UAV Trajectory Design for UAV-2-GV Communication in VANETs

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***Abstract*—Owing to the flexibility, automation and quick deployment features of unmanned aerial vehicles (UAVs), they can be used to deliver the data to the ground vehicles (GVs) efficiently in vehicular area networks (VENETs). However, the heterogeneity, high mobility and network dynamics of VANETs pose significant challenges for such communication. In this paper, we propose a trajectory design scheme for efficient UAV-2-GV communication in vehicular area networks (VANETs). Specifically, given the high traffic routes of a dense city, the UAV trajectory is optimized to serve the maximum number of GVs. The trajectory design problem is formulated under the constraints of limited UAV power and association capacities. Moreover, a simplified trajectory design scheme is proposed by exploiting the known traffic road lengths. After the deployment of the UAV according to the designed trajectory, optimal vehicle association and power allocation is performed. Simulation results reveal that the proposed UAV-assisted VANETs can deliver better rates as compared to the traditional terrestrial base-station (TBS)-based networks.**

***Index Terms*—V2V, UAV, Trajectory, VANETs**

I. Introduction

VEHICULAR communication is an essential component of modern mobile communication systems where data is delivered to and from the road vehicles for real-time transportation information delivery, entertainment data dissemination and other safety and control data delivery [1]–[3]. The high mobility and heterogeneity in the channel variations of vehicular area networks (VANETs) pertain the challenges of efficient communication system design. The proposals of road-side-units (RSUs) are the results of the devised efforts to bring the dedicated base-station at the road edge to cope such challenges [4]. However the fixed positions of RSUs limit the the resource management in VANETs. To address this issue, the number of RSUs in the metropolitan area can be increased which may result in a huge deployment cost. Moreover, these additional RSUs remain unused in the absence of heavy traffic and hence are inefficient.

Numerous schemes have been proposed to enhance the network performance and data rates in future wireless networks [5]–[7]. Recently, the use of unmanned aerial vehicles (UAVs) has been proposed in various wireless networking applications [8]–[10]. UAVs can be a promising substitute to the RSUs by acting as road-above-unit (RAU) where the flexibility, automation and mobility of UAVs can be exploited to serve a number of ground vehicles (GVs). Moreover, the line-of-sight communication link between the UAVs and GVs can deliver better rate in comparison to the RSUs.

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Despite the promising performance of UAVs-assisted VANETs, it pertain the challenges of optimal trajectory design to serve the maximum number of GVs while fully utilizing the on-board UAV energy and association capacity. Moreover, the dual mobility of flying UAVs and moving ground vehicles make such trajectory design challenging.

A. Related works

A very few UAV-based schemes are proposed to manage the resource allocation in UAV-supported VANETs [11]–[17].

For instance, in [11] the authors analyze the performance of a UAV-based vehicular network. However, they consider that the deployment position of the UAV in a hotspot with heavy traffic is already known. In [12], the authors proposed to use UAVs as a relaying node between the V2V pairs with the coexisting terrestrial network. A pricing based interference management scheme is proposed using a Stackelberg game. In [13], the authors used UAVs as a relay between vehicles to enhance the network capacity where the position of the UAVs is optimized to satisfy the QoS requirements of the ground vehicles.

In [14], the authors proposed a UAV based caching service which is provided to the vehicular networks for data dissemination where UAVs work as relay between vehicles and RSUs. In [15], the authors addressed the similar problem of data dissemination to the ground vehicles by using the UAVs as a relay node with the caching capability. In [16], the authors proposed a network of UAVs to transfer data from the vehicle to the core network where one UAV serves the vehicles and other UAVs are used to relay the data. The energy is conserved by limiting the mobility of the UAVs in a certain area. In [17], the authors proposed a UAV-based content delivery service to the vehicles where the popular content is stored at the UAVs while incorporating the UAV energy. To improve the network performance, the UAV trajectory and resource allocation is optimized.

In the aforementioned works, UAVs are mostly used as a relay node to serve the vehicles. However, the problem of trajectory design of the UAVs according to the mobility and traffic flows of the vehicular traffic still needs further investigation. Moreover, the UAV trajectory design while exploiting the geographical details of the ground roads is not studied in these works.

