quality control, health care assistance and monitoring, natural disaster early warning, household applications, vehicle tracking and detection applications, and so on. In recent years, due to the rapid development of wireless charging technology, many scholars have considered using wireless power transfer (WPT) to provide a new energy source for wireless sensor networks [1,2]. Additionally, the fading of RF wireless power transmission is analyzed under a dual-hop decoding and forwarding scheme [3,4]. In addition, the efficiency of wireless charging has been greatly improved (charging efficiency can reach more than 75% in a short distance) [5], so the wireless sensor network with rechargeable devices has become a development platform for many applications in the future. This type of network is called a wireless rechargeable sensor network (WRSN) [6]. A wireless network such as GSM or 5G and Wi-Fi can easily communicate within the layers and between them. However, energy transfer between mobile devices is extremely difficult, especially at large distances. While at close distances, a wireless, fast-charging, automatic, and high-precision landing system would be required. Moreover, the energy transfer between vehicle–vehicle, drone–drone, and sensor–sensor is practically inefficient.

To replenish the power required by the sensors, in general, the WRSN can deploy wireless chargers. Compared with static wireless chargers, the deployment of wireless charger vehicles (WCV) (that is, wireless chargers mounted on mobile vehicles or robots) has become a research topic that has attracted attention in recent years [7,8]. On the other hand, unmanned aerial vehicle (UAV) technology has been widely used in our day-to-day lives recently [9,10]. To break through the limitation of UAV battery capacity, many technologies for wireless charging of UAVs have also been developed [11]. Researchers have even begun to think about adding chargers to UAVs (called wireless charging drones or UAVs for short) [12] to provide instant charging services for WRSNs. Another new development is that the wireless charging pad (pad for short) [13] also provides brand new WPT technology for UAVs. These three different charging devices have different characteristics. How to make full use of hybrid WCV and UAV or even wireless charging pad technology in the future to construct a low-cost, high-efficiency charging system will lead the technological development of the Internet of Things in the future and at the same time generate new challenges and issues to be solved.

Motivation and Contribution

Previous studies have used wireless charging vehicles, wireless charging unmanned aerial vehicles (UAVs), or wireless charging pads alone to deploy a large-scale wireless charging system, all of which have a common disadvantage: a high construction cost, especially when deployed in a large-scale wireless sensor network. However, if we can make good use of the existing high-speed backbone transport, such as the vehicular ad hoc network (VANET) [14], it can not only consider the cost of construction and the speed of movement but also support the real-time charging service required by large-scale sensor networks. Moreover, we believe that more heterogeneous transportation systems or charging systems can be integrated in the future and that a reasonable operation mechanism for the new system can be proposed, which will provide a great opportunity to build a low-cost and high-efficiency wireless charging system. In this work, we propose an integration of heterogeneous mobile and charging vehicles, including VANET and UAV net, to provide WRSN with a low-cost and high-efficiency charging system.

The contributions of this work are listed below:

1. In this work, we try to integrate UAVs, VANET, pads, and WRSN together to construct a high-efficiency and low-cost wireless charging system for a large-scale wireless sensor network. To the best of our knowledge, no previous work mentions similar wireless charging systems.
2. The proposed system suggests that UAVs obtain energy from pads or cars in VANET, and sensors obtain energy from UAVs. Specifically, UAVs can be charged by landing on pads that are connected to a fixed power supply. Moreover, UAVs can also obtain additional power from nearby vehicles in a VANET to save a considerable amount of extra power and time for flying to and from the base station or pads. At the same time, UAVs can be carried and charged on the top of the cars in VANET to move toward the target sensor to save power and charging time.
3. Moreover, because the cars in VANET are already built, there is no need to pay a lot in deployment costs. Additionally, the system can reduce UAV deployment and management costs due to UAV sharing and improve charging efficiency at the same time.
4. In this work, a reward mechanism is mentioned to encourage private cars to provide transportation and charging capabilities to UAVs in the designed system.

The rest of this work is organized as follows: Section 2 presents the related work. Section 3 introduces the proposed three-layer charging system, followed by Section 4, which discusses the cooperation between the three layers in the proposed charging system. Finally, Section 5 concludes this work.

