UAV-assisted Data Dissemination With Proactive Caching and File Sharing in V2X Networks

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***Abstract*—Vehicle-to-Everything (V2X) communications refers to an intelligent and connected vehicular network where all vehicles and infrastructure systems are interconnected with each other. Data dissemination is playing an increasingly significant role in enhancing the network connectivity and data transmission performance. However, conventional scenarios and protocols cannot satisfy the growing pluralistic and superior quality of services (QoS) requirements of included vehicles. Therefore, in this paper, we propose a novel unmanned aerial vehicle (UAV)-assisted data dissemination protocol with proactive caching at the vehicles and an advanced file sharing strategy for revolutionizing communications. Specifically, in the proactive caching phase, we employ UAVs to act as flying base stations (BSs) for information interactions. Considering the time-variant network topology, we further propose a spatial scheduling (SS) algorithm for the trajectory optimization of each UAV, which can expedite the caching process and boost the system throughput. Then in the file sharing phase, based on the previous caching status, we provide a relay ordering algorithm to enhance the network transmission performance. Numerical results verify that our proposed UAV-assisted data transmission protocol can achieve a desirable system performance in terms of the downloading process, network throughput, and average data delivery delay.**

I. Introduction

In recent years, Vehicle-to-Everything (V2X) communications becomes one of the most prevailing research fields, which is regarded as the cornerstone of modern intelligent transportation systems (ITS) [1]. By exploiting vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), and vehicle-to- base-station (V2B) communication links, it is envisioned that, for drivers and passengers, ITS can make a revolutionary promotion in the quality of experience (QoE) under various applications, including safety protection, infotainment, and intelligent navigation [2]. In terms of the quality of services (QoS) of users, data dissemination has been widely investigated to increase the system performance along with the diminution of transmission connectivity and duration [3].

In conventional scenarios of vehicular networks, vehicles rely principally on V2V, V2I, and V2B communication links for information interactions, such as local weather, traffic congestion and commercial advertisement [2]–[4]. However, when the vehicles are out of the effective coverage of RSUs/BSs, it is difficult to maintain the required QoS with merely V2V communication links used for data transmissions due to the rapid change of the network topology.

Due to the swift deployment and flexible mobility of unmanned aerial vehicles (UAVs), UAV-assisted wireless communications have been emerging as a fascinating technology with plenty of applications, such as data collection and dissemination, emergency response, and terrestrial BS offloading [5]–[7]. Besides, the reliable line-of-sight (LoS) air-to-ground (A2G) communication links between the UAVs and ground users can provide enhanced wireless coverage and connectivity [8], and thus further promote the efficiency of data dissemination in V2X networks. Despite there exists quite a few aforementioned advantages by introducing UAVs, insufficient battery energy restricts the sustained wireless services for UAV-assisted communications.

Therefore, the proactive caching technique has recently been opened up to prevent performance degradation caused by the limited task duration of UAVs [9]. Endowed with capabilities in storage, context awareness, and social networking, vehicles are capable of pre-loading the popular contents within off-peak hours and caching them to wait for potential utilization [10]. In V2X networks, proactive caching is becoming a promising approach to resolve the problem of backhaul congestion and mitigate the redundant traffic load, which can be applied to cope with the endurance issue for UAV-assisted data dissemination systems [11].

In this paper, we propose an efficient UAV-assisted data dissemination protocol, containing two successive transmission phases, namely proactive caching and file sharing. In the proactive caching phase, we deploy UAVs as flying BSs to orderly broadcast requested data files to the included vehicles for caching. To expedite the file caching process and improve the network throughput, we further propose a spatial scheduling (SS) algorithm to optimize the trajectories of UAVs. Then in the file sharing phase, the vehicles share their cached files with one another through V2V communication links. Moreover, we provide a relay ordering algorithm, which chooses the optimal relay nodes with maximum transmission utilities at each time slot to improve the efficiency of file sharing. Numerical results demonstrate that, our proposed UAV-assisted data dissemination protocol can effectively achieve a significant improved system performance in terms of caching process, network throughput, and average file delay.