B. Contributions

To address these challenges, we propose an efficient UAV trajectory design scheme where the trajectory of UAVs, the transmission power and the GVs associated with the UAVs are jointly optimized. Specifically, the problem of VANETs data rate maximization is formulated under the constraints of limited on-board UAV energy and association capacity. For that purpose, the UAVs position and speed is adjusted such that more number of ground vehicles can be served. To further improve the efficiency of the trajectory design in VANETs, the traffic road patterns and footprints are exploited. In contrast to the traditional trajectory design schemes of UAVs, the proposed scheme can significantly reduce the decision points and hence the trajectory design is simplified significantly. The main contributions of this paper are summarized as follows:

- We formulate the problem to optimize the UAV trajectory, downlink power allocation, and vehicular association with the UAVs to maximize the sum rate of vehicular network.
- To solve the formulated problem, we first compute the optimal UAV trajectory using the network flow approach where the UAVs follow the heavy traffic flow.
- We simplify the trajectory design scheme by reducing the number of decision points at the traffic intersections only instead of deciding the trajectory at the intermediate road locations.
- To solve the vehicular association, we select the best channel gain users under the capacity constraints of the UAVs. Then the power allocation is performed to deliver a fixed threshold of SNR.
- Simulation results reveal that the proposed scheme can significantly reduce the trajectory design computation complexity. It is also observed that the data rate delivered by the UAVs is significantly higher in comparison to the RSU-based network.

To the best of our knowledge, this is the first study that utilize the ground road structures for the optimal trajectory design of UAVs according to the traffic flows to maximize the vehicular network rate of VANETs.

The rest of this paper is organized as follows. Section II presents the system model, vehicle mobility model and communication model. In Section III, we formulate the joint trajectory design and vehicular association and power allocation problem under UAV power and capacity constraints. In Section III-A, the proposed trajectory design algorithm is developed. In Section III-B, power allocation and vehicle association scheme is developed; and numerical evaluation of the proposed framework are discussed in Section IV. Conclusions future directions are given in Section V.

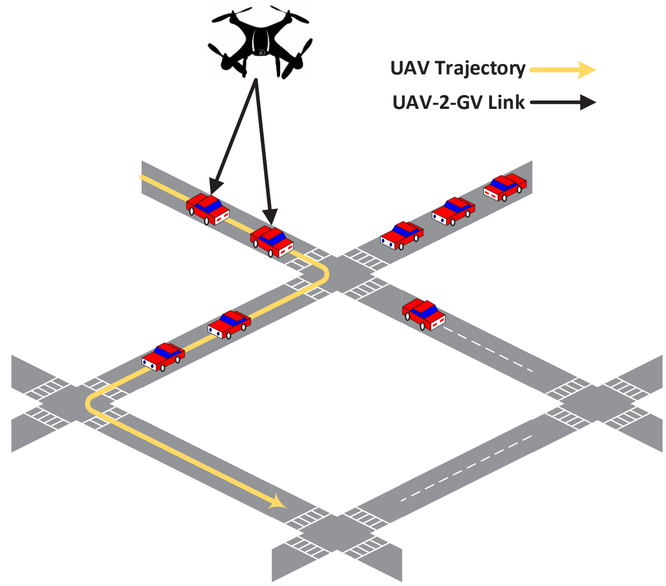


Fig. 1: System model representing the trajectory of the UAV to serve GVs. The suitable vehicles are associated with the UAV while the UAV is flying over the spots containing maximum number of vehicles.