2. Related Studies

Deploying WRSN can extend the lifetime of wireless sensor networks (WSN) and reduce the cost of re-deployment. When using a mobile charger to charge the sensor, how to effectively plan the charging path and combine charging and data collection to reduce energy consumption has also become an important research direction [15–17]. In addition, a large sensor network needs to be able to use multiple mobile chargers at the same time, which leads to issues such as cooperative charging and management between mobile chargers [18]. Recently, there have been related studies mentioning how to use the integration of wireless charging vehicles and wireless charging UAVs or integrating wireless charging UAVs and wireless charging pads to build a wireless charging sensing network, which has also achieved striking results [19,20].

With UAVs as nodes, a self-organizing network (drone net) can be formed, which is a Flying Ad-hoc Network (FANET), providing data transmission or charging services. Many routing protocols have been proposed to improve the quality of data transmission in such networks [21,22].

VANET is a quite popular research topic, and various technologies related to autonomous vehicles in VANET are carefully discussed along with their advantages, disadvantages, and challenges [23]. With the development of 5G technology, there are better options for communication between autonomous vehicles (AVs). In [24], the authors investigated the emerging techniques required for integrating 5G technology with AVs and the impact of 5G and B5G technologies on AVs and security. Of course, how to enhance the quality of inter-vehicle communication, various intra- and inter-vehicle communication, and related technologies, including intra-vehicle backbone network architectures [25], have been extensively studied and developed [26]. Note that vehicles in VANET have different power sources, such as fuel, roadway powered, electricity, etc. In addition to providing power for the vehicle, the fuel can also provide electricity for the charging board carried with the vehicle. Utilizing the inductive power transfer system (IPTS), which is widely used for wireless powering of roadway powered electric vehicles (RPEVs), can provide continuous power to special vehicles [27]. In [28], an EV charging system is proposed to utilize the bus network in urban areas through the integration of on-line electric vehicle (OLEV) systems and microwave power transfer (MPT) systems. Therefore, vehicles in VANET can not only provide transportation services but also provide charging services. Thus, a wireless charging system to assist UAVs using the bus network in urban areas was proposed [29]. The authors formulated the UAV scheduling problem based on the proposed wireless charging system to minimize the total time cost of the UAVs.

How to charge efficiently is a hotly debated topic that is further complicated by changing circumstances. Machine learning is one of the most commonly used problem-solving techniques. For example, in the face of multiple uncertainties such as arrival/departure time and electricity price, scholars use deep reinforcement learning-based methods to deal with the problem of fast charging stations for electric vehicles [30]. The charging problem of UAVs is certainly one of the important research directions in the topic of charging [31]. In [32], UAVs are used to charge UAVs, and the authors used a reinforcement learning (deep learning) technique to determine the best target to charge. The use of solar-powered UAVs is also a consideration; a deep learning model of energy harvesting can be used to predict future power harvesting from solar panels as well as a consumption model to determine user arrival rates [33]. Reinforcement learning techniques can also be used to control solar-powered UAVs so they can adapt to changing their position by determining solar density and other environmental conditions [34].

3. Integrating Heterogeneous Vehicles to Form a Novel Charging System

Based on the aforementioned reasons, this work considers the integration of VANET and UAVs, two heterogeneous mobile and charging vehicles, into a WRSN. We make use of cars in VANET and UAVs in a drone network to provide a low-cost, high-efficiency charging system for WRSN. A VANET is a self-organizing network deployed by vehicles. It uses mobile vehicles and traffic facilities as nodes and applies wireless communication technology to form a mobile network. A vehicle joining this network will become a wireless node or a wireless router. It allows cars that are in close proximity to connect to form a large-scale ad hoc network. When a vehicle leaves the signal range and leaves the network, other vehicles can join and connect to create a new mobile dynamic network.

Next, we discuss the advantages and disadvantages of VANET in assisting in providing charging and how to integrate it with UAVs and pads. First of all, a UAV is cheap, fast, and can move freely without being restricted by terrain. A drone network (drone net, for short) can be formed by using multiple UAVs. Because the power battery in a UAV is limited, its flight distance or time will also be limited. In addition, if too many UAVs fly in the same area at the same time, they may collide and be damaged. The pad can provide UAVs with an additional energy supply, but the pad can only be fixed in one position (in order to connect a steady stream of power).