The rest of this paper is organized as follows. Section

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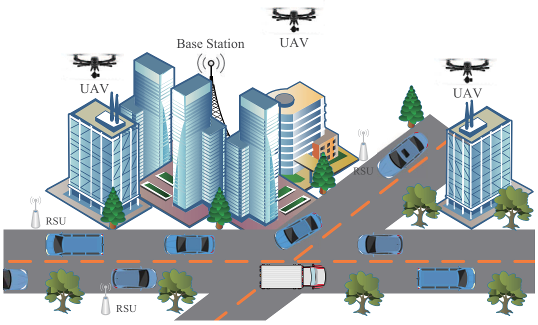

Fig. 1. UAV-assisted data dissemination in V2X networks.

II introduces the investigated system model and formulates the included proactive caching and file sharing problems. In Section III, the UAV-assisted data dissemination protocol is proposed. Section IV presents the numerical results, and finally we conclude this paper in Section V.

II. System Model

As shown in Fig. 1, we consider a data dissemination model in urban VANETs circumstance, where the V2B communication links are blocked by ubiquitous buildings and skyscrapers. Although S RSUs are located at the roadside, they cannot provide satisfactory wireless services because of limited size and coverage. Therefore, we dispatch U UAVs as flying BSs with caching capability to serve K vehicles to guarantee substantial wireless QoS demands. Suppose every vehicle and UAV is equipped with a global positioning system (GPS), thus their real-time state information, such as locations, directions and velocities can be obtained by a control server (CS), which is linked with all the RSUs through high-speed optical cables for centralized scheduling. In our system, the CS periodically disposes of the collected state information, then executes the process of data dissemination during the following two successive transmission phases: proactive caching and file sharing.

A. Phase 1: Proactive Caching

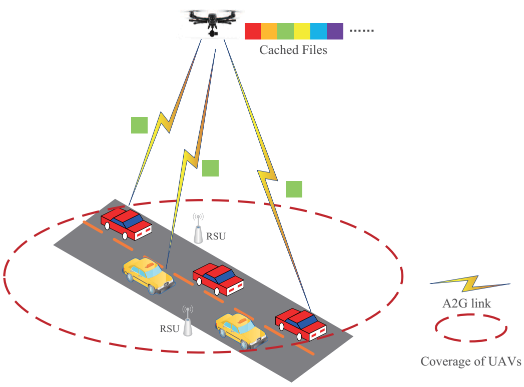

Fig. 2. Proactive caching phase.

The phase of proactive caching begins at each operation period where the UAV selects a subset of K vehicles to pre-loading the whole N files. In Fig. 2, each file distinguished by different colors is orderly cached at the UAV. Hence we assume that the UAV broadcasts each file in the same order during the proactive caching phase until all the N files are successfully cached by vehicles.

Considering each vehicle has its unique interest in N files, which brings about diverse popularities of different files. For simplicity, suppose each file has identical attraction to all vehicles, thus we introduce Zipf distribution to represent the diverse popularities of N files:

$$P_F\left(n\right) = \frac{1/n^{\varsigma}}{\sum\limits_{n=1}^{N} 1/n^{\varsigma}}, \quad n = 1, ..., N \tag{1}$$

where $P_F\left(n\right)$ denotes the popularity of file F_n and ς is the skewness of Zipf distribution whose usual range of value is in $[0.5, 1.5]$ [12]. For the special case, when $\varsigma = 0$, all the N files have equal popularity.

According to [13], A2G channel model consists of two components, line-of-sight (LoS) and non-line-of-sight (NLoS) communication links. From this literature, the occurrence probability of LoS links is

$$P_{Los} = \frac{1}{1 + a\exp\left[-b\left(\theta - a\right)\right]} \tag{2}$$

where a and b refer to S-curve coefficients, and θ denotes elevation angel. Besides, η_{LoS} and η_{NLoS} denote environmental parameters, $d_{u,k}$ is the distance between the uth UAV and kth vehicle. Hence, the path loss $L_{u,k}$ can be expressed as

$$L_{u,k} = P_{Los} \cdot A + 10\log\left\|d_{u,k}\right\|^2 + B \tag{3}$$

where $A = \eta_{LoS} - \eta_{NLoS}$, $B = 20\log f + 20\log\left(4\pi/v_l\right) + \eta_{NLoS}$, f denotes carrier frequency and v_l represents the speed of light.