II. System Model

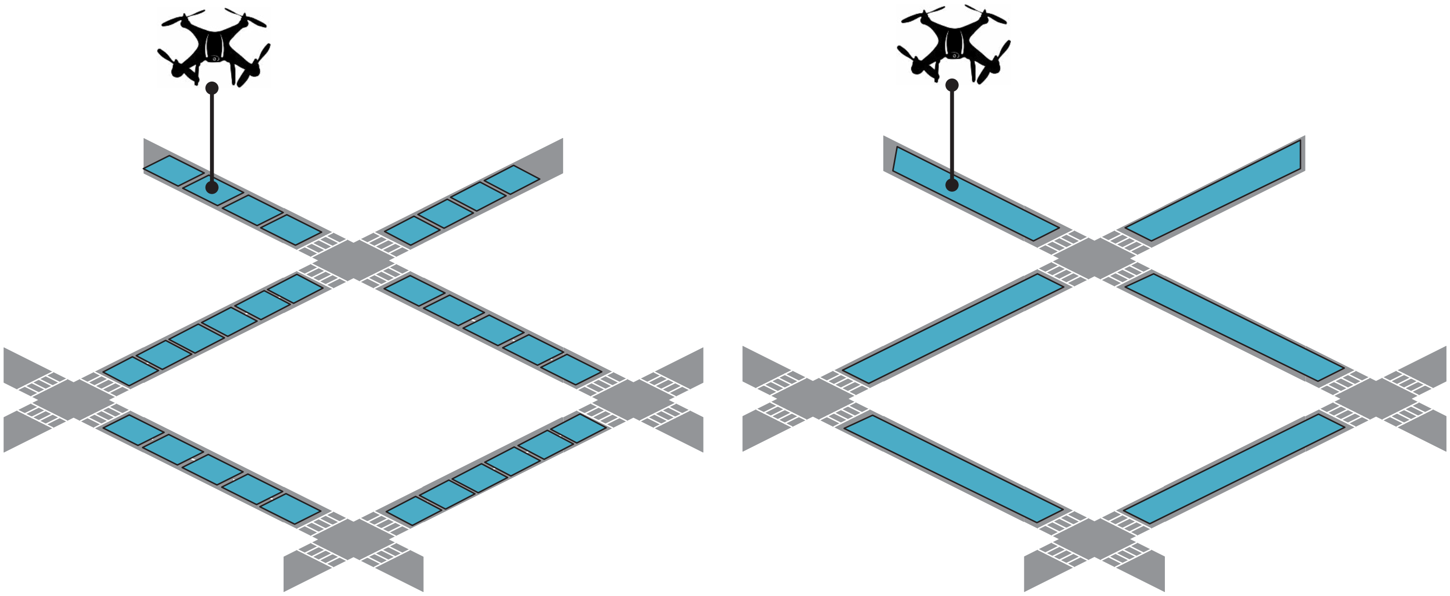
A. System Model

We consider a vehicular network in a dense city with heavy traffic flows during peak hours. To serve this vehicular network, the available RSU resources are insufficient. To address this issue, a set of flying rotary-wing UAVs denoted by $\mathcal{N} = \{1, 2, \dots, N\}$ is deployed to serve the set of vehicles denoted by $\mathcal{V} = \{1, 2, \dots, V\}$. The UAVs are capable of adjusting the speed, position and trajectory according to the flows of traffic. Therefore the aim of the UAV is to follow the route of traffic which has the highest vehicular traffic. To develop such trajectory, we consider a set of ground locations denoted by $\mathcal{L} = \{1, 2, \dots, L\}$. The UAV trajectory $\mathcal{T}$ is composed by selecting the adjacent locations from this set $\mathcal{L}$. At the traffic intersections, the traffic is distributed among different routes. The route containing the highest number of vehicles is chosen in the trajectory of the UAV.

B. Vehicle mobility model

At a time instant, there are a certain number of vehicles denoted by V_l at a graphical location, $l \in \mathcal{L}$. Based on the number of vehicles at each location, the trajectory decisions of the UAVs are made. As the vehicles are moving in a certain direction, the trajectory of the UAVs is designed according to the movement of the mass of the vehicles. For instance, suppose that a UAV is at location l_1 and is serving V_{l_1} number of vehicles. If the number of vehicles at location l_2 denoted by V_{l_2} is greater than the number of vehicles at location l_1 i.e. $V_{l_2} > V_{l_1}$, the UAV will move to the new location l_2.

The speed of each vehicle is denoted by s_v. To compute the speed of the flying UAV, the average speed of all vehicles at location l is computed. Therefore the speed of UAV at location l is given as follows:



(a) Trajectory design approach for short road areas.

(b) Trajectory design approach for long road areas.

