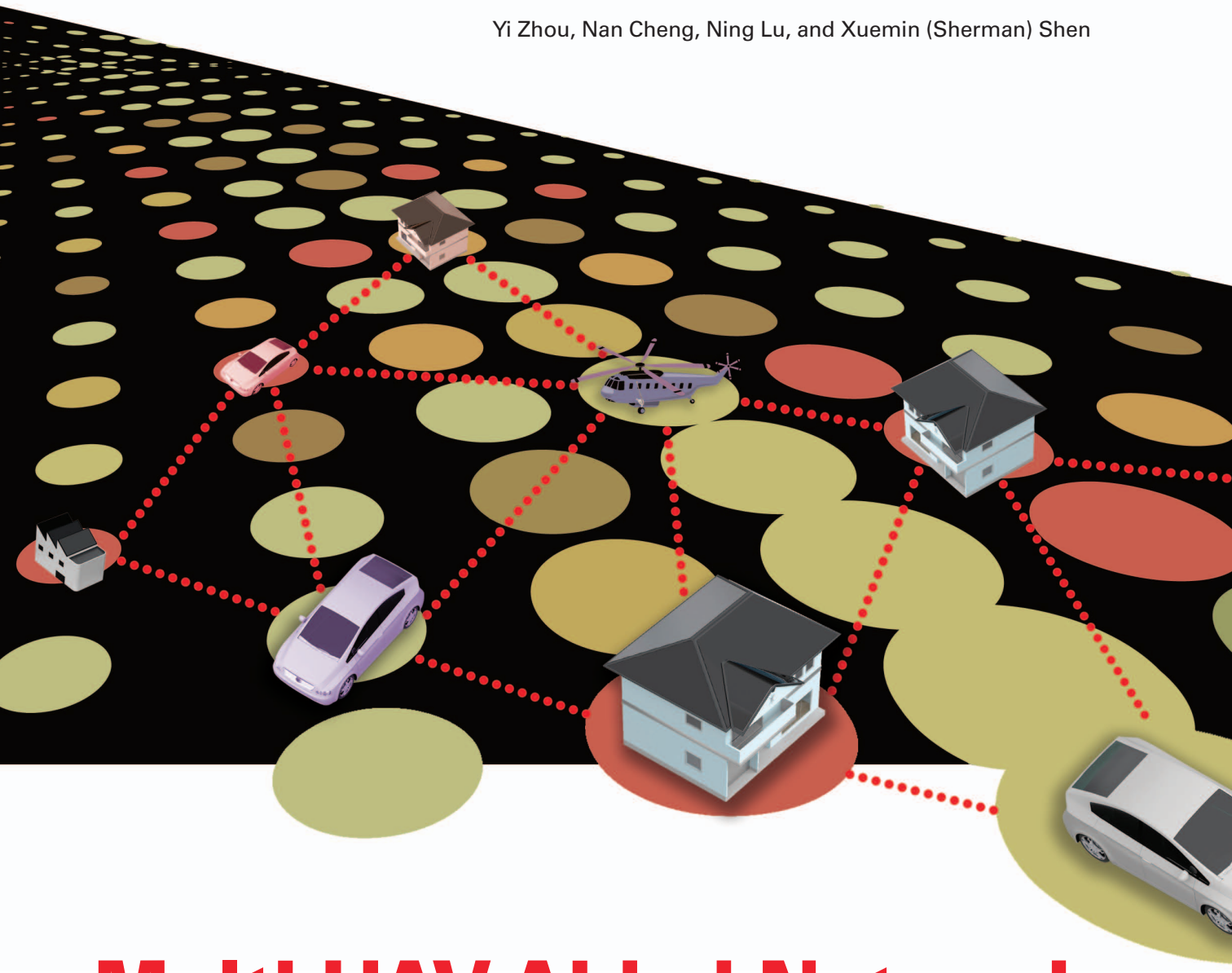
Yi Zhou, Nan Cheng, Ning Lu, and Xuemin (Sherman) Shen



