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Trajectory Planning and Resource Allocation of Multiple UAVs for Data Delivery in Vehicular Networks

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Abstract—**This letter jointly investigates the trajectory and radio resource optimization for multiple unmanned aerial vehicles (UAVs) to fully deliver critical data in vehicular networks during disaster situations. We aim to minimize the number of deployed UAVs to fully serve all vehicles. The formulated problem is generally NP-hard. To solve it, we employ a sequence of convex approximates. Then, we develop an efficient algorithm to sequentially solve this problem. Our numerical results demonstrate the effectiveness of our proposed design and show that during the mission time, the UAVs adapt their velocities in order to fulfill the requirement of each vehicle.**

Index Terms—**UAVs communication, cached contents, trajectory planning, drive-thru, emergency response.**

I. INTRODUCTION

Infrastructure-based communication networks tend to be susceptible to major damage arising from either natural disasters (e.g., hurricanes, etc.) or human-made ones (e.g., wars, explosions, etc.). Each of such events has the potential to damage or even destroy a country's communication infrastructure [1]. For instance, Hurricane *Katrina*, a major natural disaster that struck the Gulf Coast in 2005, disrupted the telecommunications infrastructure, where more than 2000 cellular towers went out-of-service. Such incidents have therefore demonstrated the need to have a quick, efficient, self-configuring, and infrastructure-less wireless network for emergency cases. Owing to their agility and mobility, UAVs are being promoted as a promising solution to provide fast network recovery when the infrastructure is temporarily unavailable. They can be deployed to enhance the coverage of cellular networks during an unplanned surge in traffic demand [2].

Despite several studies related to the deployment and trajectory optimization of UAVs, there are still many open questions that are yet to be answered. In particular, for vehicular networks, there is no framework that can provide the minimum number of UAVs to serve vehicles on a given highway segment in a high mobility scenario; most of the existing work relies on either a static environment or a single UAV to enhance the communication network. Finding the minimum number of UAVs and their optimal trajectories while serving vehicles on the road is a problem that remains, to the best of our knowledge, unaddressed.

In this letter, we propose dispatching multiple UAVs that cooperatively serve vehicles on a highway with limited or no communication infrastructure. Multiple existing works demonstrated the benefits that a single UAV can deliver in emergency situations [2] [3]. One UAV alone, however, may not likely meet the requirements of all vehicles moving at different speeds on a given road segment in a timely manner. Motivated by this, deployment of a swarm of UAVs is required to deliver critical information in vehicular networks.

In this work, we aim to minimize the number of deployed UAVs by jointly optimizing the UAVs trajectories and radio resource allocation in a given period, to guarantee the vehicles' requirements in terms of downloading all needed data subject to UAVs' and vehicles' mobility constraints, and before the vehicles depart a given road segment.

II. SYSTEM MODEL

We consider a highway segment with damaged or unavailable communication infrastructure. Further, this segment has unidirectional free traffic flow of vehicles that depart the coverage of a road side unit (RSU) as illustrated in (Fig. 1), where this RSU is assumed to be equipped with M UAVs that are intended to deliver critical data to vehicles crossing the given highway segment. The UAVs have their data cached from a centralized content server before they leave the RSU.

We consider multiple time frames with duration T where each frame (few minutes) is divided into N equal-time slots, each with length δ_t (few seconds), indexed by $n = 1, .., N$. We use $\mathcal{V}^n$ to denote the subset of vehicles to be served, in time slot n, where $\mathcal{V} = \mathcal{V}^1 .. \cup \mathcal{V}^n .. \cup \mathcal{V}^N$. We consider one time frame where the arrival and requirement for all vehicles within T can be accurately estimated. Examples of content to be delivered to vehicles include critical safety information, streaming service, etc. Each UAV has an onboard unit through which it receives and likely processes the content during its residence on the highway segment.

The UAVs are assumed to have high capacity fronthaul links (such as free space optics (FSO) or millimeter-wave (mmWave) links) with ingress RSU, where a central unit updates the content of the deployed UAVs and manages the cooperation between them. Therefore, data that cannot be completely delivered to one vehicle while being within the coverage of one UAV will resume its download once the vehicle gets connected with other deployed UAVs. By considering vehicle mobility and data requirement, this work aims is to dispatch just enough UAVs from the ingress RSU to serve all vehicles before exiting the highway segment.

