Geolocation-based UAV-assisted Caching Strategies in Vehicular Networks

*Ting Gong, Qi Zhu**

Engineering Research Center of Health Service System Based on Ubiquitous Wireless Networks,
Nanjing University of Posts and Telecommunications, China
18844228931.@163.cn, zhuqi@njupt.edu.cn

Abstract

In this paper, a geolocation-based UAV-assisted caching strategy is proposed to address the problem of large communication load of vehicular network in cities and extended time spent by vehicle users to request services. In Ad hoc Network (VANET), vehicle users may request content that is valid only in their location, such as maps, or content that is not related to geographic location, such as news. Based on this feature, we divide the content into local content and common content, let mobile vehicle users and UAVs cache only common content, and location-fixed roadside units (RSUs) cache local content and common content proportionally. Then we design a detailed content delivery method and analyze the content request latency of the vehicular network over a period of time, and establish an optimization problem for minimizing the average request latency. A joint optimization algorithm for UAV trajectory and node caching decision is designed to solve this problem. First, optimizing the proportion of common content cached by RSU through exhaustive method, then deciding the caching decision of each RSU and UAV through preference-based exchange collaborative caching algorithm, and finally using Greedy algorithm-based trajectory optimization algorithm to further optimize UAV trajectory. Simulation results show that this strategy outperforms existing common caching strategies.

Keywords: Vehicular network, Cache technology, UAV, Request delay, Request success rate

1 Introduction

With the increase in vehicle usage, people's demand for vehicle traffic is growing day by day. Applications such as intelligent transportation, self-driving, road safety and in vehicle entertainment are also gradually attracting people's attention [1]. Vehicles need to communicate with each other to exchange information to obtain a better driving experience, such as road safety information and entertainment information. Therefore, VANET has emerged in people's lives, and some studies have been carried out and achieved results [2-3]. However, vehicle users in the vehicular network have the characteristics of high-speed mobility, which makes the network topology change rapidly and vehicular communication links unstable. Therefore, people use caching technology in the vehicular network to improve service quality and reduce network load.

The caching technology in the vehicular network is to cache content at the edge nodes of the network, which allows vehicle users to access the content they need directly from surrounding nodes, thus effectively reducing the communication distance to request content from vehicle users and reducing the traffic load on content servers and networks. The Leave Copy Everywhere (LCE) strategy proposed in [4] refers to that the content will be cached when passing through each network node. The Caching with Probability strategy proposed in [5] refers to that the network node will cache the content passing through the node with a fixed probability. The next hop caching strategy (LCD) proposed in literature [6] is to cache content in the next node of the content source node. The probabilistic caching strategy proposed in [7] calculates the corresponding caching probability through the popularity of the content, the distance between the content source node and the user, and the load of the content source node. [8] divides vehicles into partners and couriers based on lane information and social relationships between vehicles, in which partners can cache some content, and couriers can deliver content to requesting vehicles, thereby improving service quality. [9] caches content on RSUs instead of vehicles and designs a content prefetching mechanism based on mobility prediction to reduce the time delay required for vehicle users to obtain content. However, the above studies only considered the caching decision of edge nodes, ignoring the influence of geographical location on caching strategy. The authors of [10] identify and formulate the problem of maximizing the average cache hit rate considering the time-varying topology of the network, vehicle mobility, user preferences, and the limited cache capacity of the RSU. And a cache update policy based on learning automata is designed to determine the appropriate content to be cached in the RSU.

The content requested by vehicle users is often related to their geographical location, and each road segment has its own unique content, so the influence of geographical factors should be considered when designing caching policies. The authors of [11] considered the vehicle's request for location-based content and popular content, respectively analyzed the delay and energy consumption of these two requests, and designed the corresponding caching strategy. [12] applies historical vehicle movement trajectory data to train an implicit Markov model to obtain the probability of vehicles

*Corresponding Author: Qi Zhu; E-mail: zhuqi@njupt.edu.cn
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passing through hotspot areas. Based on this, caching vehicles are selected based on their social similarity and forwarding capability, and the contents are cached in these caching vehicles, thus reducing the request delay of vehicle users. The authors of [13] designed a cache placement policy based on hotspot areas. This caching scheme considers geographic features and user request patterns in the cache layout decision process and can effectively provide location-sensitive data to users. The authors of [14] analyzed the location relationship between nodes and vehicle users, and designed a corresponding active caching strategy, which is to let the vehicle cache the content that may be needed later. The above studies consider the effect of geographic location on caching strategies, but none of them utilize aerial caching devices for assistance, such as UAV.