Fig. 2: (a) shows the trajectory design scheme where the whole are is divided into a set of location points and the UAV trajectory is developed by making decision at every location point to complete the trajectory. (b) shows a simplified trajectory design scheme where the trajectory design decisions are made only at the traffic intersections only to reduce the trajectory design computation complexity.

$$s_u[l] = \bar{s_v}[l], \tag{1}$$

where $\bar{s_v}[l]$ denotes the average speed of all vehicles at location l. The UAVs fly above the urban area to serve the GVs until the battery of the UAV is consumed. After that the UAV is replaced by another UAV with fully charged battery. This process is repeated till the traffic load is reduced to the level when the RSUs can solely serve the vehicles.

C. UAV-2-GV Communication Model

If a UAV is flying at a location l, the distance between the UAV and a ground vehicle v is given as follows:

$$d_{nv} = \sqrt{\|x_n - x_v\|}, \tag{2}$$

where x_n and x_v denote the geographical location of the UAV and vehicle, respectively. The corresponding path-loss is composed of the LoS and non-LoS path-losses which are given as follows [18]:

$$\gamma_{\text{LoS}} = \eta_{\text{LoS}} \left(\frac{4\pi f_c d_{nv}}{c} \right)^{\alpha}, \tag{3}$$

$$\gamma_{\text{N-LoS}} = \eta_{\text{N-LoS}} \left(\frac{4\pi f_c d_{nv}}{c} \right)^{\alpha}, \tag{4}$$

where $\eta_{\text{N-LoS}}$ and $\eta_{\text{N-LoS}}$ are the additional path-loss components which are dependent on the environmental variables. c and f_c denote the light speed and the carrier frequency, respectively. The possibility of LoS communication is modeled with the probability of LoS communication link between UAV and GV given as follows [19]:

$$P(\text{LoS}) = \frac{1}{1 + aexp(-b(\frac{180}{\pi}\theta - a))}, \tag{5}$$

where a and b are environment constants, respectively and θ is the elevation angle between UAV and GV. The probability of non-LoS link is give as follows:

$$P(\text{N-LoS}) = 1 - P(\text{LoS}). \tag{6}$$

The average path-loss incorporating both LoS and non-LoS communicaiton links is expressed as follows:

$$\gamma = P(\text{LoS})\gamma_{\text{LoS}} + P(\text{N-LoS})\gamma_{\text{N-LoS}}. \tag{7}$$

The corresponding signal-to-noise ratio for the communication link between UAV and GV is given as follows:

$$\text{SNR}_{nv} = \frac{p_{nv} g_{nv}}{\sum_{n'} p_{n'v} g_{n'v} + N_0}, \tag{8}$$

where p_{nv} is the transmit power of UAV, g_{nv} is the channel gain computed from the path-loss γ and N_0 is additive white Gaussian noise. The factor $\sum_{n'} p_{n'v} g_{n'v}$ in the denominator represents the interference from the neighboring UAVs $n' \in \mathcal{N} \setminus n$. The achievable rate of the GV is expressed as:

$$R_{uv} = W \log\left(1 + \text{SNR}_{uv}\right), \tag{9}$$

where W denotes the bandwidth of the channel. For the sake of brevity and simplicity, we assume that each UAV has a set of available orthogonal channels to serve the ground vehicles.

III. Problem formulation and proposed solution

In this section, we first formulate the joint optimization problem of UAV trajectory design and resource allocation. To solve this problem, we decompose it into two disjoint sub-problems. First the trajectory design problem is solved according to the traffic flows on the ground. Then the resource allocation is performed while the UAV is flying at a specific location l.

The joint optimization problem is given as follows:

$$\max_{\mathcal{T},\boldsymbol{p},\boldsymbol{a}} \sum_{n\in\mathcal{N}} \left(\sum_{v\in\mathcal{V}} a_{nv} R_{nv} \right), \tag{10}$$

$$\text{s.t.} \quad \text{SNR}_{nv} \geq \Gamma, \quad \forall n \in \mathcal{N}, v \in \mathcal{V}, \tag{10a}$$

$$\sum_{v\in\mathcal{V}} p_{nv} \leq P_n, \quad \forall n \in \mathcal{N}, \tag{10b}$$

$$0 \leq p_{un} \leq P_{\text{max}}, \quad \forall n \in \mathcal{N}, v \in \mathcal{V}, \tag{10c}$$