Multi-UAV-Aided Networks

Aerial–Ground Cooperative Vehicular Networking Architecture

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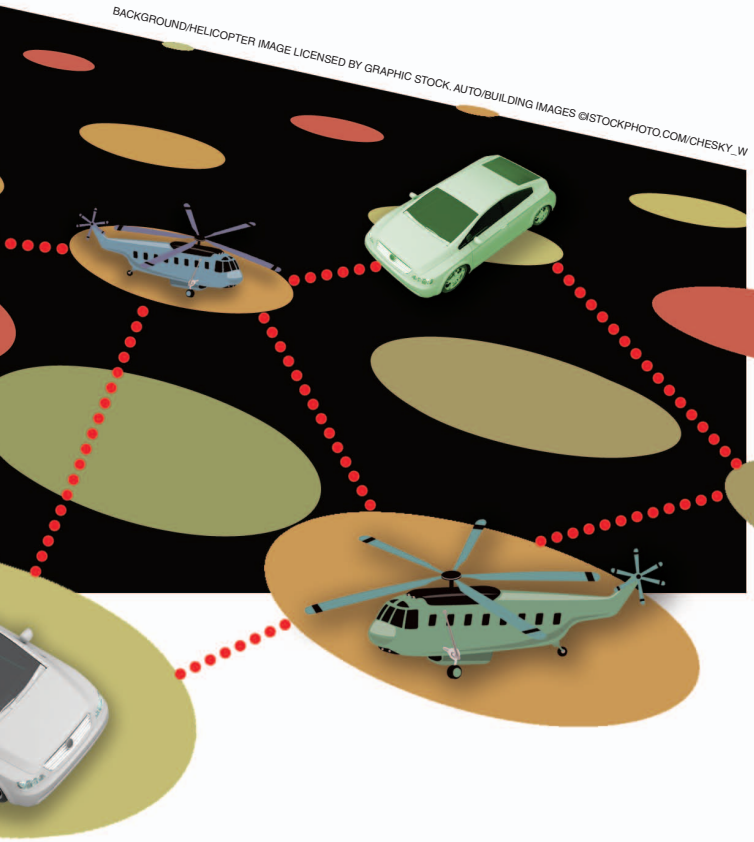
In this article, an aerial–ground cooperative vehicular networking architecture is proposed. Multiple unmanned aerial vehicles (UAVs), forming an aerial subnetwork, aid the ground vehicular subnetwork through air-to-air (A2A) and air-to-ground (A2G) communications. UAVs can be dispatched to areas of interest to collect information, and transmit it to ground vehicles. Moreover, UAVs can act as intermediate relays due to their flexible mobility when network partitions happen in the ground vehicular subnetwork. With the assistance of UAVs, the two-layer cooperative networking can facilitate applications such as disaster rescue and polluted area investigation. Potential research issues and challenges in multi-UAV-aided vehicular networks are presented and discussed, which can shed light on extending the applications of vehicular networks in an extreme environment.

UAVs CAN ACT AS INTERMEDIATE RELAYS DUE TO THEIR FLEXIBLE MOBILITY WHEN NETWORK PARTITIONS HAPPEN IN THE GROUND VEHICULAR SUBNETWORK.



Introduction

Vehicular ad hoc networks (VANETs) have been envisioned to improve the road efficiency and safety by integrating wireless communication and informatics technologies into the transportation system. By supporting vehicle-to-vehicle (V2V) communication and vehicle-to-infrastructure communication, VANETs can facilitate a myriad of applications and services, which can be divided into two categories: safety application (collision avoidance and lane change warning) and infotainment applications (mobile gaming and video streaming) [1]. However, in some extreme environments, the performance of VANETs can be compromised by the low communication quality and network partitions. For example, the infrastructure can be destroyed by a disaster or war, which can disable the infrastructure-based applications. Moreover, V2V links can be blocked or the link quality can be degraded due to obstacles, complex terrains, inaccessible geographical regions, and poor weather conditions.

UAVs, especially mini-UAVs such as quadcopters, are widely used in traffic monitoring, disaster recovery, and military reconnaissance. To address the aforementioned issues in VANETs, UAVs can be employed to form a cooperative air–ground network and to assist the vehicular network in an environment where the communication infrastructure is not available and network connectivity is poor. The two-layer air–ground network is motivated by the following aspects. First, UAVs can reach and collect information from areas where it is difficult for ground vehicles to access due to destroyed roads. Second, the information obtained by UAVs dispatched to areas of interest can be transmitted through the two-layer network to ground vehicles for the navigation and scheduling of rescue tasks. Third, UAVs can act as intermediate relays to forward data packets among vehicles when direct multihop V2V links are not available. Considering a scenario of search and rescue after an earthquake, several key issues need to be addressed.

- *Road condition exploration*: The road situation (congestion and damage) should be explored promptly to facilitate the search and rescue. However, if the communication infrastructure is not available, it is difficult to obtain the unknown information. Without such knowledge, the rescue vehicles cannot move to the accident locations quickly.
- *Information delivery*: Various types of information and data should be delivered among vehicles in an earthquake area with different service requirements, e.g., rescue commands, road exploration information, and route guidance. Efficient delivery of the information in a poor connectivity situation should be carefully studied.
- *Networking enhancement*: Unavailable support of the infrastructure often requires the vehicles to form an ad hoc network. In the case of an earthquake, most of the areas become difficult to access, which can result in connectivity holes. Therefore, proper mechanisms should be in place to enhance the network connectivity.

To deal with these issues, we propose a two-layer cooperative networking architecture that combines an aerial multi-UAV subnetwork and a ground vehicular subnetwork. Cooperative air–ground interaction relies critically on the wireless communication and networking capabilities of the whole network, which should provide