For simplicity, we assume the vehicle declares its required content to the ingress RSU before it enters the given highway segment. The content requested by each vehicle will be fully

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delivered by the UAVs within the vehicle's resident time on the considered segment. We adopt a widely used traffic model on the highway [4], where vehicles in each direction travel with different speeds generated according to a truncated Gaussian distribution in the range $[\nu_{\min},\, \nu_{\max}]$ [5]. We assume that vehicles keep the same speed during the entire navigation period along the segment [6]. The flow of vehicles entering the desired highway segment follows Poisson distribution with arrival rate λ veh/s. Moreover, the initial positions and speeds of vehicles are assumed to be known through Differential Global Positioning System (DGPS) provided by the ingress RSU, and communicated to the UAVs through the fronthaul links. Therefore, the instantaneous position w_i^n of each vehicle $i \in \mathcal{V}$, at any time slot n can be calculated. According to federal aviation regulations, all UAVs are assumed to fly at a constant altitude H above ground level and each UAV m is located at (x_m^n, 0, H), at time slot n, where the width of the lane is ignored as compared to the transmission range of vehicles and UAVs [7]. During the considered time frame, vehicles enter and leave the highway segment resulting in a change in the number of vehicles in $\mathcal{V}^n$. We are interested in the arrival and departure times of vehicles causing that change. Let a_i and d_i be the arrival and departure times of vehicle i to the highway segment, respectively. For each vehicle i, a_i and d_i can be calculated independently using the vehicle speed and highway distance. In our model, vehicles in set $\mathcal{V}$ may request different content sizes from the UAVs, and UAVs can simultaneously communicate with multiples vehicles on different spectrums by allocating appropriate resources.

In practice, the following equations govern the UAV trajectories

$$|x_m^{n+1} - x_m^n| \le V_{\max}\delta_t,\ n = 1, ..., N-1, \forall m, \tag{1}$$

$$x_m^0 = x_s, x_m^N = x_c\ , \forall m, \tag{2}$$

$$|x_m^n - x_j^n| \ge d_{min},\ \forall m, m \neq j, \tag{3}$$

Eq. 1, limits the distance travelled by one UAV in every time slot based on the maximum UAV speed V_{max} in m/s. Eq. 2, specifies the initial position of each UAV to be the beginnning of the high segment at x_s and the final position to be the end of segment at x_c. In fact, the operator may decide on those positions based on multiple factors such as the location of their managed property, legislation and/or UAVs' charging stations. Eq. 3, ensures a safety distance d_{min} between UAVs to maintain collision-free trajectories.

In typical UAV assisted communication, the channel is generally modeled using large-scale fading and small scale fading. However, in highway scenarios, such the one considered in this letter, the UAV-to-vehicle channel can be characterized with strong line-of-sight and therefore the small scale fading can be neglected. All UAVs are assumed to transmit with constant power P leading to a received power $P_{i,m}^n = h_{i,m}^n P$ in slot n, where $h_{i,m}^n$ is the channel gain from UAV m to vehicle i in time slot n. This channel gain can be written as:

$$h_{i,m}^n = h_o\Big(\sqrt{(w_i^n - x_m^n)^2 + H^2}\Big)^{-2}, \forall n, m, \tag{4}$$

where h_o is the median of the mean path gain at reference distance $d_0 = 1$ m.

We define the service amount as the amount of cached data that the UAVs deliver to each vehicle within their residence on the highway segment. The service amount concept has been proposed in multiple previous papers especially in scenarios with vehicle mobility [8], where the instantaneous rate is time-variant and does not exhibit the achievable service quality. Similarly, in our system model, the instantaneous achievable rate at each vehicle varies according to multiple factors including UAV position and speed, vehicle speed, highway distance, etc. Consequently, we utilize the service amount concept to represent the service quality between UAVs and vehicles. The service amount $S_{i,m}$ provided between UAV m and vehicle i over the mission time N can be computed based on the summation of the instantaneous achievable rates throughout the residence time on the defined highway segment, where the rate experienced by a given vehicle i is set to 0 as soon as it reaches the end of the highway segment at d_i. The service amount can be written as

$$S_{i,m} = \delta_t \sum_{n=0}^{N} s_{i,m}^n, \forall i \in \mathcal{V}, \forall m, \tag{5}$$

$$\text{where:}\quad s_{i,m}^n = \begin{cases} r_{i,m}^n, & \text{if } a_i \le n \le d_i, \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

