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An Effective MEC Sustained Charging Data Transmission Algorithm in VANET-based Smart Grids

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ABSTRACT Available charging information exchanges between mobile electric vehicles (EVs) and charging stations are significantly critical in spatio-temporal coordinated charging services introduced by smart girds. In this paper, we propose an efficient information transmission strategy for intelligent charging navigations of enormous moving EVs in large-scale urban environments. Specifically, we firstly design a heterogeneous VANET-based (vehicular ad hoc network) communication framework by means of mobile edge computing concept. In addition, based on the established multi-objective communication optimization problem, we propose an effective charging information dissemination algorithm between mobile edge computing servers and moving EVs. Moreover, in order to further increase charging information delivery efficiency and reduce redundant overheads, an improved local relaying scheme for charging information is designed on the basis of the formulated waiting time model. Finally, a series of simulation experiments are implemented to demonstrate the excellence and feasibility of our charging information transmission strategy.

INDEX TERMS Charging information transmission, electric vehicles, VANETs.

I. INTRODUCTION

SEVERE air pollution issues and traffic noise problems have significantly attracted public awarenesses in recent years, and these challenges can be alleviated with widespread use of EVs (electrical vehicles) because of their environment-friendly features, such as no direct carbon emissions, low noises, efficient energy transformations and so on [1], [2]. However, due to serious contradictions between limited charging stations and enormous EVs, uncoordinated charging schedules can lead to huge damages to the existing electric grid systems, and make EV drivers suffer from worse QoE (quality of experience) with respect to travelling time, waiting time at CSs (charging stations), charging expense and so forth. In order to solve the above chal-

lenges and achieve spatio-temporal accommodated charging services in smart grids [3], [4], for example, choosing the most suitable CSs and charging time for mobile EVs with charging demands, it is indispensable and necessary to establish efficient communications between mobile EVs and distributed CSs, to complete a large number of charging information exchanges, such as current locations of CSs and EVs with low energy levels, required energy amount of EVs, busy situations of CSs, charging decisions and all. The existing centralized cloud-based communication framework [5] is widely utilized in the optimal charging management for EVs, but this solution may lead to the common concerns of privacy and security, and the costs of communication and computation rise exponentially with the

increase of EVs. As one of the key components of 5G (5th generation) wireless communication networks, VANETs (vehicular ad hoc networks) [6], [7] demonstrate excellent transmission performance in highly dynamic environments and low communication expenses, and they are very suitable to charging services of mobile EVs. Nevertheless, existing works of information dissemination in VANETs still suffer from a lot of challenges, for example, low adaptivity, heavy communication overheads, fragile link connections and so forth [8]. To alleviate the negative effects of VANETs, available heterogeneous wireless networks [9] are designed to gather real-time charging packets by integrating VANETs and cellular networks, but tremendous charging data without any preprocessing brings heavy loads on wireless communications and may induce critical network congestions.

In this paper, to solve the aforementioned challenges, we propose an efficient charging information delivery strategy for coordinated charging services in wide-area urban scenarios. In particular, based on distributed mobile ESs (edge computing servers) and available VANETs, we first design a heterogeneous communication framework for big charging data transmission between moving EVs and CSs. Then an effective charging information delivery algorithm in VANETs is proposed by considering both local and global real-time traffic information. Moreover, an improved local charging data relaying mechanism is introduced to further reduce network overheads and enhance charging packet delivery ratio. The main contributions are described as follows.

(1) Efficient communication framework. By combining VANETs with MEC-based (mobile edge computing) concepts, we propose a heterogeneous communication framework with hybrid transmission manners, to reduce transmission network congestions and computational costs, improve the security and privacy of EV users, and enhance scalability and robustness of smart grids.

(2) Adaptive data delivery algorithm. The optimal data transmission path establishment issue in dynamic VANET-based communication environments is firstly formulated as a NP (Non-Deterministic Polynomial) optimization problem with QoS (quality of service) constraints, and then this problem is addressed by our proposed ACO-based (ant colony optimization) algorithm, to cope with the effects of rapidly-varying network topologies, high convergence time and limited network scalability.

(3) Improved local relaying mechanism. Inspired by the receiver-side forwarding election concept, an updated local relaying scheme is designed to select the best next forwarding node by considering the formulated waiting time model, which is formulated by considering both forwarding progress distance and BER (bit error ratio).

The rest of the paper is organized as follows. The related works are depicted in Section II. The proposed charging information transmission strategy is illustrated in Section III. Section IV demonstrates the performance of the designed strategy by means of a series of simulations. Finally, Sec-

tion V concludes the paper.

II. RELATED WORKS
A. COMMUNICATION FRAMEWORK FOR EV CHARGING BEHAVIORS

In literature, several works [10], [11] have proposed concordant charging strategies for EVs parking in charging stations based on available information, which is collected via short-range communication technologies, such as bluetooth, zigbee and so on. However, such communication patterns are not feasible for mobile EVs because of their low coverage and fragile links. In order to solve the above challenges, some works [12], [13] established feasible charging managements for moving EVs based on cellular networks, which own seamless connections and large coverage capacities, but it is not economical to collect enormous charging information for EV charging services by means of such networks, as the related communication fees and infrastructure construction costs are very high. In addition, cellular networks are not dedicated for EVs' charging information collections, so frequent charging information exchanges may result in serious network congestions and cause significantly negative effects on other regular cellular network-based applications. The works [14], [15] designed communication frameworks for smart grids based on VANETs, in which mobile EVs and RSUs (road side units) take charge of collecting available information and dispatching final charging decisions in a real-time manner via V2I (vehicle to infrastructure) and V2V (vehicle to vehicle) communication. However, due to high EV mobility and rapid network topology changes, the above described VANET-based communication frameworks easily suffer from frequent broken links and low packet delivery ratio. Besides, V2I-based communication needs to deploy and maintain dedicated RSUs, which make such communication structures be lacking in flexibility and scalability due to great construction costs and rigid displaying space requirements. So as to cope with the rapid growth of EV charging demands and big charging information transmission, some works adopt centralized communication frameworks based on cloud computing [16], where the cloud server behaves as a global controller and it implements computing tasks in a concentrated manner by means of the collected information from remote EVs, as a result, charging services are easily interrupted by the breakdowns of a single cloud server, and the communication robustness as well as the information security of EV drivers in such frameworks are not guaranteed. MEC [17] is an emergent architecture where cloud computing resources, such as storage and processing capacities, are extended to the edges of networks, and it supplies the end-users with high bandwidth, low transmission latency, efficient energy consumption, powerful computing capacity and so on. Based on existing cellular networks, some MEC-based communication frameworks (such as FMC [18] and CONCERT [19]) were proposed and they are regarded as the important components of 5G communication architectures, where various EV charging

services are properly supported.

B. INFORMATION DISSEMINATION IN VANETS

By means of geographic information, many existing VANET-based data delivery algorithms were proposed and they can be utilized to implement charging information dissemination. GSR [20] explores the shortest-distance routing path to the destination for data packets based on the geographic information from the attached digital map, but it ignores the real-time traffic knowledges along the route and often experiences network holes in sparse networks, which lead to high transmission delay. CAR [21] is an intersection-based transmission scheme, which regards intersections located along routing paths as relaying anchors to forward data packets, and it is more reliable and effective compared with node-based protocols in urban scenarios. However, as a reactive source-driven routing protocol, CAR makes data packets be transmitted along the explored end-to-end routing path but can not adaptively adjust forwarding routes, so this routing protocol is not able to effectively cope with the rapid topology changes in VANETs. In SADV routing protocol [22], packet transmission is assisted by static nodes located on road intersections, which can store the relayed packets for a moment to wait for appropriate forwarding vehicles along the selected best routing path. Note that, SADV is a delay-tolerant routing protocol and real-time packet transmission delay is estimated by forwarding periodic messages, which distinctly increase network loads and may cause communication congestions. In ASGR [23], the feasible end-to-end routing paths are firstly selected using the constructed spider web, and then the best route is given from the candidate available paths based on the designed models with regard to connection quality and transmission delay, but a real-time optimization scheme is required in this algorithm to update road information and track destinations' positions, which can generate tremendous network overheads. G. Sun *et al.* [24] proposed a bus trajectory-based street-centric routing algorithm (BTSC), in which an available route is built on the basis of the probability of buses appearing on every street. In order to further enhance bus relaying opportunities and reduce end-to-end transmission latency, a ACO-based forwarding strategy was designed in BTSC to search a reliable and stable multi-hop link between two relaying buses. However, the traffic features of moving buses can not reflect the comprehensive routing information. In [25], based on the devised models of link propagation delay and link transfer delay in two-dimensional traffic scenarios, an effective propagation strategy was proposed with the aids of bidirectional vehicle movements, to establish the whole end-to-end routing path with the lowest expected delivery delay.