B. Phase 2: File Sharing

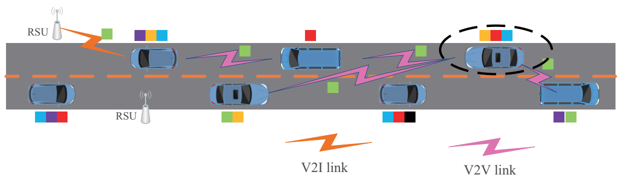

Fig. 3. File sharing phase.

When all the N files are successfully cached by vehicles, the system converts to file sharing phase, where the UAV is recalled for battery charging. In Fig. 3, the vehicle sends a request for sharing the file which is not cached in its store. Therefore, other nodes begin to share this file to the target vehicle, either acting as data resources or relays. Note that RSUs have the same N files and thus can also transmit this file to a vehicle inside its coverage for reception or relay.

To avoid interference and collision problems, we assume there is only one file allowed to be shared during each file sharing cycle until the file has been successfully received by

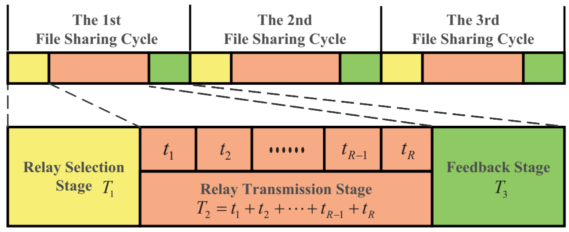

Fig. 4. Three stages of the file sharing cycle.

the target vehicle. Shown in Fig. 4, each file sharing cycle has three stages which are briefly described as follows.

1) Relay Selection Stage T_1: Based on the collected real-time state information of vehicles, the CS selects a group of appropriate relay sets $\{\Omega_1, ..., \Omega_r, ..., \Omega_R\}$ with corresponding R transmission frames $\{t_1, ..., t_r, ..., t_R\}$ to make the scheduling decision of file sharing.

2) Relay transmission Stage T_2: According to the scheduling results in former stage, vehicles and RSUs cooperatively disseminate the file from transmission frame t_1 to t_R.

3) Feedback Stage T_3: When a file request has been accomplished, each vehicle updates its current state information to the CS and waits for scheduling in the next file sharing cycle.

III. UAV-assisted Data Dissemination Scheduling Protocol

In this section, we propose a novel UAV-assisted data dissemination protocol for the sake of reducing the data transmission latency. Accordingly, we design a proactive caching policy coordinated with the UAV trajectory optimization and provide a file sharing strategy with an efficient relay order algorithm.

A. Proactive Caching Policy

For the first transmission phase, each file is considered to have equal size, which is denoted by X in bits. To mitigate the error probability during proactive caching phase, we apply the random linear code for each file which is partitioned into $Y^* = X/S_P$ packets, where S_P denotes the size of each packet. Hence with any $Y = (1+\varepsilon)Y^*$ coded packets, a file can be absolutely recovered where $\varepsilon \ll 1$ represents the coding overhead [11].

Before the UAV begins to broadcast the packet Y_y of file F_n, the CS calculates initial transmission distance $d_{u,k}^y(n)$ and then selects a subset of K vehicles that are authorized to cache file F_n. Under the consideration of valid transmission, there are three restrictions in our designed caching policy.

1) UAV Coverage: Due to the existence of elevation angel which is assumed to be fixed, the distance between UAVs and vehicles cannot exceed the critical distance, which is

$$d_{u,k}^y(n) \le d_{eff} \tag{4}$$

where $d_{eff} = h/\cos\theta$ and h is the height of UAVs.

2) Vehicular Storage: Unlike the UAVs which have sufficient memories for caching N files, the vehicles, however, are limited by maximal storage capability C. We define $\beta_{k,n}$ as the status of proactive caching, which can be denoted as

$$\beta_{k,n} = \begin{cases} 1, & \text{file } F_n \text{ is cached at vehicle } k \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

Therefore, the total number of files cached at vehicle k should satisfy the following inequality

$$\sum_{n=1}^{N} \beta_{k,n} \le C, \quad k = 1, ..., K \tag{6}$$

Besides, to ensure non-zero file sharing probability of unpopular files in the next data dissemination phase, we have

$$\sum_{k=1}^{K} \beta_{k,n} \ge 1, \quad n = 1, ..., N \tag{7}$$

3) Reception Quality: Whether the packets are successfully cached by vehicles is determined by the received signal-to-noise ratio (SNR), which is given by

$$\gamma_{u,k}^y = \frac{P_u L_{u,k}}{W_k N_0}, \quad y = 1, ..., Y \tag{8}$$

where P_u is the transmit power of UAVs, W_k denotes the A2G channel bandwidth allocated to vehicle k, and N_0 is the addictive Gaussian noise power spectral density.