During its residence on the highway segment, vehicle i served by UAV m in time slot n receives rate $r_{i,m}^n = b_{i,m}^n \log_2(1 + P_{i,m}^n/\sigma^2)$, where σ^2 is the thermal noise power which is linearly proportional to the allocated bandwidth [9], and $b_{i,m}^n$ is the fraction of the spectrum resource allocated to vehicle i in time slot n from UAV m and it is equivalent to a number of resource blocks. In practice, we can allocate part of the spectrum for each vehicle, and hence $b_{i,m}^n$ is approximately continuous between 0 and 1.

III. PROBLEM FORMULATION

To mathematically formulate the problem[1], we introduce two binary decision variables: $\gamma_m \in \{0,1\}$, $\forall m$, that takes the value of 1 if UAV m is deployed and 0 otherwise, $y_{i,m}^n \in \{0,1\}$ indicates whether UAV m is serving vehicle i in time slot n. Thus, our optimization problem is formulated as:

$$\mathcal{OP}_1\!: \min_{\substack{\gamma_m, b_{i,m}^n,\\ x_m^n, y_{i,m}^n}} \sum_{m=1}^{M} \gamma_m$$

$$\begin{aligned}
\text{s.t.}\quad & \mathcal{C}1: \delta_t \sum_{m=1}^{M}\sum_{n=0}^{N} s_{i,m}^n \ge S_i^{\min}, \forall i \in \mathcal{V}, \\
& \mathcal{C}2: \gamma_m \in \{0,1\}, \forall m, \\
& \mathcal{C}3: y_{i,m}^n \in \{0,1\}, \forall m, i \in \mathcal{V}^n, \forall n, \\
& \mathcal{C}4: |x_m^n - w_i^n| \le R_c + (1 - y_{i,m}^n)K, \forall m, i \in \mathcal{V}^n, \forall n, \\
& \mathcal{C}5: \sum_{i=1}^{\mathcal{V}^n} b_{i,m}^n \le \gamma_m,\ \forall n, m, \\
& \mathcal{C}6: 0 \le b_{i,m}^n \le y_{i,m}^n,\ \forall m, i \in \mathcal{V}^n, \forall n, \\
& \mathcal{C}7: \sum_{m=1}^{M} y_{i,m}^n \le 1,\ \forall i \in \mathcal{V}^n, \forall n, \\
& \mathcal{C}8: x_m^0 = x_s, x_m^N = \gamma_m x_c + (1-\gamma_m)x_s, \forall m, \\
& \mathcal{C}9: |x_m^n - x_j^n| \ge \big(\gamma_m + \gamma_j - 1\big)d_{min}, \\
& \qquad\qquad \forall m, m \neq j, n = 2, ..., N-1. \\
& \mathcal{C}10: |x_m^{n+1} - x_m^n| \le \gamma_m V_{\max}\delta_t, n = 1, ..., N-1, \forall m.
\end{aligned}$$

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[1] For simplicity, consider one time frame, however, the optimization can be run iteratively to account for subsequent time frames.

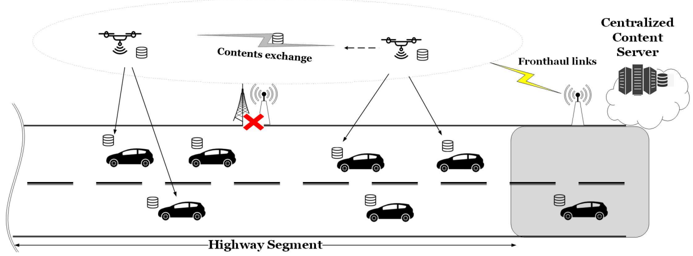


Fig. 1: A drive-thru scenario with multiple UAVs serving vehicles crossing a highway segment with damaged communication infrastructure. The shaded part of the highway marks the end of the previous segment that is covered by a RSU connected to a central unit.