Because UAVs are mobile, they are commonly used in ground and marine scenarios [15]. Introducing UAVs with caching capabilities into in-vehicle networks can have the effect of enhancing the stability of the communication link and solving the problem of short contact times between vehicle users and caching nodes with fixed locations on the ground. The authors of [16] designed a clustering-based two-layer algorithm to maximize system throughput. A time-based graph decomposition method is designed to optimize content delivery decisions and UAV's flight trajectory, and then a particle swarm optimization algorithm is used to optimize content caching decisions. In [17], UAVs dispatched by airships provide services to vehicle users. The author uses deep Q-learning to solve the problem, which is to train according to the historical request records of vehicle users, so as to improve the cache hit rate. According to factors such as file popularity, node cache capacity, and user request frequency, the authors of [18] designed an energy-aware encoding caching strategy, in which geosynchronous orbit satellites and UAVs are used as cloud servers and edge cache servers respectively. In [19], the UAV is regarded as a relay, forwarding content to the vehicle user. Vehicle users are grouped into clusters using fast global K-means, and communication between clusters is performed via UAVs, thus minimizing delay. The authors of [20] consider two complementary schemes for utilizing uplink resources when cellular downlink resources are insufficient: one is to allow vehicles to cache browsed content so that content can be shared among vehicles, and the other is to dispatch a UAV that transmits content to nearby vehicles. The delay optimization problem is established based on current conditions and long-term gains, and solved using matching-based algorithms and deep reinforcement learning-based algorithms. The authors of [21] treat UAV as SBS that provide video to mobile users in some small cells. To reduce the pressure on wireless backhaul, both UAV and SBS are equipped with caches that can store video during off-peak hours and use idle SBSs to generate jamming signals to interfere with eavesdropping. The authors of [22] propose a novel scheme to guarantee the security of UAV-relayed wireless networks with caching via jointly optimizing the UAV trajectory and time scheduling, which designed for users with different cache profiles to ensure their secrecy rate.

In summary, existing caching strategies fail to consider both the impact of geographic location and the utilization of airborne resources. Therefore, in this paper, we introduce UAV into the VANET as caching nodes with mobility to provide services to vehicle users. To reduce the average request delay and improve the success rate, we designed a collaborative caching scheme for RSUs, UAV and vehicle users, and optimized the flight trajectory of UAV, taking into account the geographical location.

(1) We introduce UAV with caching capabilities into the vehicular network so that it fly across road sections and provide services to vehicle users within its coverage area during flight. And develop a corresponding content delivery strategy so that UAV can fully cooperate with other nodes in the network, not only to transmit cached content to vehicle users, but also to act as relays to forward the content cached in roadside units to vehicle users.

(2) A geolocation-based UAV-assisted content caching strategy is proposed. The content is divided into local content and common content, and mobile vehicle users and UAV cache only common content that is not affected by geographic location; RSUs with fixed locations cache local content and common content proportionally. Then an expression for the request delay of vehicle users is derived, and an optimization problem for minimizing the average request delay is established under the constraints of cache capacity and UAV flight speed.

(3) A joint optimization algorithm for UAV trajectory and node caching decision is proposed. Specifically, the optimization problem is decomposed into three subproblems: cache proportion, cache decision and UAV trajectory optimization. Firstly, the RSU's preference list for content is established without considering the mutual influence between nodes, and the caching proportion of local content in each RSU is optimized by an exhaustive method, then a preference-based exchange collaborative caching algorithm is designed to optimize the collaborative caching decisions of the RSUs and the UAV for common content, and finally the optimal UAV trajectory is obtained based on a greedy algorithm, which further reduces the average request delay.

The next parts of this paper are organized as follows. the system model, content delivery decision and problem formulation are given in Section 2; the joint optimization algorithm for UAV trajectory and node caching decision is designed in Section 3; the simulation results of the algorithm are given and analyzed in Section 4; and the full paper is summarized in Section 5. The key symbols used in this article are summarized in Table 1.

Table 1. Summary of symbols

Symbol	Description
V	The set of vehicle users
ρ	The density of vehicle users.
v	The speed of the vehicle users.
s	The size of the contents
G	The trajectory of UAV.
H	The altitude of .
F_{com}	The set of common contents
F_{loc}	The set of common contents
$re_{n,i}^{t}$	The request indicator variable of i for f at time t.
γ	The exponential constant of the Zipf distribution

R_m	The mth RSU.
x_m	The percentage of local content cached by R_m.
CR_m	The cache capacity of R_m.
$y^R_{m,i}$	The cache indicator variable of R_m for f_i
y^U_i	The cache indicator variable of UAV for
α	The content delivery decision indicator variable
D^W	The waiting time
D^C	The content transmission delay

2 System Model and Optimization Problem

The system model is shown in Figure 1, assuming that in the urban environment each road is a two-way lane, where the lanes appear in pairs and the road is distributed with moving vehicle users. Let $V = \{v_1, ..., v_n, ..., v_N\}$ be the set of vehicle users, where v_n denotes the nth vehicle user. An RSU is deployed next to each road section. A UAV with caching function is deployed over the road section to assist the RSUs in serving the vehicle users. The time period T is divided into multiple time slots, and the UAV has the corresponding travel direction and speed in each time slot.