For assuring valid reception, we set up Γ to represent the SNR gap among the practical modulation, coding scheme and theoretical Gaussian signaling. Hence, the SNR threshold for effective reception can be expressed as $\gamma_{th} = \left(2^{R_U/B_U} - 1\right)\Gamma$, where R_U and B_U respectively denotes the UAV transmission rate and A2G channel bandwidth. As a result, the valid reception of each packet in file n can be expressed as

$$\rho_{u,k}^y(n) = \begin{cases} 1, & \gamma_{u,k}^y \ge \gamma_{th} \\ 0, & \text{otherwise} \end{cases} \tag{9}$$

Once the CS selects a group of vehicles that satisfy the aforementioned restrictions, the UAV is allowed to orderly broadcast each packet in a file. Consequently, the total transmission time for proactive caching can be formulated as

$$T = \frac{K}{U} \sum_{u=1}^{U} \sum_{n=1}^{N} \sum_{y=1}^{Y} \sum_{k=1}^{K} P_F(n) \rho_{u,k}^y(n) t_p \tag{10}$$

where $t_p = S_P/R_U$ denotes the duration of accomplishing one packet transmission.

To boost system throughput and accelerate caching process, $\sum_{y=1}^{Y} \rho_{u,k}^y$ can be optimized and thus we propose a spatial scheduling (SS) algorithm for the trajectory planning of UAVs.

TABLE I
SPATIAL SCHEDULING ALGORITHM

Initialize the state information of each node, the valid reception $\rho_{i,q}^{k}=0$ at vehicle k and the z-axis coordinate of UAV $z_{i,q}=0$
1. **Assign** $q=1$. 2. **While** $q\leq Q$ 3. Calculate d_{eff}, $\beta_{k,n}$, $\gamma_{u,k}^{y}$ and $\rho_{u,k}^{y}(n)$. 4. Detect all of the section i and reachable location j for i. 5. Execute $\sum_{k_1=1}^{K}\rho_{j,q+1}^{k_1}=\sum_{k_2=1}^{K}\rho_{i,q}^{k_2}+\Lambda$. 6. Select location j with maximum sum of valid reception. 7. Update coordinate $(x_{j,q+1},y_{j,q+1},z_{j,q+1})$ to replace section i. 8. Renew $q=q+1$. 9. **End While** 10. **Output** $\sum_{k=1}^{K}\rho_{i,q}^{k}$ for each packet.

B. Spatial Scheduling Algorithm

Suppose the CS distributes Q three-dimensional coordinate points for UAVs during the procedure of packets transmission. Namely, the CS splits ideal caching time Yt_p into Q moving sections, each of which has the duration Yt_p/Q. In section q, $q\in\{1,...,Q\}$, the UAV has a maximum horizontal velocity v_u and vertical velocity v_h, along with its azimuth α and spatial coordinate (x_q,y_q,z_q), hence we have

$$\begin{cases}(x_{j+1}-x_j)^2+(y_{j+1}-y_j)^2\leq(v_uYt_p/Q)^2\\ |z_{j+1}-z_j|\leq v_hYt_p/Q\end{cases}\tag{11}$$

Note that if the two sections i and j meet the above inequality, we define that j is reachable from i. Moreover, consider the maximum navigation distance of UAVs, we uniformly disperse the distance into $2M+1$ integer values both in horizontal plane and z-axis, with corresponding intervals $\Delta_{xy}=v_uYt_p/MQ$ and $\Delta_z=v_hYt_p/MQ$. As a result, the relationship between two contiguous moving sections is

$$\begin{cases}x_{q+1}-x_q=m\Delta_{xy}\cos\alpha\\ y_{q+1}-y_q=m\Delta_{xy}\sin\alpha\ , \quad m\in\{-M,M\}\\ z_{q+1}-z_q=m\Delta_z\end{cases}\tag{12}$$

The procedure of SS algorithm is illustrated in Table I, where Λ denotes the incremental number of vehicles that satisfy the restrictions of proactive caching policy when the UAV moves from i to j, $\sum_{k=1}^{K}\rho_{i,q}^{k}$ is the maximum sum of reception qualities of all trajectories that the UAV can reach point i in the qth section.