As long as there are roads where vehicles can travel in an area, VANET is ubiquitous, so resources can be shared appropriately. And because the car itself is shared, the cost of construction can be greatly reduced. Cars on VANET can exchange information through routing protocols. If we use a car in VANET combined with a wireless charging pad (which can be viewed as mobile charging pads) to provide charging service for UAVs, there will be many advantages:

1. Cars in a VANET often have redundant electronic power sources that can be shared with other UAVs if the owner of the cars likes to do so. The cars in VANET can be equipped with a charging dock at the root of them for possible UAVs to land on for power transfer.
2. Electric cars have become more popular with consumers in recent years, and their number is increasing in all countries.
3. Cars in VANET carried with UAVs provide an opportunity for UAVs to move quickly without consuming their own power sources, and the cars can also charge them (when moving from one place to another at the same time) with the help of a charging dock (pad) on the roof of the cars in VANET.

Nevertheless, a VANET also has the following disadvantages when it is used to implement a charging system:

1. Cars in a VANET move autonomously and uncontrolled and are not easy to predict. Especially for non-periodic vehicles, it is not easy to use these cars to plan and assist the movement of UAVs or provide additional charging services.
2. When the car in a VANET moves too fast, it may be a technical problem for a UAV to land and dock on the car.
3. A car in a VANET does not necessarily install a charging pad on the root, or its owner is unwilling to share and provide charging or moving services to other UAVs. Designing a feedback mechanism to encourage this kind of car sharing is also a challenging issue.

This work proposes a new architecture to integrate VANET, drone net, and WRSN, as shown in Figure 1. The whole system is divided into three layers:

Layer (1) All sensors in the WRSN are used to monitor the area of interest and send important monitoring information to the sink via the adopted routing protocol. In this system, the purpose of communicating at this layer is to transmit the monitored information and necessary control packets to complete the wireless charging task. Note that the charging schedule adopted for the entire WRSN can be proactive, on demand, or a mixed one.

Layer (2) In this layer, the drone net forms a wireless ad hoc network, including UAVs and WCPs. The purpose of UAVs is to provide an additional power supply to the sensors. When the system dispatches multiple UAVs to fly to the target sensors, the UAVs will wirelessly charge the relevant sensors and wait for an opportunity to return back to the base station (or the sink) after completing the charging tasks. Usually, a small number of pads are deployed in Layer (2) to provide short stays for UAVs, wireless charging to extend the flight distance of UAVs, and can also assist in communication tasks (such as being a cluster head when a hierarchy routing protocol is applied). In the proposed system, the communication task on the drone net in this layer is mainly to plan the flight path of UAVs to avoid possible UAV collisions or exchange wireless charging tasks between the two UAVs when necessary.

Layer (3) This layer is mainly composed of cars in a VANET, and its main task is to provide UAVs in the drone net with both charging and moving services. UAVs can fly to the dock mounted on the roof of a nearby vehicle to move to another place with the vehicle, and energy transfer to the UAVs can be carried out with the help of the charging equipment of this vehicle. In this system, the communication task of Layer (3) is mainly to collect the movement paths of cars in VANET and provide that to the UAV for selecting the proper cars for further moving and charging.