C. LOCAL CHARGING DATA RELAYING ALGORITHMS

Some local relaying schemes were given to select an appropriate next-hop forwarding vehicle for information delivery. The greedy carry-and-forward mechanism [20], [21]

has been widely adopted in dynamic VANET environments to ensure high packet transmission performance. However, This forwarding mechanism neglects the movements of next-hop vehicles and may suffer from disconnected links, which cause transmission failures. By considering vehicle mobilities and signal propagation characteristics, the work [23] first constructs a group of available neighbors which satisfy with some given communication limits, then a selective forwarding scheme is presented to choose the most available next-hop vehicle from these obtained neighboring vehicles to achieve better delivery performance. In [26], the best next-hop forwarding vehicle is picked out by means of evaluating scores of vehicles located in the transmission range, and the scores are assessed in terms of several QoS metrics (namely, distance to destination, trajectory, vehicle density, available bandwidth estimation and MAC layer loss). Nevertheless, these mentioned local relaying algorithms just make decisions for next-hop relaying vehicle selections at transmitter-sides, and periodic beacon broadcast is necessarily required to exchange the real-time neighboring vehicles' status information (location, speed, moving direction, etc.), so considered redundant overheads are introduced and serious network congestions may occur in VANETs with limited bandwidth. So as to solve the mentioned problems, based on a receiver-side concept [27], some efficient next-hop relaying vehicle selection approaches were proposed, where the candidate neighboring vehicles determine whether they are the most feasible next-hop relaying node by themselves rather than by the current forwarding vehicle, but the transmission interferences of neighboring vehicles and the impacts of wireless channel fading are not considered in these works.

According to the above analyses, existing charging information transmission strategies suffer from a lot of challenges, such as fragile EV users' privacy, serious costs of computation and communication, inefficient routing exploration, low network scalability, deficient adaptivity, excessive network overheads and so on, and they can not availably accommodate to the tremendous charging information delivery for mobile EVs in large-scale urban environments. To effectively resolve the above problems, this paper propose an impactful transmission mechanism of charging information for smart grids. Specifically, based on distributed ESs attached to RSUs, moving buses and so on, we firstly establish a heterogeneous communication framework combined with a hybrid communication manner. In addition, according to the presented EI (end intersection) model and ACO algorithm, an adaptive intersection-based routing protocol is proposed in VANET environments, to dynamically plan the best QoS-based routing path between mobile EVs and deployed ESs. Moreover, a new local relaying scheme is illustrated to choose the most feasible next-hop forwarding vehicle on the basis of the devised waiting time model.
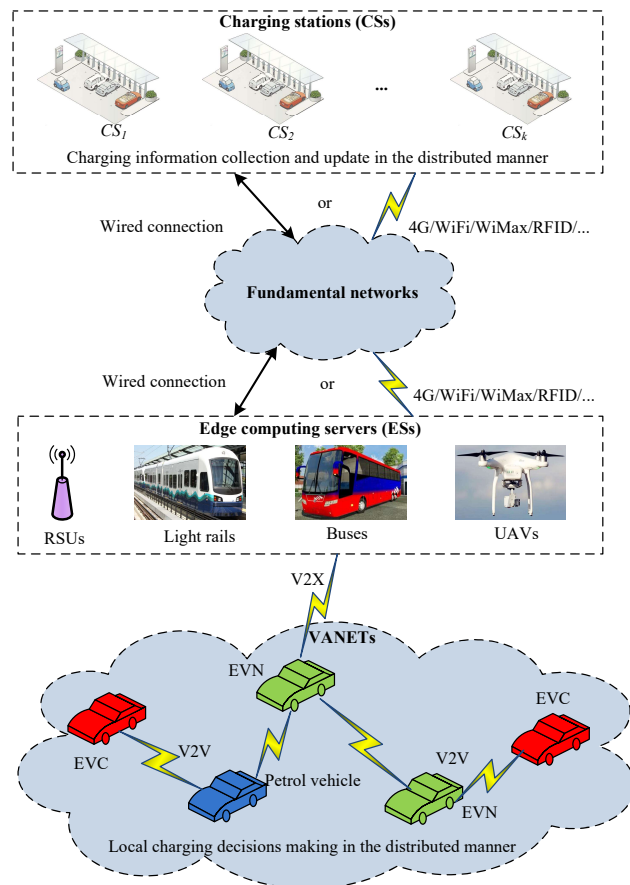
FIGURE 1. Heterogeneous MEC-based communication framework for big charging data transmission.

III. CHARGING INFORMATION DISSEMINATION STRATEGY

A. HETEROGENEOUS MEC-BASED COMMUNICATION FRAMEWORK

In large-scale urban environments, the spatio-temporal coordinated charging services in smart grid systems require efficient information exchanges between distributed CSs and a large number of mobile EVs, so it is necessary to design an effective communication structure to guarantee the reliable and secure big charging data transmission, improve huge-size network scalability and reduce communication costs. In order to achieve the above objectives, we propose a distrbuted MEC-based communication framework by means of VANETs shown in Fig. 1, which is composed of four components, namely CSs (charging stations), existing fundamental networks, mobile ESs (edge computing servers) and varying VANETs. Specifically, CSs are geographically deployed in urban scenarios to provide energy to EVs with charging demands, and each CS is equipped with special devices, which are used to collect and transmit charging information (for example, occupied slot number, reserved slot number, real-time charging price, charging reservations from EVs and so on). Fundamental networks

are a part of computer networks that interconnects various pieces of network, and they take charge of providing suitable transmission paths for the exchange of information among different subnetworks. ESs are attached to four-type entities including stationary RSUs (road side units), flying UAVs (unmanned aerial vehicles), moving light rails and buses, and they take charge of a number of middle-ware functions: i) implement data preprocessing (data mining, data aggregation, data storage, forwarding security enhancement and so on) for gathered enormous charging information from mobile EVs and CSs, and ii) provide relaying services for charging information exchanges by means of various connection technologies. VANETs are established by a group of mobile EVCs (electric vehicles with charging demands), EVNs (electric vehicles without charging demands) and petrol vehicles, which are connected with each other via V2V (vehicle-to-vehicle) communication.

B. WORKING MECHANISM OF THE COMMUNICATION FRAMEWORK

In the proposed MEC-based communication framework of smart grids, we design that each EV can carry out the intelligent charging decisions by itself in a distributed manner, by taking advantage of its own status information (such as current state of charge, position information, velocity and so on) and received charging messages from CSs (for example, busy situations of CSs), and the determined charging decisions are then required to be sent back to CSs to update their available conditions. In particular, the mobile EVs with charging demands could establish adaptive communications with the selected neighboring ESs via VANETs by considering reliable V2X approaches, and the existing fundamental networks then take charge of relaying charging information between distributed ESs and CSs with the assistance of different access approaches, such as wired links or other wireless manners (4G/WiFi/MiMax/RFID, etc.). Obviously, our proposed communication framework can effectively decrease the computation costs and network loads compared with the pure cellular networks or centralized cloud-based communication structure, where the global controller has to gather all charging information from remote EVs and carry out calculation missions for all EVs.

In addition, we propose a hybrid manner (CFHM) for charging information transmission in the designed heterogeneous communication framework, to further alleviate network congestions and decrease communication costs, as represented in Fig. 2(a). Concretely, the communications between CSs and ESs are carried out in a proactive manner, in which CSs (or ESs) periodically publish the latest processed charging information to ESs (or CSs) with time interval T. While the charging information transmission between mobile EVs and ESs is operated in a reactive style, for example, when a mobile EV is in the low SOC (state of charge) condition and requires charging information supports to select a suitable CS, this EV reactively sends information request messages to its corresponding ES, which
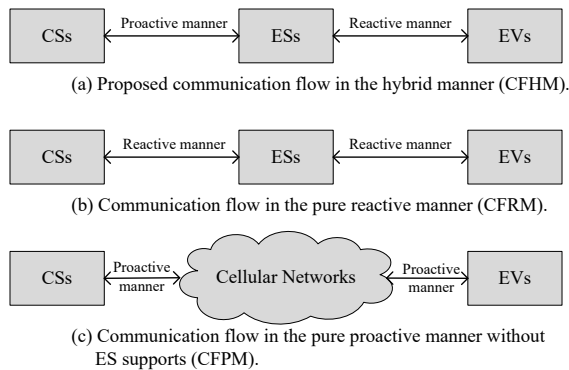
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FIGURE 2. Different communication manners.

in return responses its cached charging information to the EV. Obviously, compared with the pure periodic broadcast communication approach, the devised information dissemination manner can availably decrease redundant packet delivery and avoid broadcast storm effects.

C. THEORETICAL ANALYSIS ON THE PROPOSED COMMUNICATION FRAMEWORK

So as to analyze the performance of the proposed communication framework, we firstly set the number of charging stations, ESs, mobile EVs and mobile EVs with charging demands (EVCs) in the urban environments as N_{cs}, N_{es}, N_{ev} and N_{evc}, respectively. In addition, we assume that $N_{cs} < N_{es} < N_{evc} < N_{ev}$ on the basis of general knowledges. Moreover, two referencing communication manners are defined to demonstrate the advantages of our proposed CFHM, namely *communication flow in the pure reactive manner* (CFRM, shown in Fig. 2(b)), and *Communication flow in the pure proactive manner without ES supports* (CFPM, presented in Fig. 2(c)). In CFRM, the communication among CSs, ESs and EVs is implemented in the reactive manner based on the designed heterogeneous communication framework (shown in Fig. 1), where EVCs (or CSs) send charging information request messages to CSs (or EVCs) via the relays of ESs, and then CSs (or EVCs) carry out available charging data replies to corresponding EVCs (or CSs). Obviously, CFRM can achieve real-time charging information delivery between CSs and EVCs with the cost of high network loads. While in CFPM, CSs periodically (time interval T) broadcast charging information to all mobile EVs for smart charging selections through ubiquitous cellular networks, in which there are not any assistances of ESs, and CSs also gather the charging decisions from EVCs in each T to renew their busy situations, which can be used for upcoming EVs' charging navigations.