$$\sum_{v\in\mathcal{V}} a_{nv} \leq C_n, \quad \forall n \in \mathcal{N}, \tag{10d}$$

$$a_{nv} \in \{0,1\}, \quad \forall n \in \mathcal{N}, v \in \mathcal{V} \tag{10e}$$

$$\mathcal{T} \in \mathcal{L}, \quad \forall n \in \mathcal{N}, v \in \mathcal{V}, \tag{10f}$$

where a_{nv} denotes the association of vehicle v with UAV u. The objective function in (10) denotes the rate of vehicular network. It is obvious that the objective is directly dependent on the power allocation $\boldsymbol{p}$ and vehicle association $\boldsymbol{a}$. This association is dependent on the trajectory of the UAVs. So the aim of the problem is to maximize the network rate by optimizing the UAV trajectory to serve more number of vehicles while consuming least power resources. (10a) guarantees the minimum level of SNR for the vehicles. (10b) and (10c) represent the bounds of power allocation where P_n denotes the available on-board power of UAV n and P_{max} denotes the maximum power that can be allocated to the vehicle.

Note that, if constraint (10a) is not satisfied even after allocating the maximum power P_{max}, that vehicle is not associated with the UAV to make the problem (10) feasible. (10d) and (10e) represent the bounds of association variable where C_n is the maximum association capacity of the UAV. (10f) denotes the trajectory which is composed of the locations selected from the set $\mathcal{L}$.

It can be observed that if the number of vehicles at a location V_l is known, the problem (10) can be decomposed into sequential disjoint sub-problems. In the first sub-problem, the UAV is directed to fly on the corresponding locations according to the number of vehicles in those locations. Once the location of the UAV is decided, the resource allocation is performed in the second sub-problem. In the following, we first solve the problem of trajectory design for the UAVs.

A. UAV Trajectory Design

In the traditional UAV trajectory design schemes, the whole geographical area is divided into small deployment locations as shown in Fig. 2(a). The UAVs choose the best neighboring location to construct the trajectory. We consider that the locations and speeds of all the vehicles in the network are known. From this information, the number of vehicles V_l at a particular location $l \in \mathcal{L}$ can be computed. Therefore, the optimal deployment location of the UAV and the subsequent location selection for the trajectory design is given in the following lemma.

Lemma 1. *To start the trajectory, the UAV is deployed at the most dense location in the network containing the highest number of vehicles. This initial location is added in the trajectory as $\mathcal{T} = \{l_1\}$. After the deployment, the average speed $\bar{s_v}[l]$ of the vehicles at location l is computed which gives the UAV speed $s_u[l]$ according to (1). After that the UAV follows the flow of ground vehicles and move to one of the neighboring locations which has higher number of vehicles. This process is continued to complete the trajectory $\mathcal{T} = \{l_1, l_2, \ldots, l_m\}$ of the UAV where l_m denotes the final location in trajectory.*

It can be observed from Fig. 2 that the vehicle distribution remains the same on roads between intersections and major changes occur on the intersections only. Therefore, deciding the locations for the UAV trajectory between the intersections results in redundant and unnecessary decision making. This can be avoided by making the trajectory decisions on the traffic intersections only as shown in Fig. 2b. In this way a simplified trajectory design for the particular vehicular network is possible which can reduce the complexity significantly.

B. Vehicle Association and Power Allocation

Given the location of UAVs according to the designed trajectory $\mathcal{T}$, the second sub-problem is the optimal vehicle association and power allocation. The resource allocation subproblem is given as follows:

$$\max_{\boldsymbol{p}} \sum_{n\in\mathcal{N}} \left(\sum_{v\in\mathcal{V}} a_{un} R_{nv} \right), \tag{11}$$

$$\text{s.t.} \quad \text{SNR}_{nv} \geq \Gamma, \quad \forall n \in \mathcal{N}, v \in \mathcal{V}, \tag{11a}$$

$$\sum_{v\in\mathcal{V}} p_{nv} \leq P_n, \quad \forall n \in \mathcal{N}, \tag{11b}$$

$$0 \leq p_{un} \leq P_{\text{max}}, \quad \forall n \in \mathcal{N}, v \in \mathcal{V}. \tag{11c}$$