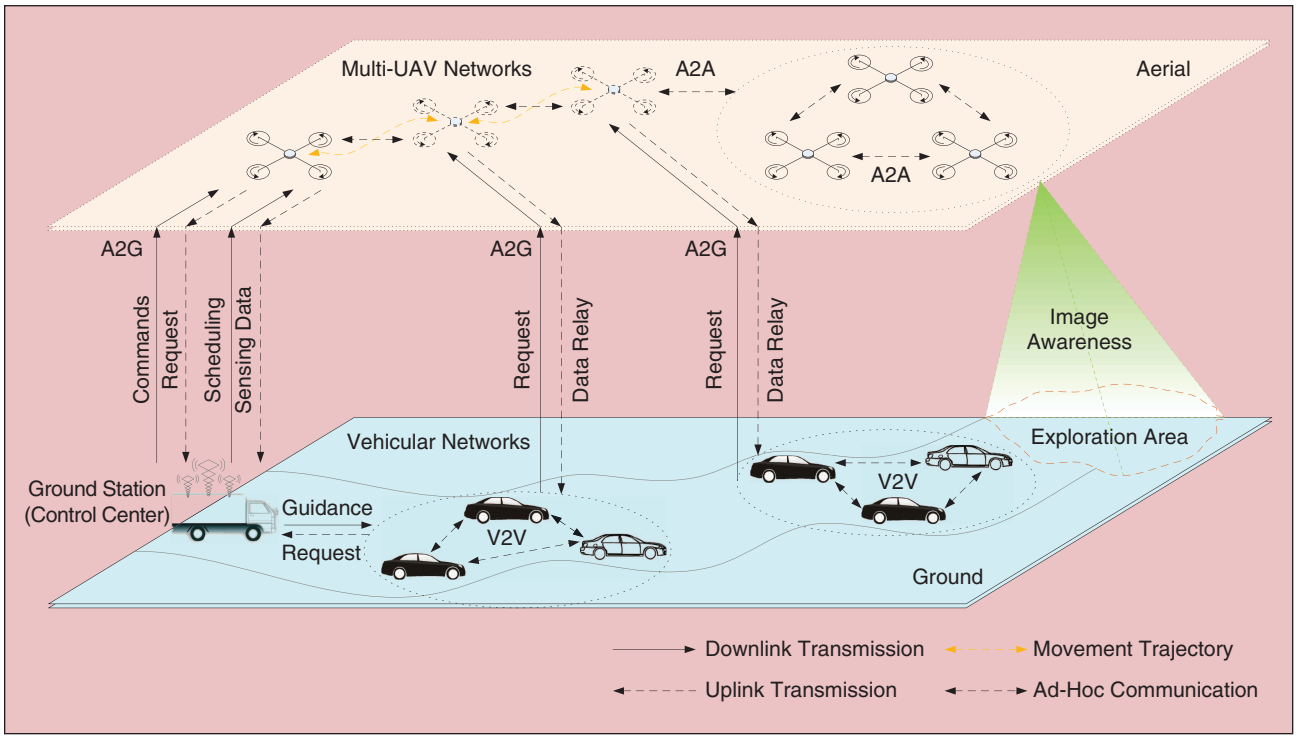


Figure 1 An overview of the multi-UAV-aided networking architecture.

reliable and delay-tolerant control links for ground vehicles and transfer sensing data efficiently. In this article, we focus on investigating the potential challenges and solutions of a multi-UAV-aided vehicular network. Our purpose is to employ UAVs to achieve resilience and adaptability of the vehicular network in a harsh networking environment.

Related Works

Incorporating UAVs into ground networks has attracted more attention from the research community. Employing UAVs to provide guidance information for ground vehicles has been studied [2], [3]. A cooperative aerial–ground robotic system is developed for a ground vehicle navigation system through visual feedback from a quadcopter in [2], in which the aerial–ground information exchange is realized through a Wi-Fi connection. Sharma and Kumar [3] proposed a cooperative networking framework for multi-UAV guided ground ad hoc networks. A neural network is used to enhance the scalability with nonredundant search and tracking.

Moreover, ways to enhance the ground network connectivity is investigated [4]–[7]. An unmanned miniature helicopter is exploited to maintain the connectivity of a wireless sensor network for flood detection in [4]. The helicopter serves as a mobile router in multihop transmission and acts as a data mule for a delay-tolerant network (DTN). Also, in [5], a UAV system is deployed to build an emergency communication system for postdisaster applications. Multihop relay communications are realized between aerial and ground mesh networks. Han et al. [6] investigate the performance improvement of the mobile ad hoc network connectivity achieved by UAVs, considering four types of network connectivities: global message connectivity, worst-case connectivity, network bisection connectivity, and k-connectivity. In particular, Goddemeier et al. [7] present an agent-based role assignment strategy to provide self-optimized air–ground connectivity, in which UAVs are assigned different roles through an agent state machine depending on the current communication topology.

Multiple (swarming) UAV networking has been well studied [8]–[12]. From the perspective of communication requirements in multi-UAV networks, Andre et al. [8] analyze the performance of both IEEE 802.11 and ZigBee for multihop networking, sense, control, and coordination. Also, Tortonesi et al. [9] investigate multi-UAV coordination and communication issues for tactical edge networks, where middleware solutions are designed for supporting cooperative UAV networks. The experimental evaluation of micro aerial vehicle networks (based on 802.11n) is discussed and both micro fixed-wing airplanes and quadcopters are deployed [10]. It is demonstrated that controlled mobility can bring benefits to network performance. Considering control schemes, a two-layer simulation is performed using a continuous airborne relay chain of UAVs [11]. The artificial potential field (APF)-based control approach is used for formation planning and UAV navigation. Daniel et al. [12] focus on the cognitive mobility and mesh topology of an UAV

swarm for autonomously exploring an incident area, where multiagent-based mobility algorithms are developed and evaluated for maintaining the connectivity in the UAV swarm.