1) Communication cost analysis

Compared with the number of ESs and EVs, CSs' number is smaller, so CSs easily become a bottleneck of the whole communication framework and may suffer from the negative influences of big charging data delivery, therefore, it is

TABLE 1. Communication cost of each CS

Transmission manner	Communication cost
CFHM	$\Theta\left(\frac{N_{es}}{T}\right)$
CFRM	$\Theta\left(N_{evc}\right)$
CFPM	$\Theta\left(\frac{N_{ev}+N_{evc}}{T}\right)$

very critical to analyze the communication cost of CSs in different delivery manners, and the definition of communication cost is given as the total number of established wireless communications per time interval on the side of each charging station. Firstly, in CFHM manner, since every CS only keeps delivery links with N_{es} ESs per T, the communication cost of each CS is scaled by $\Theta\left(\frac{N_{es}}{T}\right)$. In addition, N_{evc} EVCs request real-time charging information from every CS to make intelligent charging decisions in CFRM manner, so each CS receives the communication cost with $\Theta\left(N_{evc}\right)$. Moreover, every CS experiences the communication cost given as $\Theta\left(\frac{N_{ev}+N_{evc}}{T}\right)$ in CFPM, because each CS pushes charging information to all mobile EVs (the number is N_{ev}) and collects charging decisions from N_{evc} EVs with charging demands per time interval T. Obviously, as $N_{es} < N_{evc} < N_{ev}$, the communication cost in CFHM is much lower than those of two referencing manners and our devised communication framework indicates better performance in the aspects of big data transmission and network congestion alleviation. Based on the above illustrations, the corresponding communication cost of each CS is depicted in Table 1.

2) Scalability and robustness analysis

A series of ESs are applied in our proposed communication framework, and they can divide a large-scale communication environment into several local areas with small size, which can effectively enlarge the communication scalability and avoid fragile remote end-to-end communication between mobile EVs and CSs. In addition, the link number of each CS in CFHM manner is proportional to the limited number of ESs rather than the more enormous number of mobile EVs, so the proposed communication framework can cope with the rapid increase of EVs and present the excellent scalable capacity. Furthermore, ESs can preprocess the collected big charging information based on the attached MEC capabilities, and the volume of relaying charging data is significantly compressed, as a result, network congestions are efficiently alleviated and communication reliability is improved. To sum up, the designed heterogeneous communication framework exhibits outstanding abilities of scalability and robustness.

3) Delivery expense analysis

The whole delivery expense in the proposed communication framework is much lower, and the reasons are given as follows. First of all, a large amount of charging

information is transmitted via VANETs, in which related communication fee is almost neglected compared with the high expense of pure cellular network used in CFPM (shown in Fig. 2(c)). Besides, ESs have the functions in data mining and data aggregation in decentralized manners to reduce redundant charging data and decrease communication loads, which are beneficial to decrease the delivery costs. Finally, existing light rails, buses and UAVs are used as ESs to relay charging information rather than only RSUs, so high costs in deployments of RSUs can greatly decrease.

4) Security and privacy analysis

In our established communication framework, mobile EVs make the charging arrangements in distributed manners by virtue of their own status information and charging data from remote CSs, so moving EVs' private information (such as current location, destination, moving velocity, SOC, etc.) is not necessary to be sent to other entities, consequently, the security and privacy of EV drivers can be protected compared with other centralized charging strategies [28], where the control center has to collect EVs' status messages to implement charging navigation assignments in overall. In addition, ESs can carry out a series of data preprocessing works to make charging information transmission be in a safe mode, which is advantageous to the security improvement.

D. PROBLEM FORMULATION OF ROUTING ISSUES IN VANETS

We know that sufficiently accurate charging information plays a very important role in distributed charging managements of mobile EVs, so it is very critical and indispensable to design an effective VANET-based routing protocol (EVRP) in the above proposed communication framework, to achieve highly robust and low-delay communication between ESs and EVs in dynamic large-scale urban environments.

In order to accomplish the above objectives, we assume that each vehicle is fitted with the GPS (Global Positioning System), digital map and navigation system to supply its status information (for example, current location, moving velocity and direction) and other traffic information, such as intersections' positions, road segment lengths and so on. In addition, we abstract a urban map as graph $G(I, E)$, where I and E denote the sets of intersections and road segments, respectively, and there is a two-direction road segment e_{ij} between two neighboring intersections I_i and I_j. Moreover, we assume that there is a static node in each intersection to store the related routing information. Finally, as being in strong relation with communication channel fading effects, noise interferences, wireless transmission range, vehicle distributions, road segment lengths and so on (these parameters reflect almost whole status information of varying VANETs in urban environments), both transmission delay and corresponding delay variance are selected to evaluate the performance of established routing paths. According to

the mentioned descriptions, the issue to explore the optimal QoS-based routing path with regard to multiple constraints in EVRP can be formulated as a NP (Non-deterministic Polynomial) optimization problem, which is formulated as

$$\max_{y} QOS(y) = \lambda_1 \frac{D_{th} - D(y)}{D_{th}} + \lambda_2 \frac{DV_{th} - DV(y)}{DV_{th}} \quad (1)$$

$s.t.$

$$\begin{cases} D(y) = \sum D(e_{ij}) \leq D_{th} \\ DV(y) = \sum DV(e_{ij}) \leq DV_{th} \end{cases} \quad (2)$$

where y is a candidate backbone route between EVs and ESs, $QOS(y)$ denotes the comprehensive QoS of route y, $D(y)$ and $DV(y)$ indicate the delay and delay variance of y, respectively. λ_1 and λ_2 are weight values to adjust the effects of different QoS metrics ($\lambda_1 + \lambda_2 = 1$). D_{th} and DV_{th} mean the corresponding upper limits of route delay and delay variance, $D(e_{ij})$ and $DV(e_{ij})$ represent the transmission delay and delay variance along road segment e_{ij}, respectively.

Note that, the detailed derivation procedures of local road segment QoS (namely transmission delay $D(e_{ij})$ and delay variance $DV(e_{ij})$ are illustrated in our previous works [29], [30], and these local QoS models are used to estimate real-time local and global pheromone in our following proposed routing protocols. Compared with other QoS estimation methods, such as forwarding periodic update messages between adjacent intersections and on-the-fly collection process, our models can alleviate network congestions and decrease network overheads.

E. OPTIMAL ROUTE ESTABLISHMENT USING ACO-BASED ALGORITHM

The ACO approaches [31] are derived from the real ants' food foraging behaviors, and different ant colonies or ant individuals are able to interact and cooperate with each other to solve multi-objective problems with large complexities. There are a number of advantages in ACO including high distribution, great self-organization, excellent robustness, outstanding scalability and so on. In this section, we solve the formulated NP problem described in Section III-D by means of the proposed ACO-based algorithm, to establish the optimal routing path.

1) Feasible route discovery via reactive forward ants

Before implementing reactive charging information transmission operations, mobile EVs and ESs are required to select their corresponding EIs (end intersections). In the EI selection process, we make use of two parameters, namely moving direction of an EV (or ES) and road segment length from the current location of the EV (or ES) to its candidate neighboring intersections, to comprehensively evaluate EI's performance. If the distance from the EV (or ES) to its neighboring intersection I_m is smaller, and this EV (or ES) moves towards to I_m, we prefer to choose I_m as the EI

for this EV (or ES). According to above descriptions, an EI selection can be determined via the following expression

$$
\begin{aligned}
EI &= \arg\max_{I_m} \{G(I_m)\} \\
&= \arg\max_{I_m} \left\{ \delta \cdot \left(1 - \frac{l(I_m)}{L}\right) + (1-\delta) \cdot dr(I_m) \right\}
\end{aligned}
\tag{3}
$$

where $G(I_m)$ is an evaluation function to assess the performance of candidate intersection I_m, δ represents the weight value $(0 < \delta < 1)$, $l(I_m)$ denotes the distance between the EV (or ES) and its candidate neighboring intersection I_m, L indicates the length of road segment on which the EV (or ES) travels, $dr(I_m)$ implies the moving direction of EV (or ES) and it is set as 1 if the EV (or ES) moves towards I_m, or 0 (in the case, the EV (or ES) runs away from I_m), or 0.5 if the ES is static.

Obviously, compared with an end-to-end routing path exploring scheme for each communication pair, this EI model makes a group of communication pairs (sharing the same EIs and QoS requirements) directly forward data packets using the explored backbone paths, which are advantageous to the convergence of the optimal routing explorations and the decrease of network overheads.

Once the EI$_V$ (EI of the EV) and corresponding EI$_S$ (the ES's EI) are chosen, the routing problem between the EV and ES is translated into the available candidate routing path exploration issue between the EI$_V$ and EI$_S$. The EI$_V$ firstly checks whether it stores suitable routing information to the selected EI$_S$. If yes, the EI$_V$ responses an acknowledge to the EV to inform it to directly carry out charging information delivery processes. Otherwise, the EI$_V$ sends several groups of reactive forward ants to the EI$_S$ to initiate routing path explorations. When reaching intersection I_i, a forward ant firstly inserts I_i's index to its header, and then selects the next intersection with certain probability, which is induced based on both local and global pheromone. The probability to select the next intersection is given as follows

$$
P_{ij} = \begin{cases}
\dfrac{LQ(e_{ij})^{\gamma_1} \cdot GQ(y_{ij})^{\gamma_2}}{\sum\limits_{n=1}^{N} LQ(e_{in})^{\gamma_1} \cdot GQ(y_{in})^{\gamma_2}} & GQ(y_{ij}) > \sigma_{\min} \\[2ex]
\dfrac{LQ(e_{ij})^{\gamma_1} \cdot \sigma_{\min}}{\sum\limits_{n=1}^{N} LQ(e_{in})^{\gamma_1} \cdot \sigma_{\min}} & \text{Otherwise}
\end{cases}
\tag{4}
$$

where P_{ij} is the probability with which the forward ant (located on I_i) selects I_j as the next intersection, γ_1 and γ_2 denote the weight values to adjust the influences of local and global pheromone, respectively, N means the number of neighboring intersections of I_i, $\sigma_{\min}$ is a constant value $(0 < \sigma_{\min} < 1)$, $GQ(y_{ij})$ (derived in (7) in Section III-E2) is the global pheromone delegating the QoS of route y_{ij} from I_i to the selected EI$_S$, and this route goes through I_j, $LQ(e_{ij})$ stands for the local pheromone of the road segment from I_i to I_j, and it is expressed as follows

$$
LQ(e_{ij}) = \lambda_1 \cdot \frac{D_{th} - D(e_{ij})}{D_{th}} + \lambda_2 \cdot \frac{DV_{th} - DV(e_{ij})}{DV_{th}}
\tag{5}
$$

where e_{ij} denotes the local road segment between I_i and I_j.