It can be seen that the objective contains the binary association variable a_{nv} which makes the problem non-convex. The traditional way to solve such problem is to relax the binary variable in the continuous domain. In contrast, we associate the vehicles using the greedy approach to maximize the vehicular network rate using the following Lemma 1. For that, we first relax (11b) by considering the worst-case scenario of power allocation where each vehicle is allocated the maximum power level P_{max}. In this case, exploiting the maximum association capacity C_n of the UAVs, the total UAV power P_n can be expressed as:

$$P_n = C_n P_{\text{max}}, \tag{12}$$

where the power allocation to the vehicles is initially set maximum for the worst-case scenario as $p_{nv} = P_{\text{max}}$. In this way, (11b) is relaxed and the association of vehicles

Algorithm 1 UAV trajectory design and resource allocation algorithm

Input: $\mathcal{V}$, x_v, and s_v.
Compute V_l and $s_u[l]$ at each location $l \in \mathcal{L}$.
The UAV is deployed at most dense location with the speed $s_u[l]$.
Channel gain between UAV and vehicles is computed using (2)-(7).
SNR is computed by fixing the $p_{un} = P_{\max}$.
Vehicle association is performed using Lemma 1 according to the indicator function in (13).
Optimal power allocation is computed from (14) for the associated vehicles a^*_{un}.
The UAV is moved to the next neighboring location which has the highest number of vehicles.
Output: $\mathcal{T}$, a^*_{un}, and p^*_{un}.

is performed under the SNR threshold constraint in ((11a)) according to the following Lemma.

Lemma 2. *To associate the optimal vehicles from V_l number of vehicles at location l, we construct the sorted set of vehicles denoted by V_l' according to the received SNR level SNR_{nv}. Next we select the first C_n number of vehicles to get optimal association a^*_{un} from this set V_l' which have $SNR_{nv} > \Gamma$ which is expressed in the form of indicator function as follows:*

$$a'_{un} = \mathbb{1}\{SNR_{nv} > \Gamma\}, \forall v \in V_l' \tag{13}$$

where $\mathbb{1}\{\cdot\}$ denotes the indicator function and it represents the vehicles from the sorted set V_l' which satisfy the SNR threshold constraint. Next optimal associated vehicles a^*_{un} are chosen by selecting first C_n vehicles from a'_{un}.

For the optimally associated set of vehicles a^*_{un}, the power allocation is performed to meet the minimum SNR threshold in (11a) as follows:

$$p^*_{un} = \min\left[\frac{\Gamma\left(\sum_{n'} p_{n'v} g_{n'v} + N_0\right)}{g_{nv}}, P_{\max}\right]. \tag{14}$$

The joint trajectory design and resource allocation scheme is given in Alog. 1. The inputs of the algorithm include the number of vehicles $\mathcal{V}$ in the network, their corresponding locations x_v and their moving speeds s_v, respectively. To design the trajectory of UAVs, first the number of vehicles at every location $l \in \mathcal{L}$ is computed. The UAV is deployed at the most populated location initially with the initial speed $s_u[l]$. After that the optimal vehicle association and power allocation is performed according to (13) and (14) to compute the vehicular network rate. Then the UAV is moved to the next optimal neighboring location.

IV. Numerical Results

To validate the proposed trajectory design and resource allocation algorithm in vehicular networks, we develop a simulation setup. In this setup, there are up to 100 ground vehicles moving on the road with the speed in the range of 20 km/h to 100 km/h. For the ease of simulation, the number of vehicles and their corresponding speeds and locations are considered independent in each location. We perform the simulations for a number of runs and the results are provided by averaging the simulations. Other simulation parameters are given in Table. I.