Cooperative Networking Architecture

In a typical search and rescue application exploiting the UAV-aided vehicular network, UAVs can help ground vehicles explore the area of interest and enhance the connectivity of the vehicular network. Figure 1 depicts the cooperative networking architecture of the multi-UAV-aided vehicular network, which is composed of an aerial multi-UAV subnetwork and a ground vehicular subnetwork. In this section, we mainly investigate the system components, the two-layer networking, and the control schemes.

System Components

As depicted in Figure 1, the system components of the multi-UAV-aided vehicular network mainly include UAVs, ground vehicles, and ground stations (control centers). The functions of each component are as follows.

- *UAVs*: The UAVs are deployed to set up an aerial subnetwork, which can be used to collect and transmit the sensing data of an exploration area. Each UAV is equipped with imaging sensors, position sensors (a global positioning system, gyroscope sensors, and an acceleration transducer), embedded processors, and communication modules [10]. Therefore, UAVs can implement motion control (hovering and going up/down) of themselves through onboard sensing and processing. They can also collect the image data and communicate with the ground subnetwork. Each UAV is carried and charged by a ground parent vehicle [13], while the parent vehicle is also responsible for dispatching the carrying UAV and collecting it when the task of the UAV is completed.
- *Ground vehicles*: The ground vehicles need implement search and rescue in areas of interest, where some roads and infrastructures are destroyed. Therefore, to carry out the tasks more efficiently, ground vehicles should be aware of the road conditions, which can be obtained from the aerial UAV subnetwork. Each ground vehicle carries both communication and processing modules, which enable data transmissions among ground vehicles and UAVs. The information exchange can facilitate the cooperation between them, e.g., cooperatively assign the exploration task of the on-vehicle UAVs. In addition, the information disseminated by the ground station should be transmitted through a multihop ground vehicle route.
- *Ground stations*: If the infrastructure is destroyed, it is necessary to set up one or more (depending on the network size) emergency control centers, such as ground stations, to coordinate the two-layer network. The ground station is mainly responsible for the data fusion and processing, the scheduling of vehicles and UAVs, and bridging between the aerial subnetwork and the ground subnetwork [5]. To better adapt to the affected environment, the ground station is usually located in a mobile emergency communication vehicle, which is provisioned with the powerful communication and computing capability.

UAVs, especially mini-UAVs such as quadcopters, are widely used in traffic monitoring, disaster recovery, and military reconnaissance.

Two-Layer Networking

As depicted in Figure 1, three kinds of communication links are presented in the multi-UAV-aided vehicular network, including A2A links, V2V links, and A2G links, respectively. However, the harsh road conditions may prevent some rescue vehicles from entering the affected area. Therefore, a sparse networking scenario is focused in this proposed architecture, which means that network partitions or intermittent connections may appear at any time. To handle this networking condition, UAVs can move flexibly and act as the intermediate relay nodes to enhance the connectivity. Through the cooperative networking between the two subnetworks, the efficiency and reliability of the whole network can be improved. Correspondingly, three networking aspects are presented, where the aerial networking offers data delivery among UAVs, the ground networking provides data transmissions between ground vehicles and stations. Air–ground networking is mainly responsible for delivering sensing data and control information between the aerial and ground subnetworks. The details are as follows.

- *Aerial networking*: The aerial subnetwork provides A2A links for data delivery among UAVs. Heterogeneous radio interfaces can be considered in A2A links, such as XBee-PRO (IEEE 802.15.4) and Wi-Fi (IEEE 802.11). Both of them operate in unlicensed spectrum and can be easily integrated [8]. XBee-PRO can provide a large coverage area with low throughput and a light module, which makes it suitable for coordination (position adjustment and formation planning) in the aerial subnetwork, while Wi-Fi can be used to transmit the image-based messages since high data rates are supported in 802.11 protocols.
- *Ground networking*: The ground subnetwork is a kind of sparse VANET, in which intermittent V2V links are used for the intervehicle information exchange. IEEE 802.11p is an available protocol for wireless access in vehicular environments, which uses channels of 10-MHz bandwidth in the 5.9-GHz band [1]. The rescue

vehicle needs to broadcast real-time road conditions to other ground vehicles, and, meanwhile, it can receive the scheduling and guidance commands from the ground station. If the multihop V2V route is unavailable due to the signal block or long link distance, the vehicle can deliver the data in a store-carry-and-forward manner.

- *Air–ground networking*: Considering the sparse networking condition, it is necessary for both the aerial and ground subnetworks cooperate to enhance the networking capability. A2G links can facilitate three main functions, including subnetwork coordination, component scheduling, and communication relay [7]. The aerial subnetwork collects the image information and transmits the sensing data to the ground station through A2A and A2G links. The ground station processes the image data and extracts the road conditions, and then disseminates them to the ground subnetwork through V2V links. Meanwhile, the ground station transmits the updated scheduling commands to the aerial subnetwork through A2G links. According to different road conditions and rescue tasks, the ground station needs to design different scheduling schemes for the UAVs and rescue vehicles separately, which are also transmitted through A2G and V2V links. When the links are interrupted due to bad channel condition or long link distance, the air–ground networking can help to set up a DTN, in which the UAV can serve as an intermediate relay node to enhance the connectivity [4].