Obviously, $GQ(y_{ij})$ helps the forward ants be inclined to select the route with the optimal global QoS, and it is advantageous to the fast convergence and the prevention of the extreme routing conditions on upcoming road segments. While $LQ(e_{ij})$ is the heuristic pheromone to assist the forward ants in exploring new routing paths based on the up-to-date local QoS. Therefore, the probability P_{ij} is able to maintain the balance between prior route exploitations and new route explorations. Besides, compared to the blind flooding or broadcast schemes, the proposed opportunistic forwarding algorithm is very useful in reducing routing exploration time and restricting whole network overheads.

Based on above selection principles, the forward ants explore routing paths intersection by intersection. When a forward ant arrives its EI$_S$, and its transmission delay and delay variance fulfill the QoS constraints represented in (2), the routing path (consisted of a list of intersections) passed over by this ant is chosen as a feasible candidate route.

2) Best route selection via reactive backward ants

The best routing path is selected from a number of established feasible candidate routes based on the updated global pheromone, which is implemented by reactive backward ants at each passing through intersection. Specifically, when a reactive forward ant reaches the EI$_S$, and its explored route is regarded as an available candidate routing path, a corresponding reactive backward ant is generated and then returned back to the EI$_V$ following the same but opposite moving path of this forward ant. Once reaching a given I_i (moving from I_j), the backward ant firstly obtains the newest global pheromone $LGQ(y_{ij})$ by means of the collected local QoS of road segments along the passing through routing path, and $LGQ(y_{ij})$ is formulated as

$$
LGQ(y_{ij}) = \lambda_1 \frac{D_{th} - D(y_{ij})}{D_{th}} + \lambda_2 \frac{DV_{th} - DV(y_{ij})}{DV_{th}}
\tag{6}
$$

where y_{ij} denotes the complete routing path from intersection I_i to EI$_S$ passing over intersection I_j.

After that, this backward ant updates the global pheromone table stored at I_i to alleviate the exploration stagnancy of routing paths and inactive influences of instantaneous values of $LGQ(y_{ij})$. The pheromone renewed process is given as follows

$$
GQ(y_{ij}) \leftarrow (1 - \chi) \cdot GQ(y_{ij}) + \chi \cdot LGQ(y_{ij})
\tag{7}
$$

where χ is the weight parameter $(0 < \chi < 1)$.

The above steps are incessantly repeated until the backward ant get to the EI$_V$. When all backward ants reach the EI$_V$ and finish the operations of global pheromone calculation and update, we just compare the different values of updated global pheromone $QOS(y)$ of all the available candidate routes, and then the optimal routing path is

determined, and it is introduced as

$$y_{opt} = \arg\max_{y} \{QOS(y)\} \tag{8}$$

Finally, EI_V sends an acknowledge message to the EV to initiate charging packet transmission.

3) Pheromone evaporation and route maintenance

In ACO algorithms, the pheromone evaporation process is defined as that the amounts of global pheromone of all feasible routing paths should reduce in every time interval. This process is similar to the physical evaporation procedure of the deposited pheromone of real moving ants, and it is a significantly essential step to prevent the extremely fast convergence of proposed algorithm to a suboptimal zone. In EVRP routing protocol, a simple mathematical expression is formulated to model this evaporation mechanism, which is derived as

$$GQ(y)(t+T_{ev}) = \begin{cases} \mu \cdot GQ(y)(t) & GQ(y)(t) \geq \sigma_{\min} \\ \sigma_{\min} & \text{Otherwise} \end{cases} \tag{9}$$

where μ represents the pheromone evaporating parameter and $0 < \mu < 1$, T_{ev} denotes the time interval, $GQ(y)(t+T_{ev})$ and $GQ(y)(t)$ indicate the global pheromone on routing path y at $t + T_{ev}$ and t time instant, respectively.

In addition, a reactive route maintenance scheme is designed to further refresh the newest routing information, confront the fast topology varieties and reduce the excess overheads. In particular, once new ESs are assigned to EVs, or related EIs of moving EVs (ESs) vary, a new implementing process for the best routing path is launched following the above illustrations, if not, it is not necessary to carry out any routing maintenance process.

4) Adaptive charging data delivery

When the best QoS-based routing path between two EIs is established, we begin to carry out charging information delivery operations via intersection by intersection rather than the complete end-to-end route in other source-driven routing protocols, to cope with the dynamic traffic changes in VANETs. Particularly, when arriving in intersection I_i, charging data packets are dynamically forwarded to the next intersection based on the latest global pheromone, and if road segment e_{ij} is with the maximum global pheromone $GQ(y_{ij})$ compared with those of other adjacent road segments, I_j is selected by I_i as the most suitable next intersection for packet transmission. $GQ(y_{ij})$ is given as

$$GQ(y_{ij}) = \max_{n=1}^{N} \{GQ(y_{in})\} \tag{10}$$

where N represents the number of I_i's neighboring intersections.

5) Theoretical analysis on the proposed EVRP

(i) Convergence analysis: EVRP presents an ACO-based data delivery algorithm, and it exhibits the excellent performance in the algorithm convergence, which can be explained

as follows. (1) The proposed EI model for mobile EVs and ESs makes a group of communication pairs sharing the same EIs and QoS requirements directly forward charging packets using the established backbone paths without new routing explorations, which are beneficial to the average convergence time decrease and network congestion alleviations for the optimal route constructions compared with the scheme that an end-to-end routing path exploration for each communication pair, (2) we make use an opportunistic method to explore the candidate feasible routing paths by means of both local and global pheromone, and this mechanism is able to effectively avoid the blind routing explorations and reduce the probability of suffering from network partitions in upcoming road segments, and (3) the optimal route establishing process is implemented by means of the closed collaborations of different communication pairs and exploring ants to update the latest global pheromone, which is beneficial to coping with dynamic environments and decreasing the convergence time of the optimal route.

(ii) Adaptivity analysis: EVRP indicates excellent adaptivity in routing path selections for charging data transmission, and it can be validated by several reasons as follows. First of all, a feasible route maintenance mechanism is implemented to cope with rapid changes of traffic status and the movements of EVs and ESs. In addition, charging data packets are delivered by means of a dynamic intersection by intersection scheme rather than a complete routing path, as a result, the routing path can be adaptively selected according to the real-time conditions of VANETs. Finally, the proposed ACO-based algorithm and EI concept enable different ant colonies and communication pairs closely cooperate with each other, to update the latest pheromone and adaptively deal with fast topology varieties.

F. IMPROVED LOCAL RELAYING SCHEME FOR CHARGING DATA DELIVERY

When charging data packets are transmitted via intersection by intersection, it is pretty significant to design an effective local relaying scheme to choose the next-hop forwarding vehicles for information delivery within road segments. In this section, based on the formulated waiting time model, an improved local relaying mechanism is proposed.

1) Waiting time model

Waiting time t_k of a candidate next-hop vehicle C_k can determine whether C_k should choose itself as the most available next-hop node, and a feasible waiting time must be subject to three constraints: (1) the waiting time of the better next-hop forwarding vehicle should be less to make this preferred vehicle reply its selection decision earlier to the current transmitter, (2) it should be large enough that the gap of waiting time between the best next-hop forwarding vehicle and the second best one, so as to prevent potential synchronous response collisions, and (3) the waiting time

$$t_k = \begin{cases} T_{\max}\left(1 - \left(\frac{d_{sk}}{R}\right)^{\sigma_2}(1-2\cdot BER\,(d_{sk}))^{\sigma_3}\right)^{\sigma_1^{-1}} & \text{(if } d_{sk} \geq 0) \\ +\infty & \text{(if } d_{sk} < 0) \end{cases} \tag{11}$$

When $d_{sk} \geq 0$, candidate next-hop vehicle C_k is located in the packet forwarding direction, and it is a feasible option for current transmitter C_s. In the case of $d_{sk} < 0$, it implies that C_k is in the back of C_s, and charging data packets are transmitted following the backward direction, so C_k is not an available selection and t_k is set to $+\infty$.
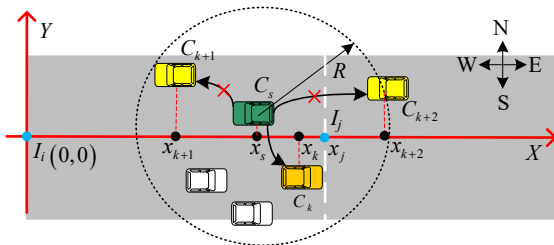

FIGURE 3. Forwarding progress distance.

should be as low as possible to decrease worthless packet transmission delay.