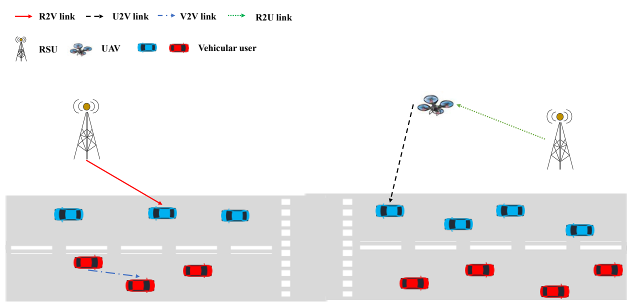

Figure 1. System model

2.1 Mobility Model

The vehicle users and UAV in the system are mobile in nature. For vehicle users, which are assumed to be traffic flow models in this paper, the relationship between vehicles' density ρ and vehicles' speed v in a road section m can be expressed as

$$v = v_{\max}\left(1 - \frac{\rho}{\rho_{\max}}\right), \tag{1}$$

where $v_{\max}$ denotes the maximum speed of the vehicle user, and $\rho_{\max}$ is the extreme traffic density when traffic congestion occurs [23]. the number of vehicles on the road section obeys a Poisson distribution with parameter λ, $\lambda = \rho \cdot v$, and the vehicle travel speeds all obey the same Truncated Normal Distribution [24].

The UAV with caching capability can provide service to the vehicle users during the flight, which flies along the road at a fixed altitude H over the road. It can choose a different flight speed and direction for each time slot, and its trajectory in time period T is G.

2.2 Content Request Model

In this paper, we classify content into two categories: local content and common content. Specifically, local content refers to content related to local geographic location, such as nearby road information and business information, which are requested by users only when they pass through the corresponding road. Common content includes entertainment information, news, weather, etc., which are not related to geographical location and may be requested by users at any location.

Assume that each road segment has a collection of local content, e.g., road segment m has A_m local contents, then its collection of local content is denoted as $F_{loc_m} = \{f_{m,1}, ..., f_{m,a_m}, ..., f_{m,A_m}\}$. There are B common contents in the vehicular network, and the set of common contents is $F_{com} = \{f_1, ..., f_b, ..., f_B\}$. When a vehicle user passes through road segment m, the set of possible desired content is $F_m = F_{loc_m} \cup F_{com} = \{f_1, ..., f_i, ..., f_{I_m}\}$, where the total number of desired contents is $I_m = A_m + B$. Assuming that the contents are equal in size, denoted as s. $re^t_{n,i}$ is the content request indicator variable. $re^t_{n,i} = 1$ denotes that f_i was requested at time slot t, otherwise $re^t_{n,i} = 0$.

The request for content approximately follows a Zipf distribution. Accordingly, the probability of a file being requested is positively correlated with the file popularity ranking, and the probability of requesting the content with popularity ranked at τ is given as follows:

$$PR_\tau = \frac{\tau^{-\gamma}}{\sum_{f=1}^{F} f^{-\gamma}}, \tau \in [1, F], \tag{2}$$

where γ denotes the exponential constant of the Zipf distribution. The larger the value of γ is, the more the user's requests are concentrated on the top-ranked files. τ denotes the popularity rank of content in the library [25].

2.3 Caching Model

We design a collaborative caching mechanism based on local content and common content in the vehicular networks in this paper. Particular, vehicle users have a small caching capacity and short dwell time in each roadway, so they only cache common content. Vehicle users cache content according to the popularity probability. The UAV is mobile, and its caching decisions will affect the flight trajectory. If local content is cached in the UAV, it may stay in a road section for a long time, which is contrary to the purpose of this paper to assist the global network, so only common content is cached in the UAV. The RSU has a fixed location, which is suitable for caching the local content of the road section where it is located, so let it cache local content and common content in a certain proportion. Assuming that the cache capacity of R_m is CR_m, then the capacity of $x_m \cdot CR_m$ is used to cache local content, and the capacity of the $(1 - x_m) \cdot CR_m$ is used to cache common content, where x_m denotes the proportion of local content cached by R_m.

$Y^R_m = \{y^R_{m,1}, ..., y^R_{m,i}, ..., y^R_{m,I_m}\}$ is the set of R_m cache decision indicator variables, where $y^R_{m,i}$ is the cache indicator variable of R_m for f_i. If R_m has cached f_i, $y^R_{m,1} = 1$, otherwise $y^R_{m,1} = 0$ Similarly, $Y^U = \{y^U_1, ..., y^U_b, ..., y^U_B\}$ is the set of cache decision indicator variables of UAV. The cache decision optimization for UAV and RSUs is described in Section 3.