Control Schemes

The performance of the cooperative networking largely depends on whether system control schemes are efficient. As depicted in Figure 2, through the collaborative control between UAVs and ground vehicles, the tasks of search and rescue can be implemented more efficiently. When receiving the scheduling commands from the ground station, both rescue vehicles and UAVs begin to work in a cooperation manner. During the collaborative control process, four key control schemes are investigated as follows.

1) *Onboard control*: After being dispatched from its parent vehicle, the UAV exploits onboard position sensors and embedded processors to autonomously control its motion posture and adjust its moving route. Onboard communication modules are used to exchange position and status information with other UAVs. Through A2A communications and onboard control, the UAVs can keep a suitable formation for better implementing the tasks, such as image sensing.
2) *Onboard sensing*: In addition to the sensing of their own motion postures, the main task of UAVs is to sense the road conditions of the exploration area. Embedded processors control onboard imaging sensors to collect information. However, the field of view of individual sensors is limited, and, therefore, multiple UAVs need to perform image sensing through cooperative formation planning.
3) *Onboard processing*: To avoid transmitting redundant information, onboard embedded processors need to preprocess raw data collected by UAVs and bundle the data together with recognition markers. UAVs can deliver the sensing data to the ground station through multihop A2A links. If the multihop route breaks, UAVs can move to deliver the data in a store-carry-and-forward manner.
4) *Onboard diagnosis*: UAV onboard diagnostics can offer self-test and energy monitoring. When a UAV runs out of power during the tasks, it will request to return for recharging. The ground station will designate its parent vehicle to collect it and, meanwhile, send the landing location to the UAV.

Key Challenges

Through communication and coordination among aerial UAV networks and ground vehicle networks, many

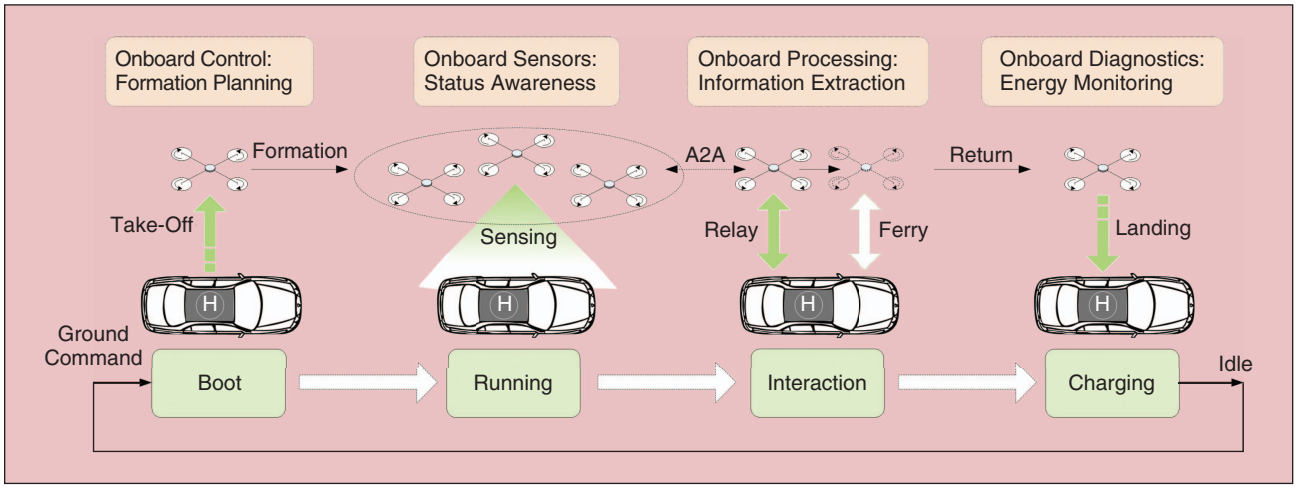


FIGURE 2 The multi-UAV-aided system control scheme.

applications and services can be facilitated. However, there are still many challenges in the research and implementation of multi-UAV-aided vehicular networks. In this section, several challenges are discussed and potential solutions are presented.

INCORPORATING UAVS INTO GROUND NETWORKS HAS ATTRACTED MORE ATTENTION FROM THE RESEARCH COMMUNITY.

Effective UAV Scheduling

The UAV scheduling efficiency is critical to functions such as connectivity enhancement and exploration of the area of interest. Therefore, it is important to design an efficient scheduling scheme. The scheduling scheme should address the following issues: the scheduling time of UAVs to carry out the tasks, the number of UAVs to perform different tasks, and efficient role switching for better cooperation.

For an unknown area, the ground station first needs to deploy one or two UAVs as scout nodes in the exploration. When the scout nodes send back the sensing data, the ground station conducts the task scheduling accordingly. More UAVs can be deployed to form an aerial ad hoc network, along with the scout nodes. When the end-to-end multihop path is not available, some UAVs can deliver the data in a store-carry-and-forward manner under the control of the ground station. When low battery warnings or system faults occurs on some of the running UAVs, they request to return immediately, and the network topology will change. Therefore, the ground station may schedule the idle UAVs to guarantee the connectivity of the aerial network. To do so, the ground station needs to schedule UAVs considering the number of idle nodes (M_I), charging nodes (M_C), running nodes (M_R), return nodes (N_R), estimated residual time required for charging (T_C), and estimated residual time for running (T_R).