To achieve the above objectives, we make use of both forwarding progress distance and BER as assessing parameters for the waiting time derivation, and promise that the shorter waiting time is given to the candidate vehicles with larger forwarding progress distance and lower BER. In addition, the deduced waiting time is restricted in $[0, T_{max}]$ time interval to alleviate the negative effects on data forwarding delay, and T_{max} denotes the maximum value of t_k. According to the above analysis, we formulate the waiting time by means of the curve fitting theory, and it is expressed as (11), where t_k is the waiting time of candidate next-hop vehicle C_k, d_{sk} means the forwarding progress distance from current transmitting vehicle C_s to candidate next-hop vehicle C_k, R represents the wireless communication range of relaying vehicles and $d_{sk} \leq R$, σ_1, σ_2 and σ_3 intend weight values and they take charge of adjusting relative priorities of various evaluating parameters and extending the waiting time gaps of potential next-hop relaying vehicles, $BER\,(d_{sk})$ stands for the delivery BER when a packet is transmitted from C_s to C_k passing through d_{sk}.

Obviously, so order to obtain the value of waiting time, it is necessary to induce the expressions of d_{sk} and $BER\,(d_{sk})$, respectively, and the concrete derivations are illustrated as follows. When inducing the expression of d_{sk}, we neglect the width effects of road segments, as the wireless communication range of relaying vehicles R is far more than the width of 2-lane road segments. As presented in Fig. 3, we set up a two-dimensional coordinate, and the locations of two adjacent intersections I_i and I_j located in a road segment are given as $(0,0)$ and $(x_j,0)$, respectively. In addition, as the road segment's width is ignored, the coordinates on y axis of current transmitter C_s and candidate next-hop relaying vehicle C_k can be set as 0, and their corresponding positions are $(x_s,0)$ and $(x_k,0)$. Moreover,

we configure packet forwarding direction to be eastward, and I_j is the target relaying intersection. Obviously, in order to decrease forwarding hops, more available C_k should be close to I_j and far away from C_s to obtain larger d_{sk}, and if being outside the current road segment between I_i and I_j, C_k is not preferred as EVRP is an intersection-based routing algorithm and the next target relaying junction is dynamically determined. Based on the above analysis, d_{sk} is formulated as

$$d_{sk} = \begin{cases} x_k - x_s & C_k \text{ is in the current road segment} \\ 0 & \text{Otherwize} \end{cases} \tag{12}$$

When deriving $BER\,(d_{sk})$, we suppose that RTS/CTS mechanism is utilized in the wireless communication, to eliminate the interferences from synchronous transmissions and hidden terminals, but some possible interferences still exist, and they are from the communicating vehicles located in the road segments beyond communication range R of both current transmitter C_s and candidate receiver C_k but inside C_k's interference range R_{inf}. As presented in Fig. 4, because of the beneficial effects of the RTS/CTS scheme, the potential interfering vehicles are only located in two road segments (their lengths are set to L_{inf1} and L_{inf2}, respectively, where $L_{inf1} = R_{inf} - R$, and $L_{inf2} = R_{inf} - R - d_{sk}$), and the number of interfering vehicles in per $2 \cdot R$ range is no more than one within these two road segments. According to the above illustrations, the maximal value of interfering vehicle number is derived as

$$\begin{aligned} \max\{N_{inf}\} &= \left\lceil \frac{L_{inf1}}{2 \cdot R} \right\rceil + \left\lceil \frac{L_{inf2}}{2 \cdot R} \right\rceil \\ &= \left\lceil \frac{R_{inf} - R}{2 \cdot R} \right\rceil + \left\lceil \frac{R_{inf} - R - d_{sk}}{2 \cdot R} \right\rceil \end{aligned} \tag{13}$$

where N_{inf} denotes the number of interfering vehicles for candidate next-hop vehicle C_k.

Based on the adopted Rayleigh fading model [32] and coherent BPSK (Binary Phase Shift Keying) modulation scheme [33], $BER\,(d_{sk})$ can be expressed as follows

$$BER\,(d_{sk}) = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma_0\,(d_{sk})}{\gamma_0\,(d_{sk}) + 1}}\right) \tag{14}$$

where $\gamma_0\,(d_{sk})$ is the average ratio of the received signal with d_{sk} to the sum of interferences and noise, and it can
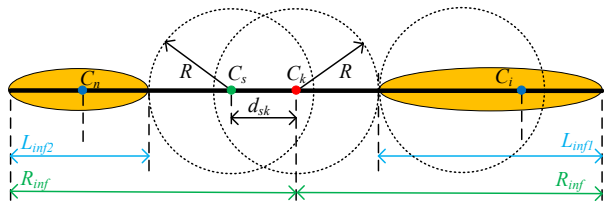
FIGURE 4. Interference analysis. Here a road segment is abstracted as a line, C_i and C_n are interfering vehicles, and the road segments with possible communication interferences are labelled by the orange ellipses.

be given as

$$\gamma_0\left(d_{sk}\right) = \frac{2\alpha^2 \cdot P_r\left(d_{sk}\right)}{P_{tn} + \sum_{i=1}^{N_{inf}} P_{inf}^i} \qquad (15)$$

where $2\alpha^2$ denotes the average random variables' value in Rayleigh Distribution, P_{tn} indicates the thermal noise power, $P_r\left(d_{sk}\right)$ delegates the received signal power at distance d_{sk} from C_s to C_k, P_{inf}^i represents the received interference, and both $P_r\left(d_{sk}\right)$ and P_{inf}^i can be obtained based on the derivations in [34].

By substituting (13) and (15) into (14), $BER\left(d_{sk}\right)$ can be finally formulated.

2) Receiver-based relaying scheme

According to the receiver-side relay election concept [35], we propose an enhanced charging data packet forwarding algorithm to select the next relaying vehicle using the existing RTS/CTS (Request To Send/Clear To Send) exchange scheme in terms of forwarding progress distance and BER.

First of all, a modified RTS frame is broadcast to all neighboring EVs located in the communication range of current transmitter C_s. The modified RTS frame includes the current location of C_s and its target relaying intersection I_j, both of which are utilized in selecting the next relaying vehicle. Besides, a flag information is added into the modified RTS frame to ask all candidate next-hop vehicles to process the RTS frame, while only the expected receiver deals with this frame in the initial RTS/CTS scheme.

In addition, once acquiring the modified RTS frame from C_s, each candidate next-hop vehicle C_k replies a CTS frame in the broadcast manner after its estimated waiting time, which is derived in (11). When receiving the first CTS from C_{opt}, C_s regards C_{opt} as the best next-hop vehicle, other candidate vehicles terminate their CTS responses and abandon the competitions in the most feasible next-hop relaying node selection. Obviously, the deduced waiting time in the receiver-side is an evaluating indicator that how favorable a candidate next-hop vehicle is, and the preferred candidate next-hop vehicle has the positive correlation with the less waiting time.

Note that, once receiving other correct CTS frames in a while for the same data packet transmission, C_s directly discards the later CTS frames to avoid any packet relaying repetitions. For example, the earliest CTS frame from C_k is

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Algorithm 1 Local relaying scheme at candidate next-hop vehicle C_k.

1: Notation:
2:    I_j: target next intersection.
3:    C_s: current transmitter vehicle C_s.
4:    C_k, C_m: candidate next-hop vehicles.
5:    t_k: waiting time of C_k.
6:    ID_s, ID_m and ID_k: corresponding ID of C_s, C_m, C_k.
7:    X_j, Y_j and X_s, Y_s: corresponding coordinate position of of I_j and C_s.
8: **if** receiving $RTS\left(X_s, Y_s, X_j, Y_j, flag\right)$ from C_s **then**
9:    Calculate t_k using (11).
10:    Set the timer to t_k.
11:    **if** $t < t_k$ **then**
12:       **if** receiving $CTS\left(ID_s, ID_m\right)$ from C_m **then**
13:          Terminate the timer and give up next-hop selection competition.
14:       **else**
15:          Continue to overhear CTS frame.
16:       **end if**
17:    **else**
18:       Response $CTS\left(ID_s, ID_k\right)$ to C_s.
19:    **end if**
20: **end if**
21: **if** Obtaining a data packet from C_s **then**
22:    Reply an acknowledge message to C_s.
23: **end if**

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not heard by candidate next-hop vehicle C_{k+1} because of link failure, and a CTS frame from C_{k+1} is also broadcast to C_s after its waiting time, based on the above principle, C_s only forwards the packet to C_k, and C_{k+1} is not regarded as the next-hop relaying node for this packet. In the case of no CTS frame received by C_s, it implies that the local optimum is encountered by C_s, which will carry the charging data packets by itself until meeting other appropriate next-hop relaying vehicles. The detailed processes of proposed local relaying scheme are described in Algorithm 1.

IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of proposed charging information transmission strategy. In addition, to better illustrate the advantages of our designed EVRP transmission algorithm, four referring intersection-based data delivery schemes are utilized as the benchmarks including CAR [21] (source-driven end-to-end minimum delay protocol), GSR [20] (the optimization objective is to search the routing path with the shortest relaying distance), ASGR [23] (an efficient bio-inspired QoS-based routing method) and EVRP_GC (a defined version of EVRP where a simple greedy carry-and-forward scheme is used within road segments rather than the proposed local relaying scheme).
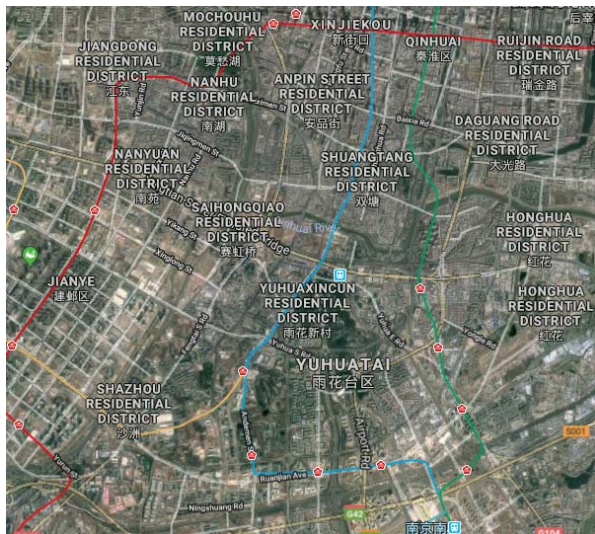
FIGURE 5. A snapshot of the realistic simulation area.

TABLE 2. Major parameters in the simulations.

Parameter	Value
Urban scenario scale	10 km × 9 km
Mobility model of vehicles	IDM_IM
Vehicle velocity	$10 \sim 20$ m/s
Vehicle spacing density	$0.01 \sim 0.02$ vehicles/m
packet size	512 Bytes
EVs penetration	20%
EVs with charging demands ratio	10%
channel capacity	6 Mbps
Wireless channel model	Rayleigh fading model
Propagation path loss model	Shadowing model
Packet generating rate	1 packet/s
R and R_{inf}	250 m and 500 m
D_{th}, DV_{th} and $\sigma_{\min}$	20 s, 5 and 0.3
QoS weight values λ_1 and λ_2	0.6 and 0.4
EI selection parameter δ	0.6
ACO parameters γ_1, γ_2, χ, μ and T_{ev}	8, 5, 0.25, 0.95 and 0.5 s
Local relaying values σ_1, σ_2, σ_3, T_{max}	0.1, 1, 200 and 0.002 s

A. EXPERIMENTAL ENVIRONMENT

To carry out our experiments, a realistic urban scenario extracted from Nanjing city (Jiangsu province, China) is considered in the simulations, and it is restricted in a 10 kilometers (km) × 9 km area, as shown in Fig. 5. In addition, mobile vehicles are geographically deployed along the roads and vehicle spacing density is set as $0.01 \sim 0.02$ vehicles/meter (m), where EV penetration level is given as 20% and the ratio of EVs with charging demands to total EVs is 10%, for example, there are 1000 vehicles in the simulation area, and the number of EVs and EVs with charging demands is 200 and 20, respectively. Moreover, the mobility model of vehicles is set to Intelligent Driver Model with Intersection Management (IDM_IM, and it is generated by traffic simulator VanetMobiSim [36]), in which original locations of mobile vehicles are given randomly and vehicle velocity is set as $10 \sim 20$ m/s. Furthermore, based on the network simulation tool (NS2), wireless communication range of vehicles and ESs R and interference range R_{inf} are fixed to 250 m and 500 m, respectively, wireless channel transmission capacity is set to 6 Mbps, packet size is 512 Bytes, MAC layer protocol is given as 802.11p, the propagation path loss model and wireless channel model are set to the Shadowing model [37] and the Rayleigh fading channel model [32], respectively, the request-to-send/clear-to-send (RTS/CTS) mechanism and binary phase shift keying (BPSK) scheme [33] are used in the physical layer. Lastly, the simulation duration is set to 6000 s and every experiment is repeated for 30 times by means of various seeds to achieve the arithmetic mean and eliminate the passive effects of uncertainty. The detailed simulation parameters are described in Table 2.
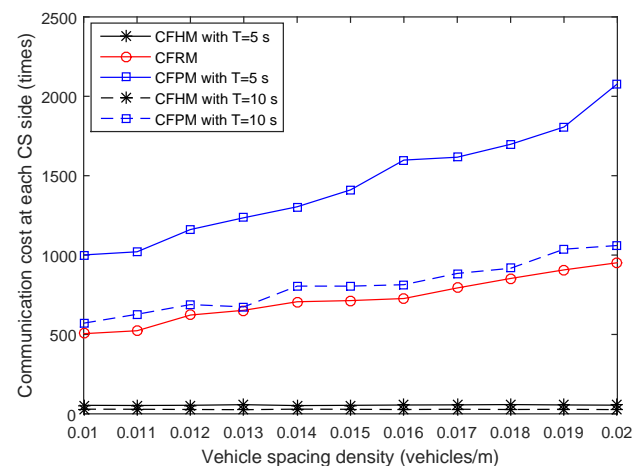

FIGURE 6. Communication cost vs. various vehicle spacing density.

B. PERFORMANCE EVALUATION ON THE PROPOSED COMMUNICATION FRAMEWORK

Fig. 6 presents the communication cost (which is evaluated by the wireless communication times per time interval at each CS side) of our proposed heterogeneous MEC-based communication framework in different manners including CFHM, CFRM and CFPM. In this experiment, the number of ESs N_{es} is set to 200, and the forwarding time interval of each CS or ES T is given as 5 s or 10 s. We observe that the communication cost in CFHM manner is lowest and it even decreases with the increase of T. Besides, the communication costs in both CFPM and CFRM are directly proportional to the vehicle spacing density phi, and higher phi results in more communication costs. Note that, because CFRM is implemented in the reactive way and it is entirely unrelated to periodical forwarding time interval T, the performance shown in CFRM does not varies with different values of T. Obviously, the above simulation results satisfy with our previous theoretical analysis in SectionIII-C and validate the effectiveness of our communication framework.
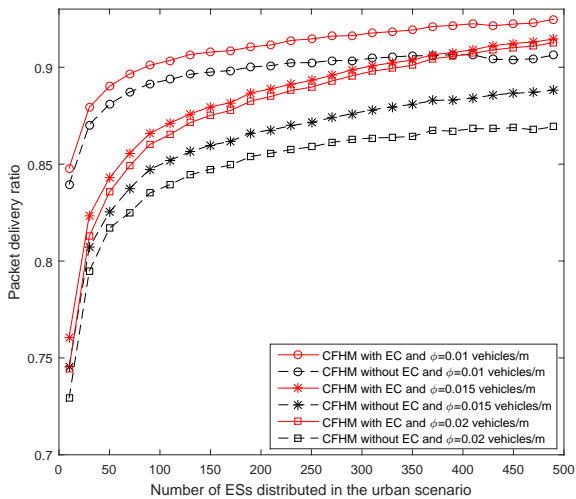
As indicated in Fig. 7, by means of the proposed com-

FIGURE 7. Packet delivery ratio vs. ES number.

FIGURE 8. Transmission delay vs. vehicle spacing density and ES number.

munication framework with CFHM manner, we display the end-to-end packet delivery ratio between CSs and mobile EVs with charging demands based on different ES number. In this experiment, our proposed EVRP routing protocol and local relaying scheme are utilized in VANET environments. From this figure, we see that the communication makes higher packet deliver ratio if ESs (e.g., RSU, bus, UAV and light rail) own MEC capacities compared to those without MEC functions (in this case, ESs only take charge of information relay), the reason is very evident: attached MEC capacities on each ES can implement data mining and aggregation operations, and unqualified packets are removed to further decrease network loads, which are beneficial to alleviate communication congestions and reduce transmission interferences. Besides, more ESs can divide the huge urban scenario into smaller local areas, and information messages just reach their destinations by going through shorter wireless distance, which implies less effects of channel fading, wireless noise and so on, so packet delivery ratio can be further enhanced.

C. PERFORMANCE EVALUATION ON THE PROPOSED EVRP

In order to fairly compare the performance of EVRP with those of other referring routing protocols, the following simulations are just carried out in VANET scenarios and the communication connections are implemented between mobile EVs and ESs. Besides, the CBR (constant bit rate) sessions are initiated in the delivery flows and CBR connection count is equal to the number of EVs with charging demands, which is proportional to the vehicle spacing density.
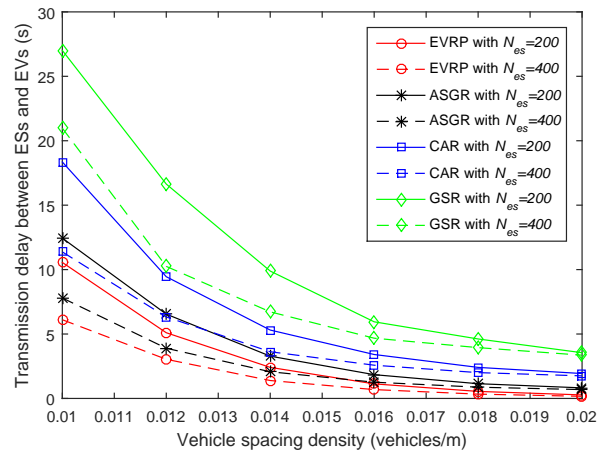
1) Transmission delay

Fig. 8 presents the average transmission delay between mobile EVs and ESs with various vehicle spacing density and ES number. From this figure, we observe that when vehicle spacing density and ES number increase, network connectivity is significantly enhanced and average packet delivery distance descends, as a result, more packets can be relayed via wireless delivery and pass through less forwarding hops, and transmission delay of all routing protocols decreases. In addition, compared with other routing protocols, EVRP gives the lowest transmission delay. It is obvious that EVRP enables the closed collaborations among different ants and communication pairs to refresh the latest routing information based on the ACO algorithm, and this scheme is advantageous to cope with fast network topology varieties, and thus the transmission delay has reduction. The other reason is that the best routing path established by EVRP is between two end intersections rather than that between individual mobile EV and its corresponding ES, so several communication pairs with same EIs and QoS requirements can directly implement data transmission using the existing routing path without any routing explorations, which can help to reduce the whole transmission delay. While GSR operates packet transmission on the basis of the shortest-distance path rule, which is unable to adapt dynamic VANET scenarios and leads to considerable increase in transmission delay. In the case of CAR, a min-delay routing path is provided for packet transmission, but real-time traffic information along the selected route can not be renewed in time, so upcoming data packets may incur serious network congestions or sparse networks which induce much higher transmission delay. ASGR selects the best routing path with respect to delivery delay and network connectivity, but it forwards packets via the complete end-to-end route, which is not adaptive to varying VANET environments.