Constraint $\mathcal{C}1$ guarantees that each vehicle downloads its requested amount of data $S_i^{\min}$ in (bits/Hz) within their residence on the highway segment. $\mathcal{C}3$ and $\mathcal{C}4$ ensure that vehicle i lies within the UAV communication range R_c projected on the ground, if it is served by the deployed UAV m, , where K is a large number that is used to ensure the validity of $\mathcal{C}4$. $\mathcal{C}5$ prevents wasting radio resources to UAVs that are not dispatched. $\mathcal{C}6$ ensures that the total allocated resources by one UAV is less than the available resource for every deployed UAV. $\mathcal{C}7$ ensures that one vehicle is served by at most one UAV at a time. $\mathcal{C}8$ indicates the initial and the final positions of the UAVs. $\mathcal{C}9$ guarantees that the deployed UAVs are sufficiently separated a minimum safety distance d_{min}.. Finally, $\mathcal{C}10$ limits the distance traveled by one UAV in one time slot based on its maximum speed.

There are several challenges to solve $\mathcal{OP}_1$ including the nonconvexity of $\mathcal{C}1$ with respect to UAVs' trajectories and the binary variables. Therefore, $\mathcal{OP}_1$ constitutes mixed-integer non-convex problem, which is difficult to be optimally solved.

IV. Proposed Solution

In this section, we attempt to efficiently solve our problem defined in $\mathcal{OP}_1$ based on convex approximation methods and multiple equivalent transformations to generate a more efficient but sub-optimal solution. The nonconvex constraint in $\mathcal{C}1$ is transformed into another equivalent convex constraint form and successive convex approximation, SCA, optimization method is applied to solve it iteratively. As mentioned earlier, the Problem $\mathcal{OP}_1$ is non-convex due to having $s_{i,m}^n$ as a function of the UAVs' trajectories and the resource allocation $b_{i,m}^n$ in $\mathcal{C}1$. To tackle the problem, we introduce slack variables $u_{i,m}^n \geq 0, \forall n, m, i \in \mathcal{V}$ and $t_{i,m}^n \geq 0, \forall n, m, i \in \mathcal{V}$, and rewrite $\mathcal{C}1$ as $\mathcal{C}1.1$, $\mathcal{C}1.2$, and $\mathcal{C}1.3$, where $u_{i,m}^n$ is lower bounded by a convex approximation approximation $\zeta_{i,m}^n$ with respect to $(w_i^n - x_m^n)^2$, where at each r^{th} iteration:

$$\zeta_{i,m}^n = F_{i,m}^{r,n} - G_{i,m}^{r,n}\Big((w_i^n - x_m^n)^2 - (w_i^n - x_m^{r,n})^2\Big),$$

$$F_{i,m}^{r,n} = \log_2\left(1 + \frac{Ph_0}{\sigma^2\Big(H^2 + (x_i^n - x_m^{r,n})^2\Big)}\right), \forall i \in \mathcal{V}^n, n,$$

$$G_{i,m}^{r,n} = \frac{(Ph_0/\sigma^2)\log_2 e}{\Big(H^2 + (x_i^n - x_m^{r,n})^2 + (Ph_0/\sigma^2)\Big)\Big(H^2 + (x_i^n - x_m^{r,n})^2\Big)}, \tag{8}$$

Next, we relax and rewrite the binary constraint in $\mathcal{C}3$ in the following equivalent form [10]:

$$y_{i,m}^n - (y_{i,m}^n)^2 \leq 0 \tag{9a}$$

$$0 \leq y_{i,m}^n \leq 1 \tag{9b}$$

Solving the approximated problem by applying the SCA method remains infeasible due to (9), which leads to a failed convergence of the SCA method. Inspired by the approach in [10], we overcome this issue by reformulating the objective function as presented in $\mathcal{OP}_2$:

$$\mathcal{OP}_2\!: \min_{\substack{\gamma_m, b_{i,m}^n, \\ x_m^n, u_{i,m}^n \geq 0, \\ , t_{i,m}^n \geq 0, \theta_{i,m}^n}} \sum_{m=1}^{M} \gamma_m + A \sum_{m}^{M} \sum_{n}^{N} \sum_{i \in \mathcal{V}} \theta_{i,m}^n$$