2.4 Content Delivery Policy

In this paper, there are multiple cache nodes in the scenario, and vehicle users can get their desired contents in multiple ways, so how to choose the access is a problem to be solved. Therefore, we design a delivery strategy with the process shown in Algorithm 1. The vehicle user obtains the content in five ways, denoted as $\{1, ..., e, ..., E\}$, $E = 5$. The content delivery decision indicator variable $\alpha^t_{n,i,e}$ is placed: $\alpha^t_{n,i,e} = 1$ indicates that v_n obtains content f_i through method e at time slot t, otherwise $\alpha^t_{n,i,e} = 0$. Each vehicle can only obtain content through one method, i.e. $\sum_{e=1}^{E} \alpha^t_{n,i,e} = 1$. The specific process for vehicle user to obtain content is as follows.

① The requesting vehicle first looks for the desired content within one hop in the same direction lane, and if it can be found, the requesting vehicle will obtain the content from the content source vehicle;

② If the content does not exist within one hop of the vehicle in the same direction lane, the information is queried in the reverse lane. The short meeting time between vehicles traveling in opposite directions leads to a low success rate of content delivery. Therefore, we calculate the time they can communicate by the speed and distance of the vehicles, and the requesting vehicle will choose to get content from the vehicle in the reverse lane only if the communication time is greater than the time required for content delivery;

③ If none of the neighboring vehicles of the requesting vehicle caches the content and it can communicate with the RSU, the information will be queried from the RSU. If the RSU has cached the desired content, it will be transmitted directly to the requesting vehicle;

④ If the requesting vehicle cannot communicate with the RSU, or the RSU does not cache the content, but the it is within the coverage area of the UAV, the information will be queried to the UAV. If the desired content is found, the UAV will transmit the content to the requesting vehicle;

⑤ If the UAV has not cached the desired content, but it can communicate with the RSU which has cached the desired content, the UAV will act as a relay and forward the content out of the RSU to the requesting vehicle.

If none of the above methods can obtain the content and the waiting time D^W does not exceed the maximum allowed waiting time $D^W_{\max}$, the vehicle user will continue to wait and repeat the first five steps in the next time slot until a feasible delivery method is found. If a suitable decision is not found within the maximum waiting time or the communication link is broken during the content transmission, the content request is considered to have failed.

Algorithm 1. Content delivery process

```
Vehicle V request content f, D^w = 0
If D^w ≥ D^w_max
    Cache did not hit, request faileed
Else
    If f is cached in vehicles with one-hop distance
    away from v on the same lane
        V obtains f from vehicle in the same direction
    Else if f is cached in vehicles with one-hop
    distance away from v on the same lane
        V obtains f from vehicle in the reverse direction
    Else if f is cached in the RSU and v is in the RSU
    communication range
        V obtains f from RSU
    Else if f is cached in the UAV and v is in the
    UAV communication range
        V obtains f from UAV
    Else if f is cached in the RSU and the UAV is in
    the RSU communication range
        V via UAV relay to obtain f from RSU
    Else
        D^w = D^w + 1
```

2.5 Communication Model and Delay Analysis

From the above analysis, it can be seen that the request delay of the vehicle user is equal to the sum of the content transmission delay $D^{t,c}_{n,i,e}$ and the waiting time $D^{t,w}_{n,i,e}$. The waiting time is the time from the vehicle user's request to the decision of delivery, which can be obtained by the delivery decision according to the specific situation. The content transmission delay is the time required for the cache node to transmit the content to the vehicle user after the delivery decision has been decided, and is calculated as shown in Figure 2. Assume that the length of each time slot is D and the vehicle user acquires content f from node o at moment t_0. The lth time slot after t_0 is denoted as t_l, then the amount of data that can be transmitted in that time slot is $s_c(t_l) = D{\cdot}R^o(t_l)$ and the size of the uncompleted data in that time slot is $s_r(t_l) = s - \sum_{j=1}^{l-1} D \cdot R^o(t_j)$. If $s_r(t_l) > s_c(t_l)$, it means that the content delivery cannot be completed in t_l and the next time slot will continue transmission. If $s_r(t_l) \le s_c(t_l)$, it means that content delivery can be completed in t_l, the time used to transmit data is $s_r(t_l)/R^o(t_l)$, and content transmission ends at this time slot. The transmission delay is the sum of the time used to transmit data for all time slots.

① If v_n acquires content f_i through $v_{n'}$ at time slot t_0 , $\alpha^{t_0}_{n,i,1} = 1$ or $\alpha^{t_0}_{n,i,2} = 1$. The transmission rate between v_n and $v_{n'}$ at time slot t can be expressed as

$$R^{VV}_{n',n}(t) = Blog_2\left(1 + \frac{P_{n'}G_{n',n}(t)}{\sigma^2}\right), \tag{3}$$

where $P_{n'}$ is the transmit power of $v_{n'}$, σ^2 is the Gaussian white noise variance at the receiver, $G_{n',n}(t) = X \cdot d_{n',n}(t)^{-\delta}$ is the channel gain between v_n and $v_{n'}$ at time slot t, δ is the path loss index, X is the channel fading gain, and $d_{n',n}(t)$ is the distance between v_n and $v_{n'}$. The transmission delay $D^{t_0}_{n,i,e}$ for v_n to get f_i from $v_{n'}$ can be expressed as

$$D_{n,i,e}^{t_0} = \sum_{l=1}^{L} D + \frac{s - \sum_{j=1}^{L} D \cdot R_{n',n}^{VV}\left(t_j\right)}{R_{n',n}^{VV}\left(t_{L+1}\right)}, e \in \left(1,2\right). \quad (4)$$