C. File Sharing Strategy

When the last file has been successfully cached by vehicles, UAVs are removed for energy supplement. Therefore, there only exists V2V and V2I communication links in the file sharing phase. According to Fig. 4, the CS chooses R subsets of K vehicles acting as relay nodes in T_1 and then orderly transmit file F_n which is divided into G packets in T_2.

Assume R_{n_x}, which might be a vehicle or a RSU, is the candidate relay node, while R_{n_y} denotes a corresponding reception node which is either a demander or another relay node. When transmitting packet g in t_{r-1}, $\psi_{n_x}^{r-1,g}$ represents the decoding status of R_{n_x}. For $r=1$, $\psi_{n_x}^{0,g}$ equals to the initial decoding status at the beginning of file sharing cycle, while for $r=2,3,...,R$, $\psi_{n_x}^{r-1,g}$ relies on the relay set Ω_{r-1}.

TABLE II
RELAY ORDERING ALGORITHM

Initialize the optimal relay scheduling set $\Re=\{(n_x,g)\vert n_x\in S+K,g\in G\}$ and $\Theta_r=\emptyset$
While executed 1. Remove (n_x,g) with the largest $\Phi_{n_x}^{r,g}$ from $\Re$. 2. Add (n_x,g) to the optimal scheduling relay set Θ_r. 3. Delete all of (n_z,g) in which $n_z\in\mathcal{N}_{n_x}^{r}$ from $\Re$. 4. Eliminate all of (n_z,g) in which $\mathcal{N}_{n_x}^{r}\cap\mathcal{N}_{n_z}^{r}\neq\emptyset$ from $\Re$. **Until** $\Re=\emptyset$.

Consequently, in t_r, the CS dispatches the entire network nodes with the proposed file sharing strategy which is presented as follows.

1) Path loss Channel Model: Due to the duration of each transmission frame t_r is relatively transient, we consider the channel characteristics remain approximately stationary. As a result, the path loss channel model for V2I and V2V communication links in t_r can be simulated as

$$L_{n_x,n_y}^{r}=20\log_{10}\left|d_{n_x,n_y}^{r}\right|^2+10\log_{10}|f|^2-10\log_{10}\left|h_{R_{n_x}}h_{R_{n_y}}\right|^2\tag{13}$$

where $h_{R_{n_x}}$ and $h_{R_{n_y}}$ represent the height of R_{n_x} and R_{n_y}, respectively.

2) SNR Calculation: Similarly, we also calculate the received SNR to evaluate whether the packet transmission is efficacious in t_r, which is expressed by

$$\lambda_{n_x,n_y}^{r}=\frac{P_{n_x}L_{n_x,n_y}^{r}}{WN_0}\tag{14}$$

where P_{n_x} is the transmitted power of R_{n_x} and W denotes the available bandwidth for V2I and V2V communication links.

3) Decoding Status Decision: After receiving the packet relayed by R_{n_x}, the decoding status to decode packet g at R_{n_y} is given by

$$\psi_{n_x,n_y}^{r,g}=\begin{cases}1, & \lambda_{n_x,n_y}^{r}\geq\lambda_{th}\\ 0, & \lambda_{n_x,n_y}^{r}<\lambda_{th}\end{cases}\tag{15}$$

where λ_{th} denotes the successful decoding threshold.

4) Utility Computation: Based on aforementioned contents, the utility of relaying packet g at node R_{n_x} in t_r can be represented as

$$\Phi_{n_x}^{r,g}=\sum_{n_y=1,R_{n_y}\in\mathcal{N}_{n_x}^{r}}^{S+K}\left(\psi_{n_x,n_y}^{r,g}-\psi_{n_x,n_y}^{r-1,g}\right)\tag{16}$$

where $\mathcal{N}_{n_x}^{r}$ denotes the neighboring node set of R_{n_x}.