$$\begin{aligned}
\text{s.t.}\quad & \mathcal{C}1.1: \delta_t \sum_{m=1}^{M} \sum_{n=1}^{N} t_{i,m}^n \geq S_i^{\min},\ i \in \mathcal{V}, \\
& \mathcal{C}1.2: t_{i,m}^n \leq b_{i,m}^n u_{i,m}^n,\ \forall n, m, i \in \mathcal{V}, \\
& \mathcal{C}1.3: u_{i,m}^n \leq \zeta_{i,m}^n,\ \forall m, i \in \mathcal{V}^n, \forall n, \\
& \mathcal{C}3.1: y_{i,m}^n - (y_{i,m}^n)^2 \leq \theta_{i,m}^n,\ \forall m, i \in \mathcal{V}^n, \forall n, \\
& \mathcal{C}3.2: 0 \leq y_{i,m}^n \leq 1,\ \forall n, m, i \in \mathcal{V}, \\
& \mathcal{C}2\ , \mathcal{C}4\ , \mathcal{C}5\ , \mathcal{C}6\ , \mathcal{C}7\ , \mathcal{C}8\ , \mathcal{C}9, \mathcal{C}10\ .
\end{aligned}$$

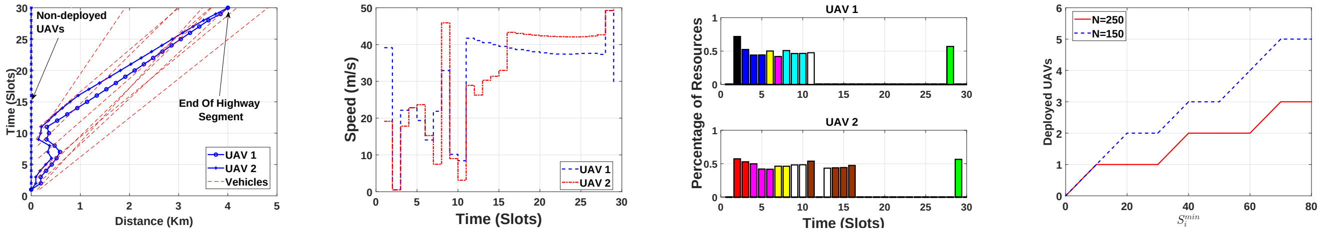
where $\{\theta_{i,m}^n \geq 0, \forall n, m, i \in \mathcal{V}\}$ is a new slack variable and $A \geq 0$ is the penalty parameter. Examining $\mathcal{C}1.2$, the non-convexity factor $b_i^n u_i^n$ is on the greater side of the inequality. To deal with this constraint, we simply replace the right hand side of $\mathcal{C}1.2$ by an equivalent difference-of-convex (DC) function $b_i^n u_i^n = \frac{1}{4}[(b_i^n + u_i^n)^2 - (b_i^n - u_i^n)^2]$, and linearize the concave term $(b_i^n + u_i^n)^2$ at iteration r. Hence, $\mathcal{C}1.2$ is approximated as

$$-\frac{(b_i^{r,n} + u_i^{r,n})^2}{4} - \frac{(b_i^{r,n} - u_i^{r,n})(b_i^n - b_i^{r,n} + u_i^n - u_i^{r,n})}{2} + \frac{(b_i^n - u_i^n)^2}{4} + t_i^n \leq 0. \tag{11}$$

Similarly, we approximate the non-convex constraint $\mathcal{C}3.1$ as $y_{i,m}^n - 2y_{i,m}^{r,n} y_{i,m}^n + y_{i,m}^{r,n} \leq \theta_{i,m}^n$. Using the above approximation, $\mathcal{OP}_2$ transforms into a Mixed Integer Quadratically Constrained Program (MIQCP) making several linear programming (LP) methods handy including CVX-MOSEK toolbox [11]. The algorithm proceeds until the number of UAVs converges. The overall complexity of solving $\mathcal{OP}_2$ depends on the solver that is employed to solve $\mathcal{OP}_2$. In particular, $\mathcal{OP}_2$ is a MIQCP and, thus, several interior-point solvers can be employed to solve it. Therefore, we can employ the number of Newton steps, as a metric to measure its complexity. Therefore, the overall complexity of solving $\mathcal{OP}_2$ is approximately $I\sqrt{M(4NV + N + 1)}$ in the worst-case, where I is a finite number of iterations.