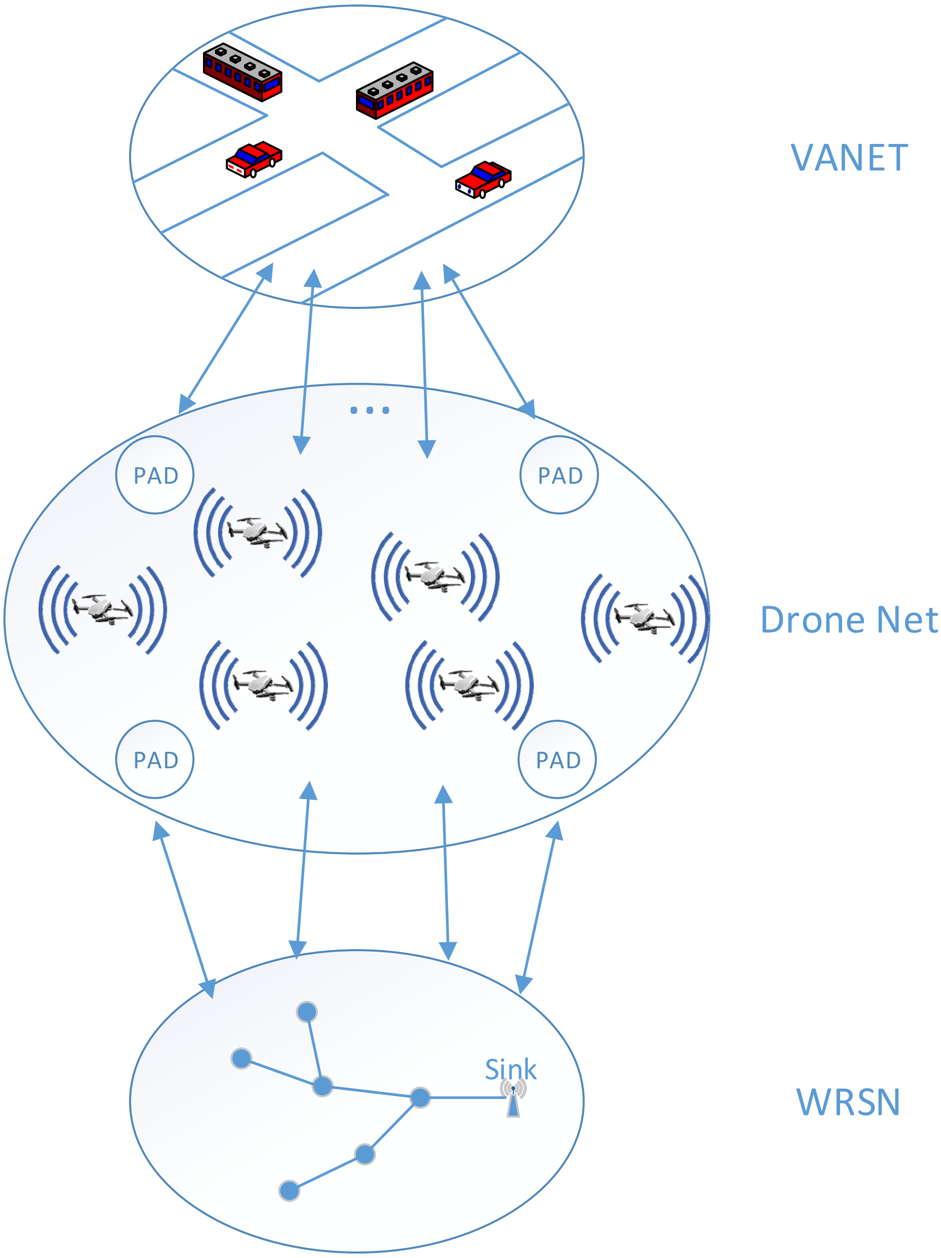

Figure 1. The proposed system that integrates VANET, drone net, and WRSN together.

4. Cooperation between the Three Layers in the Proposed Charging System

In this wireless charging system that integrates VANET, drone net, and pads, there are some factors to consider on how to effectively provide the necessary power for the sensors in time in WRSN. Generally, charging schedules are divided into three categories: proactive schedules, on-demand schedules, and mixed schedules. Proactive schedules arrange the sensors in a fixed order to charge them for UAVs. However, in on-demand schedules, when the power of the sensors is lower than a certain threshold, the charging request packet is sent to the sink. After collecting sufficient charging requests, the system will send some UAVs to execute the charging missions in the system. Of course, the mixed schedules are a mixture of the above two strategies.

Assuming that the system adopts an on-demand schedule, when the power of a sensor is lower than a certain threshold, the sensor will send a charging request packet, and the charging request will be transmitted through the communication protocol in WRSNs in Layer (1) to the sink. The sink in the system schedules the collected charging requests in a timely manner and arranges suitable UAVs to carry out wireless charging rescue missions. When a UAV is given a mission, the system will either plan for the UAV to fly directly, use the pad on the drone net as a relay, or wait for the mobile and charging services provided by VANET to reach the target sensor for rescue. When the UAV is performing a flight mission, it needs to use the information on the drone net in Layer (2) to arrange a flight path that will not collide with other UAVs. However, when a UAV wants to move for a long-distance mission through Layer (3), it first waits for a suitable car (in VANET) to come near the pad at the place where the UAV is parked. UAVs complete the collection of information on the VANET through the routing protocol in Layer (3) and then select and wait for the arrival of a suitable vehicle. When the UAV makes use of cars in VANET to move to the vicinity of the target sensor, it will leave VANET and perform wireless charging tasks directly. If a UAV cannot use a single car to complete the necessary long-distance movement, it may need to use multiple cars instead in the VANET, and the transfer positions are some of the pads.