5) Relay Ordering: Denote the optimal relay scheduling set in t_r as $\Theta_r=\{(n_{x1},g_1),(n_{x2},g_2),...,(n_{xr},g_r)\}$, where $\{n_{x1},n_{x2},...,n_{xr}\}$ is the selected relay nodes and $\{g_1,g_2,...g_r\}$ represents the packets need to be transmitted. Hence, the problem aiming to achieve the largest transmission

TABLE III
SIMULATION PARAMETERS

Parameters	Settings
Number of vehicles K	100
Transmission power of vehicles P_v	20dBm
Transmission rate of vehicles R_V	50kb/s
V2I and V2V channel bandwidth W	100kHz
Velocity of vehicles	$[24, 72]$km/h randomly
Number of UAVs U	4
Transmission power of UAVs P_u	10dBm
Transmission rate of UAVs R_U	100kb/s
A2G channel bandwidth B_U	100kHz
Initialized height of UAVs h	100m
Maximum speed of UAVs v_u	15m/s
A2G path loss model	$a = 20$, $b = 0.3$, $\eta_{LoS} = 1$, $\eta_{NLoS} = 20$ [13] α=θ= 30°
Number of RSUs S	4
Transmission power of RSUs P_u	30dBm
Transmission rate of RSUs R_U	200kb/s
Number of files N	20
Maximal storage capability C	3
File size X	500kbits
Packet size S_P	2kbits
SNR gap Γ	8dB [11]
SNR threshold λ_{th}	3dB [14]
Carrier frequency f	5.9GHz
Packet number G	1000
Number of discrete sampling M	100
Height of ground nodes	RSU:8m Vehicles:1m
Duration of T_1 and T_3	100ms
Number of transmission frame R	100

utility can be formulated as

$$\Theta_r = \arg\max_{\Theta_r} \sum_{\forall (n_x, g) \subseteq \Theta_r} \Phi_{n_x}^{r,g} \tag{17}$$

Shown in Table II, we utilize a relay ordering algorithm to solve equation (17). Note that a node cannot simultaneously transmit and receive a packet, the CS would delete the adjacent nodes of R_{n_x}. Moreover, to alleviate interference, the nodes that share the same neighboring nodes with R_{n_x} would also been eliminated.

6) Decoding Status Updating: After the accomplishment of transmitting a frame t_r, the vehicles update their decoding status for next transmission frame.

IV. NUMERICAL RESULTS

In this section, we investigate the system performance in terms of downloading caching process, network throughput and average file delay under the circumstance of urban scenario which includes four RSUs located in a 2km×2km area with three north-south and east-west oriented roads. The set up of related simulation parameters is given in Table III.

A. Downloading Caching Process

Fig. 5 illustrates the caching process of N files for all vehicles during the proactive caching data dissemination phase. Without the employment of UAVs (non-UAV), the duration for caching all files is the longest which demonstrates from the side that UAV-enabled communication system can effectively expedite the data dissemination process and thus decrease the caching time. Besides, by exploiting different UAV trajectory scheduling algorithms, such as proposed SS algorithm and the maximum vehicle coverage (MVC) algorithm [15], it is

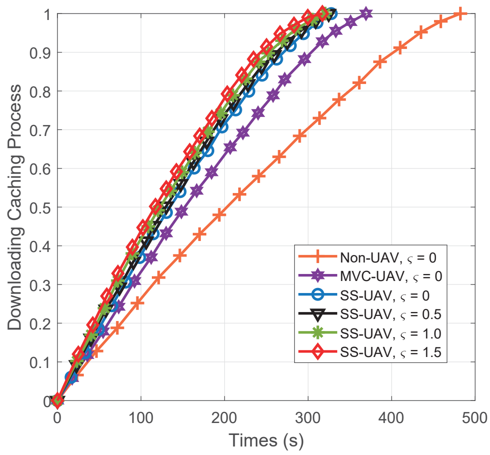

Fig. 5. The downloading caching process of all files.