Parameters	Values
SNR threshold (Γ)	-120 dBm
Minimum vehicular speed	20 km/h
Maximum vehicular speed	100 km/h
Noise (N_0)	-97.5 dBm
TBS Radius	100 m
Frequency (f)	2.5 GHz
UAV Radius	200 m
Bandwidth (W)	270 kHz
Maximum transmission power	0.5 W
Path Loss (TBS)	$16.62 + 37.6log(d))$

TABLE I: Simulation Parameters

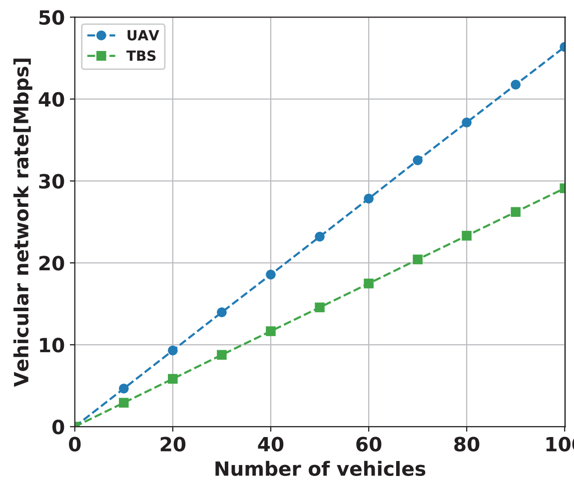


Fig. 3: Network rate vs number of vehicles for UAV-based and ground network.

In Fig. 3, we show the total vehicular network rate vs the increasing number of vehicles in the network for the UAV-based and terrestrial base-station (TBS)-based networks. It can be observed that the UAV-based network can achieve high data rate as compared to the terrestrial network. Specifically, when there are 100 number of vehicles in the network, there is 53% improvement in the data rate of UAV-based network as compared to the TBS-based network. This is due to the fact that there is the possibility of LoS links for the UAV-based networks which provides better channel gain. Moreover, the efficient trajectory design significantly reduces the distance between UAVs and the vehicles which results in better achievable rate.

Next, we show the comparison of the traditional trajectory design and the simplified trajectory design schemes. To plot this result, we develop the scenarios of long and short roads in the city. The short road length and long road length is considered 2 km and 5 km, respectively. For the traditional trajectory design scheme, the length of each location is con-

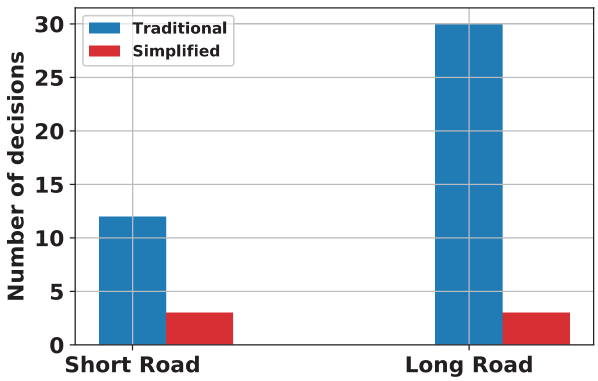


Fig. 4: Simplified Trajectory design results vs the traditional trajectory design.

sidered 500 m. In the simplified scheme, the length of each location is considered to be equal to the distance between two intersections.

In Fig. 4, we show the number of decisions required to choose the trajectory of UAV for the traditional and simplified schemes. It can be observed that the traditional scheme requires more number of decisions as compared to the simplified scheme. Specifically, traditional scheme requires 4 times more number of decisions for the short road as compared to the simplified scheme. This difference is significantly high for the long road scenario. On the other hand, the simplified scheme pertain the same of number of decisions required. This is due to the fact that the simplified scheme makes the decision of choosing the trajectory on the traffic intersections only. Therefore, the trajectory design becomes independent of the length of the road.

V. Conclusion and Future Directions

In this paper, we have studied the UAV-based vehicular network in dense urban environment to support the ground terrestrial network in peak traffic hours. We formulate the joint optimization problem for the trajectory design of UAV and resource allocation to the vehicular communication. We solve the problem by decomposing it into two disjoint sub-problems. We propose a simplified trajectory design scheme while exploiting the lengths of the roads in the city. After that we perform the resource allocation to maximize the vehicular network rate. We present the simulation results to reveal that the UAV-based scheme can enhance the vehicular network rate significantly.

In the future, we will extend this work to design the mobility model for the UAVs to reduce the huge message passing overhead for the instantaneous vehicular speed and location information. Moreover, we will design the framework for the interference management with the coexisting terrestrial network.

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