4.1. Roles and Numbers of Pads in the Proposed System

Pads participate in the operation of three layers and have different functions at different layers. Pads at Layer (1) are connected to the same network as sensors in WRSN to facilitate connection with the system and conduct necessary communication. Pads at Layer (2) provide UAVs with path information for other UAVs not to collide. Pads provide extra charge for UAVs at Layer (3) who await a suitable car from VANET to arrive here.

When the movement trajectory of the car in VANET is periodic (for example, the moving route of a truck is fixed), because its future movement is predictable (called a *periodical vehicle*), it is especially suitable to be used to assist UAVs in moving to a specific destination. On the contrary, if the movement trajectory of the car in VANET is non-periodic (called a *non-periodical vehicle*), that is, its future movement path is random and not conducive to being used to assist a UAV's movement to a specific destination. When the periodical vehicles occupy the majority (called a *dense deployment*) in the VANET, the UAV can move to the destination in a short period of time; on the contrary, when the periodical vehicles occupy a minority (called a *sparse deployment*), the UAV might take a long time to move to the destination within. The UAV stays on the car not only to use it to move but also to obtain additional power. On the other hand, when the sparse deployment is in progress, the system might need to deploy more pads in the area to obtain more opportunities for UAVs to move in the VANET. The summary is listed in Table 1.

When the UAV is nearby in the area for rescue and does not need to move long distances, it only obtains additional power through VANET. Besides, the UAV may hop between cars to gain enough power; when the car specified by the system is close to the UAV, the UAV will fly to the car's charging dock to obtain power, but when the car is far away from the sensor location due to an unexpected reason, the UAV will give up the car immediately and try to wait near the sensor or pad for the next suitable car to arrive.

Table 1. The expected number of required pads for different schedules in the proposed system.

WRSN / VANET	Proactive Schedule	On-Demand Schedule
dense deployment	less pads	minimum pads required
sparse deployment	maximum pads required	more pads

4.2. Reward Mechanism

For a large-scale WRSN, it seems impractical to use dedicated vehicles just for assisting UAVs due to their high cost. Instead, using the public transportation system, such as the MRT or bus, as the backbone of transportation would be a quite possible choice. Moreover, instead of deploying dedicated vehicles, a UAV company may sign a contract with a taxi company or a public transportation department that owns a lot of vehicles to support the transportation and charging of UAVs. When the proposed system is implemented, the government can force public transportation systems such as MRT, buses, and railways to join the operation through legal influence and mandatory regulations.

As for private vehicles, it is more suitable to use the reward strategy. Most users are not willing to provide private vehicles in VANET for others to use for free. However, if an appropriate reward mechanism can be designed and used to stimulate the participation of private cars in VANET, these numerous private cars may provide additional intensive transportation and charging capabilities to UAVs in the proposed charging system. For example, private vehicles can obtain electricity from solar panels and then "sell" the excess electricity to UAV companies if their owners allow them to be used for others' UAVs. Another possible reward mechanism, such as an equivalent free charging service, can be designed and applied for private vehicle owners by allowing other UAVs to land on their vehicles for charging.

4.3. Discussions and Comparisons

In terms of reducing the establishment cost, the framework proposed in this work uses free mobile resources in VANET to increase the usable range of UAVs, achieve the effect of sharing, and reduce the procurement and maintenance costs of UAVs. In addition, vehicles and pads are used to provide and store electrical energy, forming a decentralized architecture and reducing charging base station construction costs (land, power supply, network, etc.). In terms of improving efficiency, the mobile capability provided by VANET is used to reduce the mobile energy consumption of UAVs and improve the charging efficiency. The shared use of drone networks also improves the efficiency (cost/performance value) of UAVs. The decentralized architecture expands the service scope of fixed base stations, enables UAVs to obtain nearby power sources, dock resources, etc., and provides the possibility of parallel charging.

In Figure 2, four far-separated sensors require four base stations and four UAVs due to the flight distance limitation of UAVs. If the architecture proposed in this work is used, due to the free VANET, only one UAV is needed to serve four sensors. When considering the acquisition of a stable power supply, it can be achieved by setting up only one base station or pad in the proposed system.