The role of each UAV may be switched when the network topology changes or tasks are updated. An efficient scheduling scheme is also required for the UAVs to switch roles. Multiagent-based role assignment is employed for optimizing the scheduling in [7], where different roles can be determined by an agent state machine. The agent analyzes the current and next states of each role in real time so that the adaptive role switching can be performed.

Adaptive Formation Planning

Formation planning has significant impacts on the performance of multi-UAV-aided vehicular networks such as efficiency and link stability. Therefore, the UAV formation should be considered to reduce power consumption and facilitate the coordination. One formation is similar to the V-shape formation that is used by geese when migrate [14]. The V-shape formation can conserve energy and makes it easy to keep track individual UAVs in the formation. When arriving at the target area, UAVs need to make a new formation for conducting exploration. They can hover at the vertices of a polygon, whose size depends on the exploration area, the distance above the ground, and the focal length of the camera. The sensing data should be delivered reliably and efficiently to the ground station or ground vehicles requesting it. Therefore, the UAV formation affects the performance of multi-UAV-aided vehicular networks, including network reliability, connectivity, and data delivery.

Adaptive formation planning is an important issue in multi-UAV-aided vehicular networks. APF applied in robotic navigation can be used to realize the adaptive path planning and collision avoidance [11]. By using communication aware potential fields [7], virtual repelling and attracting forces are calculated based on practical communication metrics such as the received signal strength indication sensitive force of different connections. Adaptive resonance theory is mainly used in pattern recognition and prediction based on neural network models, which can be extended to a cooperative adaptive formation planning [3]. Adaptive neurons can be used for interaction between aerial UAVs and ground vehicles, which forms autonomously updatable networks to provide adaptive formation planning.

Energy-Efficient Networking

Energy efficiency is critical in multi-UAV-aided vehicular networks since UAVs have limited energy with batteries. Therefore, energy-efficient networking should be investigated considering different energy consumption situations, including UAV posture, wind direction, and flight altitude. In [10], the average power consumption of three movement postures, hovering, moving, and circling, are measured using quadcopters. The experimental results indicate that the energy consumption of hovering posture is the lowest. Ueyama et al. [4] measured the impact of the flight height on the energy consumption of UAVs in different situations (weather condition and engine status), when ZigBee is utilized for communication.

Since energy consumption is affected by different factors, it is required that these factors are considered when designing networking protocols and conducting data delivery. Since hovering posture consumes less power, most UAVs should remain hovering to form the multihop routes for data delivery. When certain UAVs return to ground due to low battery or other faults, the multihop routes may not be available. There are two subsituations. In the situation of downwind, the node can move to ferry the data to another node, which is the typical

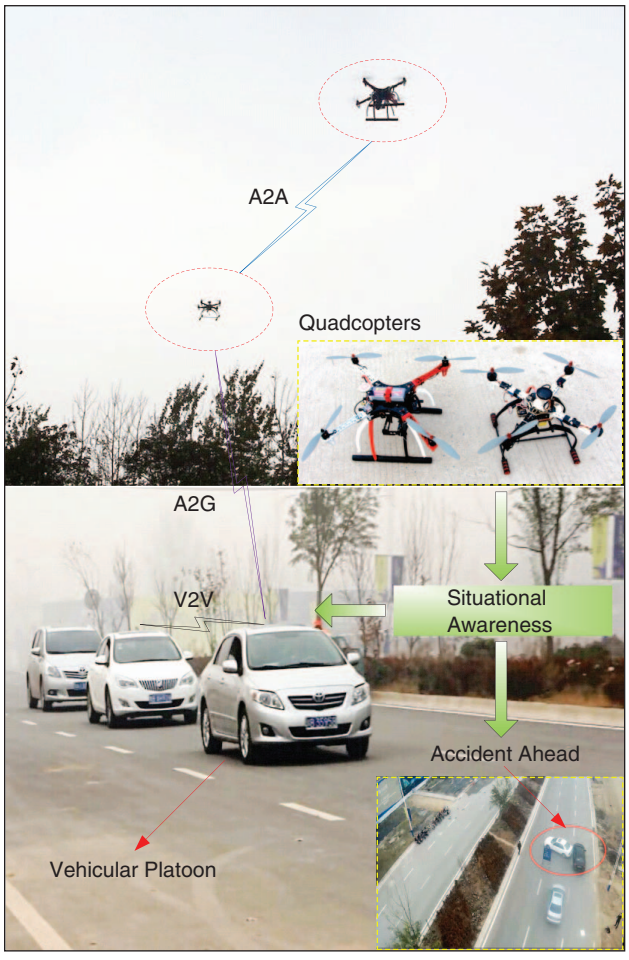


FIGURE 3 The system prototype.

store-carry-forward data delivery method. When going against the wind, the aerial and ground networks can coordinate to form aerial–ground routes to deliver the data, which is more reliable than solely using aerial or ground network. The energy-efficient networking is based on the overall network planning. The tradeoff issue between energy consumption and network scheduling should also be considered.

Multidimensional Channel Modeling

Terrestrial channel modeling has attracted much research attention, such as standard models WINNER II, spatial channel model extended, and International Mobile Telecommunications-Advanced. However, when introducing aerial networks, it is necessary to reconsider the multidimensional channel characterization from time, frequency, and spatial domain. Time-variant propagation channels have a great impact on the coverage, capacity, and reliability of multi-UAV-aided vehicular networks. Accurate and realistic models of propagation channels are crucial for network optimization and performance evaluation.