② If v_n acquires content f through R_m at time slot t_0, $\alpha_{n,i,3}^{t_0}$ = 1. By Shannon formula, the rate of content delivery from R_m to v_n at time slot t is

$$R_{m,n}^{RV}\left(t\right) = Blog_2\left(1 + \frac{P_m G_{m,n}\left(t\right)}{\sigma^2}\right), \quad (5)$$

where P_m is the transmit power of R_m, $G_{m,n}(t) = X \cdot d_{m,n}(t)^{-\delta}$ is the channel gain between R_m and v_n at time slot t, and $d_{m,n}(t)$ is the distance between R_m and v_n. The transmission delay $D_{n,i,3}^{t_0}$ for v_n to get f_i from $v_{n'}$ can be expressed as

$$D_{n,i,3}^{t_0} = \sum_{l=1}^{L} D + \frac{s - \sum_{j=1}^{L} D \cdot R_{m,n}^{RV}\left(t_j\right)}{R_{m,n}^{RV}\left(t_{L+1}\right)}. \quad (6)$$

③ If v_n acquires f_i through the UAV at time slot t_0, $\alpha_{n,i,4}^{t_0}$ = 1. The communication of UAV and the vehicle user is regarded as an air-to-ground communication, which concludes two transmission channels: the line-of-sight channel and the non-line-of-sight channel. The probability of line-of-sight transmission is [26]

$$P_{LoS} = \frac{1}{1 + \beta_1 \exp\left[-\beta_2\left(\theta - \beta_1\right)\right]}. \quad (7)$$

The probability of non-line-of-sight transmission is $P_{NLoS} = 1 - P_{LoS}$, where θ denotes the elevation angle from the UAV to the vehicle user, and β_1 and β_2 represent environment-specific coefficients. The path loss between the UAV and its associated vehicle user can be expressed as

$$\begin{cases} L_{Los} == \eta_{LoS}\left(\frac{\pi f_c}{c}\right) d_{u\ n}^{t} \\ L_{NLos} = \eta_{NLoS}\left(\frac{\pi f_c}{c}\right) d_{u\ n}^{t} \end{cases} \quad (8)$$

where η_{LoS} and η_{NLos} are the attenuation factors corresponding to the line-of-sight and non-line-of-sight links, f_c is the carrier frequency, c denotes the speed of light, and $d_{u,n}(t)$ denotes the distance between the UAV and v_n. Therefore, we can obtain the average path loss of the UAV to vehicle user link as

$$\overline{L} = P_{Los} L_{Los} + P_{NLos} L_{NLos}. \quad (9)$$

The transmission rate between the UAV and v_n at time slot t is

$$R_{u,n}^{UV}\left(t\right) = Blog_2\left(1 + \frac{P_U}{\overline{L}\left(d_{uv}\right)\sigma^2 B}\right). \quad (10)$$

where B denotes the bandwidth, P_U denotes the transmission power of the UAV, and σ^2 is the Gaussian white noise variance at the receiver. The transmission delay $D_{n,i,4}^{t_0}$ for v_n to get f_i from $v_{n'}$ can be expressed as

$$D_{n,i,4}^{t_0} = \sum_{l=1}^{L} D + \frac{s - \sum_{j=1}^{L} D \cdot R_{u,n}^{UV}\left(t_j\right)}{R_{u,n}^{UV}\left(t_{L+1}\right)}. \quad (11)$$

④ If v_n obtains f_i from R_m through the UAV relay at time slot t_0, i.e., $\alpha_{n,i,5}^{t_0}$ = 1. The transmission delay $D_{n,i,5}^{t_0}$ is the sum of the delay of R_m transmitting f_i to the UAV and the delay of the UAV transmitting f_i to v_n, which can be expressed as

$$D_{n,i,5}^{t_0} = \sum_{l=1}^{L} D + \frac{s - \left(D - \frac{s - \sum_{j'=1}^{L'} D \cdot R_{m,u}^{RU}\left(t_{j'}\right)}{R_{m,u}^{RU}\left(t_{L'+1}\right)}\right) \cdot R_{u,n}^{UV}\left(t_{l'+1}\right) - \sum_{j=l'+2}^{L} D \cdot R_{u,n}^{UV}\left(t_j\right)}{R_{u,n}^{UV}\left(t_{L+1}\right)}, \quad (12)$$

where L' denotes that the UAV acquires the desired content completely in the L'+1th time slot after t_0. $R_{m,u}^{RU}$ denotes the communication rate between R_m and the UAV. L' and $R_{m,u}^{RU}$ are calculated as in case ② .