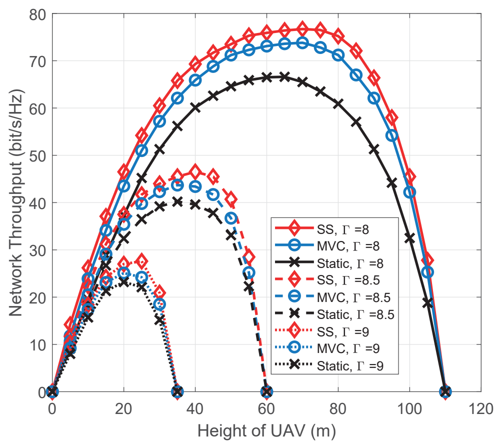

Fig. 6. Network throughput versus height of UAV.

clear that the performance of SS algorithm is superior to the MVC algorithm, since it can achieve more valid receptions by means of three-dimensional spatial scheduling. Moreover, we adjust the skewness of Zipf distribution ς to investigate whether the diverse popularities of files lead to the different caching times. According to our simulations, we find that the value of ς nearly fails to enhance the whole caching time of N files, but can contribute to a separate one. For the reason that prevailing files can attract more vehicles which results in various packets transmission success rates, the caching time of each file is in direct proportional to its popularity.

B. Network Throughput

In Fig. 6, with $\varsigma = 0$, we investigate the relationship between network throughput and UAV height during the proactive caching phase in comparison of different UAV trajectory scheduling algorithms and SNR gaps Γ. Regardless of the value of Γ, the network throughput becomes lowest when the UAV keeps static in the same height. What's more, compared with the MVC algorithm, the simulation results prove the superiority of proposed SS algorithm again.

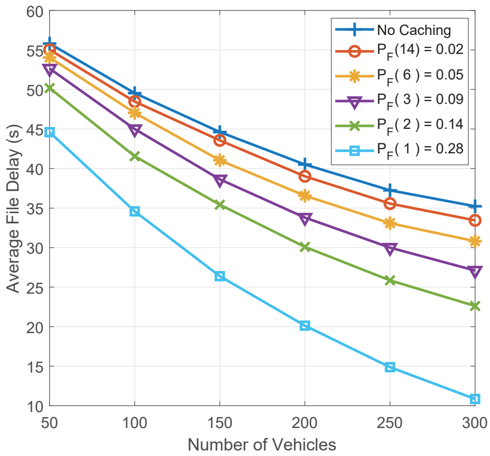

Fig. 7. Average file delay in file sharing phase.

In addition, there is an obvious trade-off between network throughput and UAV height. When the UAV flies higher, its coverage is synchronously expanded that could serve more vehicles and thus raise the network throughput. However, once the received SNR is below the threshold γ_{th}, valid transmission decreases and thus causes the attenuation of network throughput.

C. Average File Delay

We choose F_1, F_2, F_3, F_6, and F_{14} with their corresponding file popularities to depict the relationship between average file delay and number of vehicles during the file sharing data dissemination phase, which is clearly shown in Fig. 7 with $\varsigma = 1$. Apparently, without exploiting the proactive caching policy (No Caching), the network has always demonstrated the highest average file delay. On the contrary, no matter how popular the file is, proactive caching can effectively reduce the average file delay in varying degrees. As expected, the file with higher popularity is generally cached by more vehicles so that it can be shared with lower transmission latency. Besides, the decrement of average file delay is gradually slackened when the number of vehicles increases, that's because the mechanism of proposed relay selection algorithm with the elimination of adjacent transmission nodes.

V. Conclusion

In this paper, by employing the proactive caching policy and the file sharing strategy, we proposed a novel UAV-assisted data dissemination protocol for V2X networks. To expedite the caching process and improve network throughput, we introduced the UAVs to ensure proactive caching and proposed the SS algorithm to optimize the trajectories of UAVs. Moreover, relying on the previous caching status, we further provided a file sharing strategy with a relay ordering algorithm to maximize transmission utilities and thus reduce file delivery latency. Simulation results have verified our proposed UAV-assisted data dissemination protocol can effectively achieve a significant reduction in data transmission lantency and an obvious improvement in network throughput.

Acknowledgement

This work was in part supported by the Ministry National Key Research and Development Project under Grant 2017YFE0121400, the National Science and Technology Major Project under Grant 2018ZX03001031, the Major Project from Beijing Municipal Science and Technology Commission under Grant Z181100003218007, Shenzhen Fundamental Research Fund under Grant No. JCYJ20170411102217994 and Guangdong province under grant No. 2017ZT07X152, the National Natural Science Foundation of China under Grants 61622101 and 61571020, and the National Science Foundation under Grant CPS-1932413 and ECCS-1935915.

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