TABLE 1 *The experimental parameters of UAVs.*

Overall dimension	45 × 45 cm
Overall weight	1.5 kg
Maximum cruise speed	36 km/h
Maximum flight altitude	100 m
Battery capacity (lifetime)	5,200 mAh (<20 min)
Maximum motor speed	950 KV
Motor dimension	40 × 23 mm
Maximum continuous power	300 W
Radio interface	ZigBee: CC2530/ 2.4 GHz/1 km
	Wi-Fi: 802.11a/ 5.2 GHz/300 m

TABLE 2 *The preliminary evaluation results.*

Specifications	*Values*	*Objects*
Average latency (A2A)	25 ms	ZigBee (command)
	230 ms	802.11a (sensing data)
Average latency (A2G)	42 ms	ZigBee (command)
	380 ms	802.11a (sensing data)
Two-hop latency (A2A-A2G)	106 ms	ZigBee (command)
	840 ms	802.11a (sensing data)
Throughput (A2A)	64 kb/s	ZigBee
	19 Mb/s	802.11a [User Datagram Protocol (UDP)]
Throughput (A2G)	48 kb/s	ZigBee
	13 Mb/s	802.11a (UDP)
Two-hop throughput (A2A-A2G)	16 kb/s	ZigBee
	5 Mb/s	802.11a (UDP)
Average power	220 W	UAV (hovering)
Detection rate	98.6%	Road signs
	97.3%	Vehicles
	82.5%	Pedestrians
False alarm rate	0.35%	Potential accidents

Two additional links, A2A and A2G, need to be characterized from large-scale fading (pathloss and shadowing) to small-scale fading (multipath effects). It is essential to study the impacts of height, velocity, and orientation of UAVs. In [4], it is found that the ZigBee communication performance in flight is better than the one on the ground in terms of energy consumption and delay. Yanmaz et al. [15] conducted real air–ground measurements between a ground station and mini quadcopters, where the channel characteristics and network performance of air–ground links are measured using IEEE 802.11 networks at 5 GHz. It is found that antenna radiation in both azimuth and elevation planes can benefit UAV communications. Through

practical measurements, multidimensional channel impulse response can be obtained with parameters in time, delay, and directions of departure and arrival. Through parameter estimation and statistical modeling, the empirical channel models can be built for multi-UAV-aided vehicular networks. In addition, through the geometrical-based stochastic channel modeling, multilink channel simulation can be implemented by considering the correlation between links.

Preliminary Prototype Evaluations

We have conducted a preliminary prototype evaluation on the multi-UAV-aided vehicular network. As depicted in Figure 3, two UAVs (quadcopters) are deployed to cooperate with three ground vehicles. The first quadcopter collects the image information of the road situation ahead and the second one can relay the information to the guided vehicle. Two quadcopters can communicate with each other through Wi-Fi (802.11a) and ZigBee modules, where the Wi-Fi module is for the image transmission and the ZigBee module is for command message delivery. The guided vehicle can process the data and extract the important information to guide the vehicle platoon.

The Federal Aviation Administration (FAA) has proposed a framework of regulations that would allow routine use of certain small unmanned aircraft systems [16]. We strictly followed the proposed rules of the FAA while conducting experimental measurements. Table 1 presents the experimental parameters of the two quadcopters. For the UAV model, we use an Arduino-based Arducopter model (ArduPilotMega 2.6), which has an open-source quadcopter architecture.

Some preliminary evaluation results are given in Table 2. We have analyzed the performance of A2A (UAV–UAV) and A2G (UAV–guided vehicle) links for ZigBee and 802.11a, respectively. The performance of delay and throughput of the A2A link is better than the A2G link because the quadcopters communicate with each other in light-of-sight propagation and the aerial scatters are relatively smaller than the ground ones. Moreover, the performance of a two-hop link, from A2A to A2G, is also evaluated in terms of average latency and throughput. A relatively large latency can be observed since when video data are transmitted, one UAV may backoff when another UAV is transmitting, which causes a higher latency than the summation of one-hop A2A link latency and A2G latency. Since we need the aerial image data of exploration areas to guide the vehicle platoon, the image detection rate and false alarm rate are also investigated. The results indicate that it is feasible to deploy UAVs to cooperate with the ground vehicular network.