Fig. 9 specifies the transmission delay variance as the function of vehicle spacing density. This figure clearly
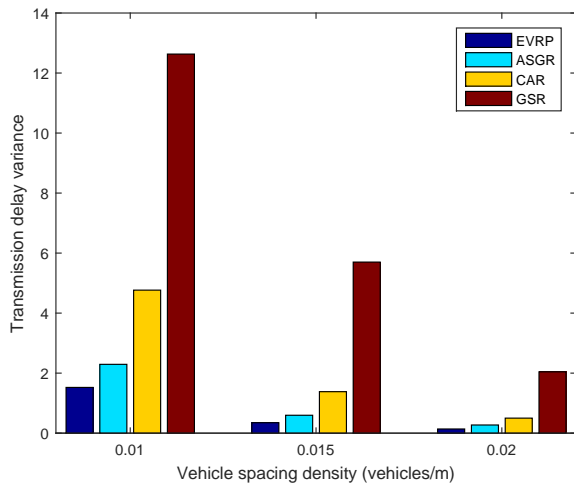
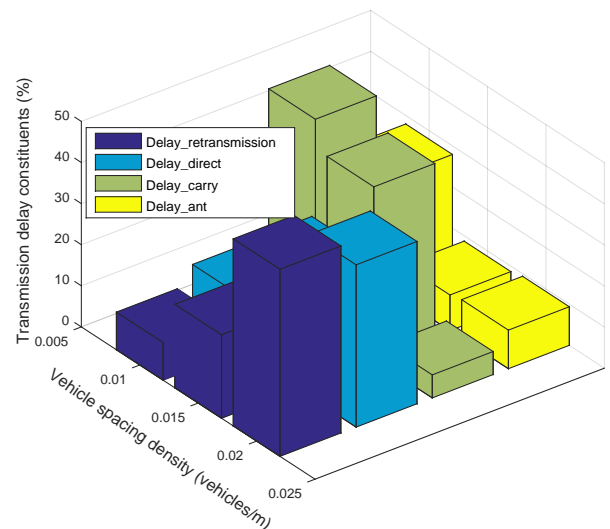**FIGURE 9.** Transmission delay variance vs. vehicle spacing density.

FIGURE 10. The percentage of each transmission delay component in EVRP.

points out that the transmission delay variance of EVRP is lowest compared with that in other referring routing protocols, and it implies those the optimal routing path established by EVRP is more stable and feasible. The results are explained as follows: (1) transmission delay variance is considered by EVRP to carry out both the candidate routing discovery and best routing selection processes, and the routes exceeding delay variance threshold DV_{th} are neglected, (2) the best route in EVRP is explored and built based on both local and global pheromone, which is conductive to maintain transmission delay stability and prevent data packet communication from encountering extreme transmission conditions (e.g., network holes or communication jams), and (3) when forwarding packets, EVRP dynamically selects the next target intersection by means of the latest global pheromone, which helps to adaptively cope with network topology changes and decrease delay variance.

Fig. 10 displays the constituents of transmission delay in EVRP in terms of varying vehicle spacing density. The packet transmission delay is composed of four components, namely Delay_ant (routing establishment delay caused by forward ants and backward ants for future packet transmission), Delay_carry (transmission delay introduced by packets carried by mobile EVs rather than forwarded via wireless connections), Delay_retransmission (transmission delay caused by packet retransmission because of relaying failures) and Delay_direct (transmission delay given by direct wireless communication without any retransmission). Specifically, from Fig. 10, we can see that the proportions of Delay_carry and Delay_ant in the whole transmission delay reduce when vehicle spacing density increases, but the transmission delay generated by wireless communication including Delay_retransmission and Delay_direct is proportional to vehicle spacing density. Such results are clarified as follows: wireless connection breaks can be almost repaired with the rise of vehicle spacing density, so the routing estab-

lishing processes can be accelerated and data packets prefer to be relayed by means of hop-by-hop wireless links rather than be carried by current mobile vehicles. However, higher vehicle spacing density means that more mobile EVs with communication demands on road segments and may result in severe transmission interferences from neighboring EVs and serious wireless channel access contentions, so successful relaying behaviors for charging packets easily deteriorate and more retransmission actions are implemented, which can lead to the increase of Delay_retransmission percentage.

2) Packet delivery ratio

Fig. 11 describes the packet delivery ratio with various vehicle spacing density and ES number for different routing protocols. As shown in this figure, the proposed EVRP routing protocol achieves the best packet delivery ratio compared with those of other three baseline routing protocols including CAR, GSR and ASGR. The reasons are given as follows. Firstly, both BER and forwarding progress distance are taken into account in EVRP for the next-hop forwarding vehicle selection, and it is beneficial to the improvements of packet delivery ratio. Secondly, EVRP establishes the optimal routing path by means of the ACO algorithm, which adopts different ants and communication pairs to cooperate with each other to renew the latest pheromone and cope with rapid topology changes in VANET environments. Nonetheless, CAR forwards charging data packets based on only one complete end-to-end routing path without any backup routes, and once there is no available path to the destination, the ongoing transmission falls in the failures. While GSR only makes use of the curve distance between transmitters and corresponding destinations to determine the routing path selections, and other suitable traffic information is neglected, so packet transmission may become infected with serious
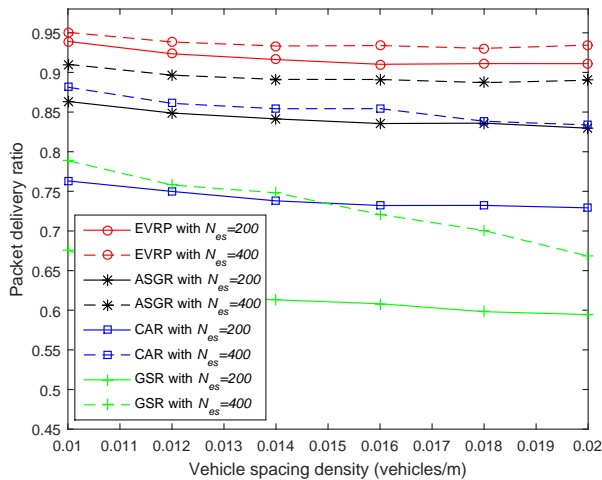
FIGURE 11. Packet delivery ratio vs. vehicle spacing density and ES number.
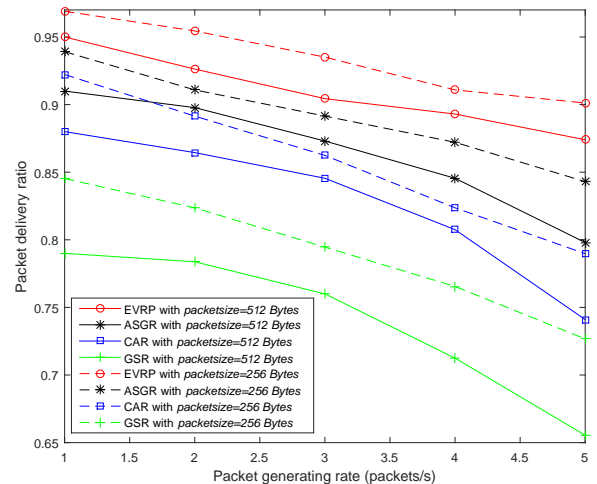

FIGURE 12. Packet delivery ratio vs. packet generating rate and packet size.

channel congestions causing high data loss. ASGR is an efficient artificial spider geographic routing protocol where link duration, connectivity and delay are considered, but communication interferences from neighboring vehicles are neglected, as a consequence, packet delivery may suffer from serious transmission collisions, which can induce high packet loss. In addition, the packet delivery ratio in EVRP shows almost stable feature with the increase of vehicle spacing density, and it indicates the adaptivity and effectiveness of EVRP. However, when vehicle spacing density rises, the packet delivery ratio of other routing protocols has some reductions, which can be illustrated as follows: (1) higher vehicle spacing density is beneficial to increase network connectivity, and more packets are delivered via wireless hop-by-hop patterns, which signify that packet transmission processes may suffer from more effects of channel fading, transmission collisions and communication interferences, (2) the number of CBR sessions between EVs and ESs have positive correlations with vehicle spacing density, and more packets can pour into VANETs with the increase of vehicle spacing density, thus the probability of channel congestions is growing and the buffers attached to mobile vehicles may incur overflows, which lead to lower packet delivery ratio.

We explore the impacts of packet generating rate and packet size on packet delivery ratio, and related results are depicted in Fig. 12. In this experiment, vehicle spacing density ϕ and ES number N_{es} are set as 0.01 vehicles/m and 400, respectively. From this figure, it is easily observed that with the rise of packet generating rate, the packet delivery ratio of all four routing protocols is reducing. This is because that the larger packet generating rate on the sides of packet senders can lead to fierce channel access competitions or transmission delay deadline meeting due to network congestions, and packet delivery suffers from failures. Besides, as shown in Fig. 12, the bigger packet size also bring the greater probability of packet delivery loss

owing to serious buffer storage overflow and transmission collisions.