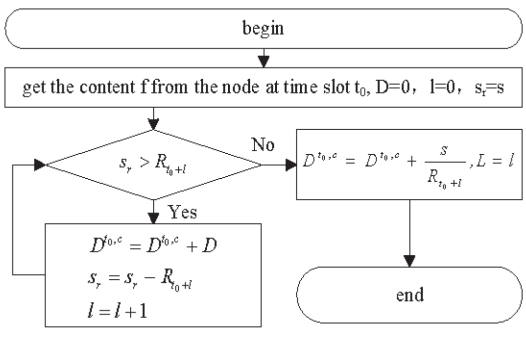

Figure 2. Transmission delay calculation process

2.6 Optimization Problem

In order to minimize the average request delay of vehicle users in the vehicle network during time period T, the proportion X of local content cached by RSUs, the caching decision Y^R and Y^U and the trajectory G of the UAV should be jointly optimized. By analyzing the delay above, the problem can be expressed as

$$\begin{aligned} P: \min_{X,Y^R,Y^U,G} D_{ave} &= \frac{\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{e=1}^{E} re_{n,i}^{t}\alpha_{n,i,e}^{t}\left(D_{n,i,e}^{t,c} + D_{n,i,e}^{t,w}\right)}{\sum_{t=1}^{T}\sum_{i=1}^{N}\sum_{i=1}^{I} re_{n,i}^{t}} \\ s.t.\quad & (C1)\, 0 \le x_m \le 1, m \in \left(0, M\right) \\ & (C2) \sum_{i=1}^{I} y_{m,i}^{R} s \le CR;\ \sum_{i=1}^{I} y_i^U s \le CU \\ & (C3)\, 0 \le V^U \le V_{\max}^{U} \\ & (C4)\, y^R, y^U, re_{n,i}^{t}, \alpha_{n,i,e}^{t} \in \left(0,1\right) \end{aligned} \quad (13)$$

where (C1) is a constraint on the proportion of RSU cache space utilized. x_m denotes the proportion of the RSU's capacity for caching local content to its total cache capacity, and takes values ranging from 0 to 1. (C2) indicates that the cache content data size cannot exceed the maximum cache capacity, where y_i is the cache indicator variable of caching node for f_i. If the caching node has cached f_i, $y_i = 1$, otherwise $y_i = 0$; (C3) is a constraint on the flight speed of the UAV; and (C4) indicates the cache decision indicator variable, content request indicator variable and content delivery indicator variable, which take values of 0 or 1.

3 Joint Cache and Trajectory Optimization Algorithm

In this section, a joint optimization algorithm for UAV trajectory and node cache decision is proposed to solve the above optimization problem with known vehicle user content requests. Since problem P is an NP-hard problem, we divides the problem into three sub-problems: cache proportion, cache decision and UAV trajectory optimization. Firstly, an exhaustive method is used to derive the local content cache proportion of each RSU; secondly, a preference-based switching collaborative caching algorithm is designed to optimize the cache decision of RSUs and UAV; finally, a greedy algorithm-based trajectory optimization algorithm is used to optimize the flight trajectory.

It should be noted that the caching decision of frequent node replacement will incur a large overhead. Therefore, the optimization of the cache decision is a long-term optimization, i.e., the cache decision is optimized once for multiple time slots. While the UAV is mobile and needs to plan the flight trajectory for each time slot, which is a short-term optimization. The relationship between the two is shown in Figure 3.

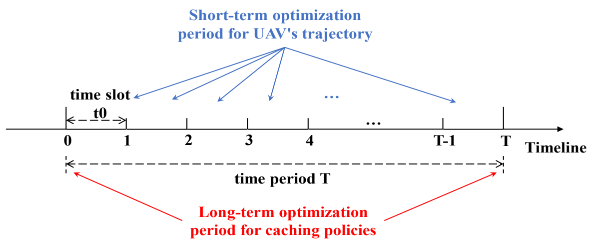

Figure 3. Long-time optimization versus short-time optimization

3.1 Cache Proportion Optimization

Given the UAV trajectory G in time period T, the initial preference list of the node for each content can be established. Then, according to the list, the cache proportion of the RSU can be optimized. At this point the problem is expressed as

$$P1: \min_{x} D_{ave} = \frac{\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{e=1}^{E} re_{n,i}^{t}\alpha_{n,i,e}^{t}\left(D_{n,i,e}^{t,c} + D_{n,i,e}^{t,w}\right)}{\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{I} re_{n,i}^{t}} \quad (14)$$