V. Simulation And Numerical Analysis

In order to deliver realistic results, the simulation parameters should be an accurate representation of a real highway scenario. We assume a highway segment of length 4km in which multiple UAVs are dispatched with safety distance $d_{min} =$ 100m with communication range $R_c = 50$m to provide streaming services to vehicles. The flow of vehicles entering the highway segment follows Poisson distribution with arrival rate 0.5veh/s. Vehicles velocities are randomly generated using a truncated Gaussian distribution with mean equal 90km/h, variance 16km/h, and velocities can be varied between 20–140km/h. The channel power gain has been taken equal to $|h|^2 = -50$dB, noise power is $N_o = -110$dBm. We consider UAVs fly at a constant altitude $H = 100$m, with transmit



(a) UAVs trajectories (b) UAVs speeds (c) Resource allocation (d) Impact of $S_i^{\min}$

Fig. 2: Optimizing the UAVs' trajectories and radio allocation.

power $P = 0.1$W, and maximum speed $V_{\max} = 50$m/s.

The CVX toolbox and numerical convex optimization solver MOSEK are used to solve our optimization. Without loss of generality, we assume that, at time $n = 0$, all UAVs are located at position $x_s = 0$m and the final location of deployed UAVs is the end the highway segment $x_c = 4$km. Fig. 2(a) depicts the UAVs trajectories to provide services to vehicles (for $\mathcal{V} = 9$ vehicles with $S_i^{\min} = 30$bits/Hz) over a period $N = 30$ time slots. Each time slot is of length 5s. The vehicles enter the highway segment at different times as depicted in the figure. It also shows that only 2 UAVs are needed to fulfill the requirements of all vehicles within the considered time period.

Due to the flexibility of UAVs (rotary-wing UAVs), Fig. 2(a) also shows that the UAVs start their trajectories by following the first batch of arriving vehicle(s) then move to follow the second subsequent batch and so on. Fig. 2(b) presents the change in speed of both UAVs to allow them follow the batch of vehicles they are serving then. Examining (a) and (b) of Fig. 2, one notes that both UAVs fly at a very high speed to reach the end of the highway segment and serve vehicles before they depart and before the mission time is over. We also observe that, while a UAV decreases its speed to follow a batch of vehicles, the second UAV dramatically drops its speed to maintain the safety distance d_{min}.

Fig. 2(c), demonstrates that at each time slot n the UAVs allocate the radio resources unequally among the vehicles depending on their arriving times and current locations. In this figure, resources allocated to different vehicles are marked in different colors. Fig. 2(c) also shows that the same vehicle may be served by both UAVs but each in a different time slot. It can be also seen that, due to dynamics of vehicles, the UAVs may not be able to allocate its resources continuously and have to serve some vehicles toward the end of the highway segment.

Clearly, 2 UAVs may not able to meet the vehicles' requirements for all service rates. Next, we study the impact of the minimum service amount S_i^{min} on the proposed solution over different mission time (in time slots). As shown in Fig. 2(d), with the lower service amount, optimizing the radio resources is sufficient to fulfill the vehicles' requirements with one or 2 UAVs. With increasing the minimum service amount, 2 UAVs cannot anymore fulfill to fully serve the vehicles through optimizing their radio resources. Increasing the number of deployed UAVs and optimizing their trajectories to fly closer to vehicles become more crucial for achieving better communication channels to increase the transmission rate and achieve larger service amount. As a result, the required number of UAVs increases by increasing the required service amount while keeping the other system parameters intact including fixed mission time and radio resources per each UAV. Fig. 2(d) also demonstrates that a larger mission time allows fewer number of UAVs to fully serve all vehicles. If the required service amount is 40 bits/Hz, only 2 UAVs are needed when the mission time is 250 time slots while 3 UAVs will be required if the mission time drops to 150 time slots.

VI. CONCLUSION

This letter studied the trajectories of multiple UAVs to serve vehicles in a mobility environment. Since vehicles have different requirements within their residence on the highway segment, the UAVs trajectories and radio resource allocation are optimized to provide vehicles with a differentiated amount of data. We formulated our optimization problem to minimize the number of UAVs while guaranteeing service to all vehicles before exiting the highway segment. Resulting in a non-convex problem, we proposed a low-complexity solution and examined its behavior to fulfill the requirement of all vehicles.

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