The framework discussed above is indeed a simple solution. However, it has the following disadvantages when compared to the proposed system:

1. The flying range is more limited. Due to the power required to charge the sensor, the UAV's flying distance is shorter, and it can only charge a small-scale sensor network.
2. Poor charging efficiency. In order to charge a sensor, the UAV needs to fly the distance to and from the base station, utilizing a considerable amount of extra power and time.
3. For a sensor network with a wide distribution range, the establishment cost is extremely high. Limited by the flight distance of UAVs, a large-scale sensor network needs to be divided into many small subnetworks, and each such network owns a base station and dedicated UAVs, which increases deployment costs a lot. Moreover,

the deployed UAVs of each sub-network cannot be shared, resulting in the dilemma that some spare UAVs in one subnetwork cannot support charging missions in another subnetwork.
4. The segmentation of each sub-network and the corresponding base station deployment are static, which cannot dynamically adapt to a more dynamic network.

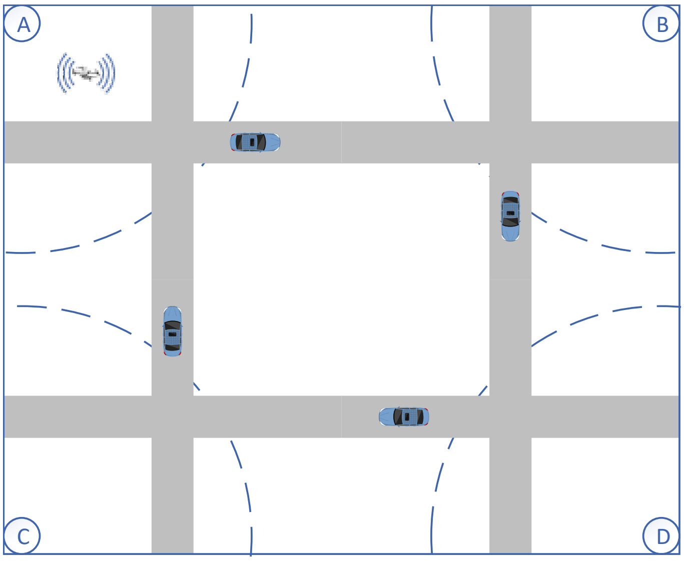

Figure 2. A simple framework for comparison.

Consequently, the charging system proposed in this work is more suitable for large and widely distributed WRSNs for the following reasons:

1. In the proposed system, UAVs are used to charge the requested sensors in a WRSN. When the amount of batteries in UAVs is below a predefined threshold, these UAVs can be charged by landing on pads that are connected to a fixed power supply. In the system, we use pads to extend the flight distance of UAVs and improve charging efficiency at a very low deployment cost.
2. Due to the wide deployment area and cost considerations, we cannot deploy pads everywhere in the proposed system. However, UAVs can also obtain additional power from nearby vehicles in a VANET to save a considerable amount of extra power and time for flying to and from the base station or pads. Moreover, because the cars in VANET are already built, there is no need to spend a lot on deployment costs. At the same time, UAVs can also use the cars in VANET to move toward the target sensor to save power and charging time. Moreover, the system can reduce UAV deployment and management costs due to UAV sharing and improve charging efficiency at the same time.
3. These pads are also equipped with a wireless communication system that can be used to communicate with UAVs, a car in VANET, and sensors in the deployed sensor networks. From this perspective, pads are more akin to a gateway that connects WRSN, drone net, and VANET.

5. Conclusions

In this work, we proposed a novel system that integrates VANET, pads, and UAVs together to provide WRSN with a low-cost and high-efficiency charging system. A very challenging research topic that still remains is how to optimize this system and minimize its deployment cost while maximizing its charging efficiency simultaneously. Although reward mechanisms have been mentioned in this work, we also need to design some practical methods to make some cars through a VANET and integrate them in a WRSN charging system. In the framework proposed in this work, there are many places where optimization problems for dynamic changes in requirements, objects, resources, etc., such as how to allocate UAVs to charge sensors or allocate vehicles in VANET to transport UAVs. These are all worth thinking about in terms of how to use efficient algorithms such as machine learning techniques to find solutions. Moreover, these three-layer charging systems have different functions for communication, but VANET and drone net have the problem of unreliable or untimely communication, and WRSN has the problem of a large amount of power consumption due to communication. Another interesting problem that deserves thorough discussion is the integration of the communication functions of these three layers to complement each other. At last, deploying numerous pads requires sufficient power sources and fixed sites, which are sometimes not very easy to achieve. These pads can also be used as a roadside facility for VANET to save important information, as a charging device for UAVs in drone net, or even as multiple sinks or cluster heads in WRSN. Overall, the role of pads can be used as a communication bridge between the three layers of the combined system. How to use pads to form a seamless and integrated system will be another interesting challenge.

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