$$s.t.\ (C1)\ 0 \le x_m \le 1, m \in (0, M)$$

The preference lists of RSUs and UAV for each content are first established. For local content, since only RSUs will cache them and the local content in each road segment is different, the caching decision of each RSU for them does not affect other RSUs. Therefore, the local content can be sorted by popularity as the preference list of RSUs for the local content of the road segment. For common content, since vehicle users, roadside RSUs and UAV can cache them, the nodes' caching decisions for common content may affect the preference lists of other nodes. In the phase of optimizing the cache ratio, the initial preference degree of each RSU and UAV for common contents is calculated separately without considering the interactions between nodes for the time being for convenience. Specifically, taking R_m as an example, first, with all vehicle user locations, cached contents and requests known, calculate the average request delay D_0 when all nodes except vehicle users do not cache contents in time period T. Then, calculate the average request delay $D_{m,i}$ in time period T when all RSUs and UAV except R_m and vehicle users do not cache any contents and only common content f_i is cached in R_m. the value of $D_0 - D_{m,i}$ is considered as the gain of R_m caching f_i without considering inter-node effects, which is used as the initial preference weight of R_m for f_i. Similarly, the preference weight of R_m for all common contents can be calculated. By arranging the contents in descending order according to the preference weights, a list of R_m's preferences for common contents can be obtained. In summary, each RSU has two preference lists: a preference list for local content and a preference list for common content. The UAV only caches common content so it only has the preference list for common content.

The caching decisions are initialized based on the preference lists. The UAV can cache up to CN_U contents, where $CN_U = \frac{CR_U}{s}$, so it will cache the first CN_U local contents in its local preference list. The maximum number of cached contents for the RSU is $CN_R = \frac{CR_R}{s}$, and its caching decision will be made based on the caching proportion in the order of the preference lists for local content and the common content. Take R_m as an example, its maximum number of cached contents is CN_m and the caching proportion of local content is x_m. Then it will cache the first $CN_m^l = x_m \cdot CN_m$ contents of the preference list for local content and the first $CN_m^c = (1 - x_m) \cdot CN_m$ contents of the preference list for common content, $x_m = \frac{CN_m^l}{CN_m}$, where CN_m^l denotes the number of local contents cached in R_m, $CN_m^l \in (0, CN_m)$.

Iterating over all the cache proportions, each of which corresponds to a caching scheme, we can calculate the corresponding average request delay over the time period T. Comparing all the latencies, the cache proportion corresponding to the smallest delay is taken as the final local content cache proportion of the RSU.

3.2 Caching Decision Optimization

Given the cache proportion of the RSU and the flight trajectory of the UAV, the common content caching decisions can be further optimized. The problem can be expressed as follows.

$$P2:\min_{Y^R,Y^U} D_{ave}=\frac{\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{e=1}^{E} re_{n,i}^{t}\alpha_{n,i,e}^{t}\left(D_{n,i,e}^{t,c}+D_{n,i,e}^{t,w}\right)}{\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{I} re_{n,i}^{t}}$$
$$s.t.\ (C2)\sum_{i=1}^{I} y_{m,i}^{R}s\le CR;\ \sum_{i=1}^{I} y_{i}^{U}s\le CU$$
$$(C4)\,y^R,y^U\in(0,1) \quad \textbf{(15)}$$

Since multiple nodes in the vehicular network are capable of caching common content, the caching decisions between nodes for common content may influence each other, so the initialized caching strategy proposed above without considering the influence between nodes may not achieve desired results. For example, compared to the case where only the R_m caches f_i, if the UAV also caches content f_i, some of the vehicles requesting f_i may meet the UAV before reaching the coverage of R_m and obtain content from the UAV, which will cause the actual gain of R_m caching f_i to be inconsistent with the initial caching gain calculated above, thus affecting the ranking of the preference list for common content of R_m. Therefore, it is necessary to further optimize the common content caching decisions of UAVs and RSUs, which is a global placement problem and the traditional dynamic planning solution will cause a dimensional catastrophe. Therefore, we propose a preference-based exchange collaborative caching algorithm based on the initial content preference list.

It is assumed that the RSUs and UAV have been initially cached according to the initial content preference list and the optimized caching proportion. For the sake of discussion, the caching decisions of all RSUs and UAV are considered as a set $Y=\{Y_1, ..., Y_k, ..., Y_K\}$, where $K=M+1$. The preference list for common content of each node to be optimized (all RSUs and UAV) is swapped. Specifically in the case of R_m, R_m caches the first CN_m^c contents of its preference list for common content, and the request delay in T time period is D_0^m. From the CN_m^c+1th to the last content in the list, the caching decision is exchanged with the first CN_m^c contents in the list in turn. For the CN_m^c+1th content, we first exchange the CN_m^c+1th content and the CN_m^cth content cache decision, and calculate the average request delay $D_{p,q}^m$ in time period T for this caching decision. If $D_{p,q}^m < D_0^m$, the caching decision is kept and the two contents are exchanged in the preference list to end the exchange of the CN_m^c+1th content; If $D_{p,q}^m \ge D_0^m$, the exchange of these two content caching decisions is revoked and the initial caching decision continues to be used, then the CN_m^c+1th content continues to be exchanged forward, i.e., the caching decision is exchanged with the CN_m^c−1th content. The above steps are repeated until the average request delay less than D_0^m or the exchange with all the first CN_m^c contents is completed. After completing the exchange of the CN_m^c+1th content, the exchange of the CN_m^c+2th content continues in the same way, advancing backward in sequence. The further the content is ranked in the preference list of R_m, the fewer vehicle users request that content in the vicinity of R_m in time period T, so the probability of being able to exchange cache decisions with the first CN_m^c contents at the end of the list is smaller. Therefore, to reduce the number of computations and the complexity of the algorithm, a maximum number of exchange failures $rep_{\max}$ is set. If $rep_{\max}$ consecutive contents fail to exchange cache decisions with the first CN_m^c contents during the optimization of R_m, the optimization of cache decisions for R_m is directly ended. The $rep_{\max}$ affects the accuracy of the algorithm, the larger the value the better the optimization effect, but the higher the complexity will be. This value can be chosen according to the actual situation of the on-board network and the requirement of accuracy. All nodes to be optimized are optimized according to this method, as shown in Algorithm 2.