Figures 4 and 5 show some results of UAV posture impacts on power consumption and delay. Figure 4 shows the fluctuation process of power consumption

THE GROUND STATION TRANSMITS THE UPDATED SCHEDULING COMMANDS TO THE AERIAL SUBNETWORK THROUGH A2G LINKS.

during UAV flight. As the posture of a UAV changes, the corresponding power consumption also fluctuates, which can be used as an important reference for designing the energy-efficient networking protocols. Figure 5 shows the A2G round-trip time (RTT) through ZigBee, in which four UAV postures are tested including idle on ground (I), climbing up (U), hovering (H), and moving in a straight line (M). Messages with both 10 and 20 B are involved in the measurements. The ground-reflecting propagation and other mobile scatters may cause some abnormal RTT values during measurements. Figure 5 indicates that both postures of UAVs and channel propagation states affect the system performance, which need

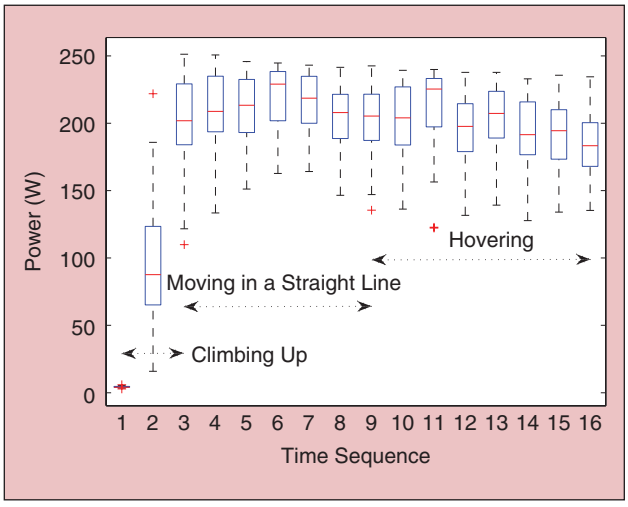


FIGURE 4 The power consumption during UAV flight.

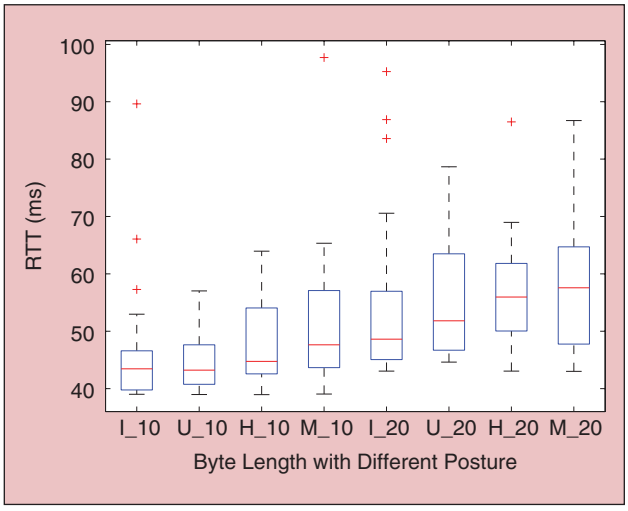


FIGURE 5 The A2G RTT for ZigBee links.

energy-efficient scheduling, formation, and networking. Furthermore, the channel characteristics of A2A and A2G also need to be investigated.

Conclusions

In this article, we have proposed multi-UAV-aided vehicular networks in which UAV aerial networks are incorporated into ground vehicular networks to facilitate many applications and improve the performance of vehicular networks in harsh environments. We have described the scenarios and applications of multi-UAV-aided vehicular networks. The challenges and research issues have been discussed, and the state of the art has been reviewed. A prototype of the multi-UAV-aided vehicular networks has been introduced. We expect that our work can provide insights to facilitate more useful applications and improve the performance of VANETs in extreme environments.

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Author Information

Yi Zhou (y375zhou@uwaterloo.ca) earned his Ph.D. degree from Tongji University, Shanghai, China, in 2011. He works as an associate professor in the School of Computer and Information Engineering, Henan University, Kaifeng, China. He is currently working as a postdoctoral fellow in the Department of Electrical and Computer Engineering, University of Waterloo, Ontario, Canada. His research interests include vehicular cyberphysical systems and multiagent design for vehicular networks.

Nan Cheng (n5cheng@uwaterloo.ca) earned his B.S. and M.S. degrees from Tongji University, China, in 2009 and 2012, respectively. He is currently a Ph.D. candidate in the Department of Electrical and Computer Engineering, University of Waterloo, Ontario, Canada. Since 2012, he has been a research assistant in the Broadband Communication Research Group in the Department of Electrical and Computer Engineering Department, University of Waterloo. His research interests include vehicular communication networks, cognitive radio networks, and resource allocation in the smart grid.

Ning Lu (n7lu@uwaterloo.ca) earned his B.S. and M.S. degrees from Tongji University, Shanghai, China, in 2007 and 2010, respectively. He is currently working toward the Ph.D. degree in the Department of Electrical and Computer Engineering, University of Waterloo, Ontario, Canada. His current research interests include capacity and delay analysis, real-time scheduling, and cross-layer design for vehicular networks.

Xuemin (Sherman) Shen (sshen@uwaterloo.ca) earned his B.S. degree from Dalian Maritime University, China, in 1982 and the M.S. and Ph.D. degrees from Rutgers University, New Jersey, in 1987 and 1990, respectively, all in electrical engineering. He is a professor and university research chair in the Department of Electrical and Computer Engineering, University of Waterloo, Ontario, Canada. He was the associate chair for graduate studies from 2004 to 2008. His research interests include resource management in interconnected wireless/wired networks, wireless network security, wireless body area networks, and vehicular ad hoc and sensor networks. He is a registered professional engineer of Ontario, Canada, an IEEE Fellow, a fellow of the Canadian Academy of Engineering, a fellow of the Engineering Institute of Canada, and a Distinguished Lecturer of the IEEE Vehicular Technology Society and Communications Society.

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