3) Impacts of forward ant number

In order to analyze the influences of forward ants number in EVRP, we set vehicle spacing density ϕ, ES number N_{es} and forward ants number N_{fant} to 0.015 vehicles/m, 200 and $10 \sim 200$ in the experiments, respectively. Note that the normalized QoS is evaluated based on both transmission delay and delay variance, and it is expressed in (1). From Table 3, we can see that the normalized QoS improves with the increase of forward ant number, because more forward ants can be utilized to strengthen the global routing exploration capacities in EVRP and set up more candidate feasible routing paths, which are advantageous to the best route selection and QoS advancement. However, the rise of forward ants number significantly enlarge the randomness of routing exploration, which causes lower efficiency in the best routing path establishment and induces higher algorithm convergence time. In addition, we notice that when the number of forward ants varies from 50 to 200, the normalized QoS obtains a little improvement with more convergence time. According to the above illustrations, the number of forward ants plays an important role in effecting EVRP's performance, and an appropriate value of N_{fant} is able to keep the reasonable balance between high routing performance and short convergence time.

D. PERFORMANCE EVALUATION ON THE PROPOSED LOCAL RELAYING SCHEME

1) Waiting time analysis

An available waiting time model plays a critical role in our proposed local relaying scheme, and Fig. 13 presents the designed waiting time as the function of different forwarding progress distances and weight values. In order to validate the proposed model's effectiveness and efficiency, a referring

TABLE 3. The effects of forward ants number in EVRP.

N_{fant}	Normalized QoS	Convergence time
10	0.7135	0.1656 s
20	0.8216	0.2863 s
50	0.8853	0.3082 s
100	0.8897	0.6889 s
200	0.8902	1.1692 s
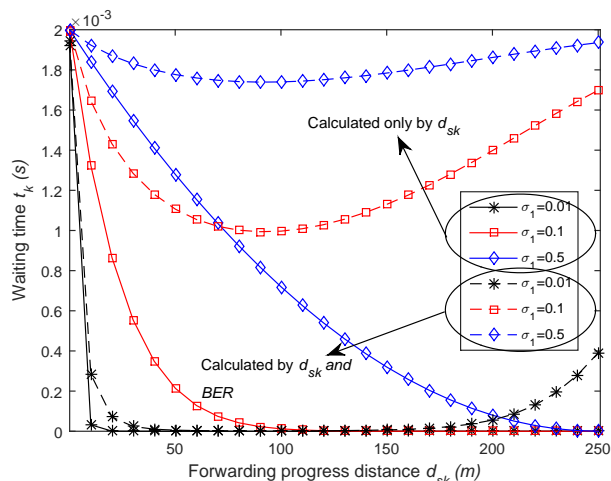
FIGURE 13. Waiting time vs. forwarding progress distance.

FIGURE 14. Packet delivery ratio vs. packet size.

waiting time model is given and it is derived with respect to only forwarding progress distance, the concrete expression is represented as $t_k = \left(1 - \left(\frac{d_{sk}}{R}\right)^{\sigma_2}\right)^{\sigma_1^{-1}} \cdot T_{\max}$. From Fig. 13, we see that the waiting time based on only forwarding progress distance (shown in the solid lines) decreases with the rise of forwarding progress distance, and it implies that the neighboring vehicle being farthest from the current transmitter is selected as the next-hop relaying vehicle, which makes data transmission neglect the negative influences of channel fading and communication interferences from neighboring nodes, and suffer from higher packet loss. While in the case of our proposed waiting time model with regard to both forwarding progress distance and BER, we observe that the lower waiting time values (displayed in dashed lines) are concerned with the median forwarding progress distance falling in the range $70 \sim 130$ m, and this model is capable of maintaining a suitable balance between low BER and high forwarding progress distance, which is beneficial to the reductions of relaying hops and transmission delay. In addition, we confirm that smaller σ_1 is in positive relation with lower waiting time, which be is conducive to decrease the whole relaying delay. However, lower σ_1 leads to more smooth curve of waiting time in the certain range interval of forwarding progress distance, and it signifies that the differences of various candidate next-hop vehicles' waiting time are very narrowing and lightly induce CTS response collisions, which easily lead to packet
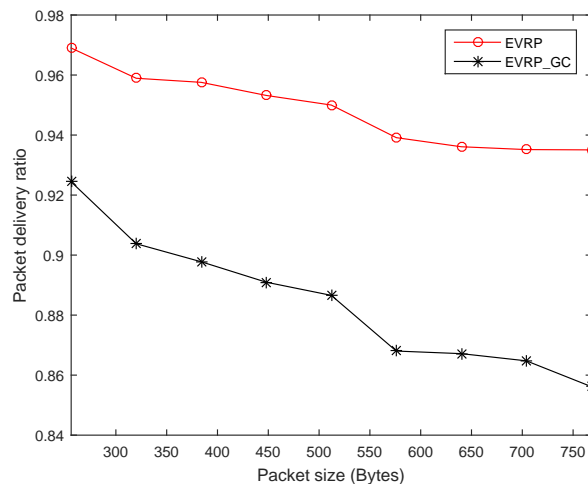
delivery failures. Obviously, a desirable value of σ_1 is very critical in waiting time calculations, here σ_1 is set as 0.1 in our experiments.

2) packet delivery ratio analysis

Fig. 14 shows the packet delivery ratio with different packet size, and it indicates that the performance of EVRP is more excellent compared to that of EVRP_GC. The reasons are very obvious. Firstly of all, EVRP utilizes the modified RTS/CTS pattern rather than periodic hello exchanges to obtain neighboring information for next-hop relaying vehicle selections, and this scheme can effectively reduce the overhead amount and ease the negative influences of serious transmission loads. Besides, compared with only curve relaying length used in EVRP_GC to evaluate the candidate next-hop vehicles, EVRP takes advantage of both BER and forwarding progress distance, which can convincingly rise packet delivery ratio.

3) Overhead analysis

The whole network overheads of different routing algorithms in terms of varying vehicle spacing density are shown in Fig. 15. Here the overhead is defined as the ratio of the total additional packet bytes involving various control and signaling messages to the overall bytes of successfully transmitted packets. It is evident that EVRP achieves the lowest overheads compared with other referencing routing methods, and there are three advantages of EVRP to illustrate such outcomes. First of all, by means of the ACO-based algorithm, EVRP is competent to adaptively select the best routing path to relay charging data packets based on the freshest global pheromone, which is advantageous to improve packet delivery ratio and thus reduce the overheads. Besides, EVRP makes use of EI concepts to further decrease redundant routing explorations, and the network overheads are diminished in return. Furthermore, instead of periodic
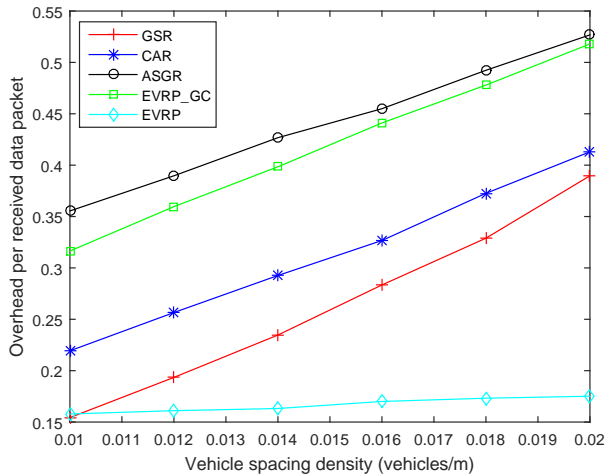
FIGURE 15. Normalized overheads vs. vehicle spacing density.

beacon transmission in four baseline routing protocols, EVRP takes charge of exchanging neighboring information and selecting next-hop relaying vehicles by means of the proposed local relaying scheme on the basis of the modified RTS/CTS frames, of which the generator number is fewer and transferring frequency is lower. While there are not proactive routing exploration overheads in GSR, which can result in lower overheads with the cost of worse routing performance in delay and packet delivery ratio. CAR just makes use of the on-the-fly scheme to collect routing information along the roads, and the related overheads are not huge. ASGR takes advantage of artificial spiders to obtain the traffic information of all end-to-end routing paths, and adopts real-time protocol optimization scheme to update road information and track the locations of destinations, thus more overheads are produced. From Fig. 15, we also see that the overheads generated by referencing routing protocols are positive proportional to vehicle spacing density, as the major part of the overall overheads is taken up by periodic beacon control packets, of which the number is primarily determined by vehicle spacing density.

V. CONCLUSION

In this paper, we have proposed an efficient charging information transmission strategy for highly coordinated charging managements of mobile EVs. First of all, based on the MEC concept and dynamic VANETs, a heterogeneous communication framework with the hybrid information exchange manner is devised, and related analysis is illustrated in terms of communication cost, scalability and so on. Secondly, we have proposed an ACO-based charging data delivery algorithm in varying VANET environments on the basis of the constrained QoS requirements. Thirdly, an effective local relaying mechanism has been designed for charging information forwarding within road segments, to further improve packet successful delivery ratio and decrease overheads. Finally, our proposed charging infor-

mation transmission strategy has been demonstrated via a number of simulations. For future works, we would further improve the performances of EVRP, and design an adaptive mechanism to adjust the weight values in EVRP for various charging services.

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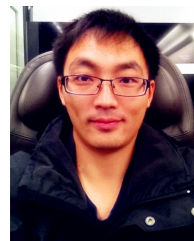
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