Algorithm 2. Preference-based exchange collaborative caching algorithm

---

Input: flight trajectory for the time period T, local content cache proportion for the RSU
Output: cache decisions for the RSUs and the UAV

```
Initialize: y_{k,i}=1, k∈(1,M+1), i∈(1,num_c^k);
            y_{k,j}=0, k∈(1,M+1), j∈(num_c^m+1,B)
For k = 1 to K do
  Calculate the initial time delay D_0^k
  For p = CN_k^c + 1 to B do
    For q = 1 to CN_k^c do
      y_{k,p} = 1, y_{k,q} = 0
      calculate the time delay for the time period
      T under this cache decision D_{p,q}
      If D_{p,q}^k < D_0^k , rep = 0
        break
      Else
        y_{k,p} = 0, y_{k,q} = 1
      End If
    rep = rep + 1
    End For
    If rep = rep_max
      break
  End For
End For
```

3.3 UAV Trajectory Optimization

With the known cache decision, the trajectory G of the UAV is further optimized, and the problem can be simplified as:

$$P3:\min_{G} D_{ave}=\frac{\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{I}\sum_{e=1}^{E} re_{n,i}^{t}\alpha_{n,i,e}^{t}\left(D_{n,i,e}^{t,c}+D_{n,i,e}^{t,w}\right)}{\sum_{t=1}^{T}\sum_{n=1}^{N}\sum_{i=1}^{I} re_{n,i}^{t}}$$
$$s.t.\ (C3)\,0\le V^U\le V_{\max}^U \quad \textbf{(16)}$$

If the UAV is about to run out of energy mid-flight, it will fly back to a nearby RSU, which will deploy another UAV to continue its work. To facilitate the calculation, the speed of the UAV is discretized into a finite number of values, which can be expressed as $\{v_0, v_1, ..., v_{\max}\}$, then the position it will reach at the next moment can also be divided into multiple points. Since the time delay for vehicle users to obtain content is often greater than one time slot, the content request delay resulting from the selection of the UAV's next moment of flight position is influenced by the previous flight path. As shown in Figure 4, the trajectories of the UAV are represented by lines of different colors. Taking the current moment as o_2, both trajectories are at position ③ at the current moment and both decide to arrive at position ④ at the next moment. However, their positions at the previous moment are different, which leads to different vehicle users served by the UAV of the two trajectories at the current moment, i.e., the UAV of the red trajectory at moment o_2 transmits content for v_1 and the UAV of the blue trajectory transmits content for v_2. Therefore, although the two trajectories make the same decision, the decision causes different impacts: at moment o_3, the red trajectory will be disconnected from v_1 and the transmission fails, and this decision does not reduce the transmission delay; the blue trajectory's communication link with v_2 is not disconnected and the content is successfully delivered to v_2, and this decision reduces the total transmission delay. This makes the traditional path planning algorithm not suitable for solving this problem. And as the time period T grows, the computational complexity increases dramatically so the dynamic planning algorithm is not easy to implement. Therefore, this paper designs a UAV trajectory optimization algorithm based on the greedy algorithm.

Because the request delay of the vehicle user needs to wait until the content is completely transmitted before it can be calculated, and the number of successful content delivery reflects the size of the total delay, where the more successful times the smaller the total delay, so the number of successful content delivery content in the vehicular network is used as the basis for measuring the merit of the trajectory. First, the time period T is divided into multiple equal-length small time periods, and each small time period is used as a trajectory optimization cycle. Then, within each optimization cycle, the UAV can choose different directions and flight speeds. To facilitate the calculation, we discretize the flight speed, which can be expressed as y. Because the UAV flies over the road, its flight trajectory is one-dimensional, with only two directions. Therefore, the set of possible locations of the UAV after one optimization cycle is j, where k denotes the initial position of the UAV in this cycle, l denotes the length of the optimization cycle, and - denotes the negative direction. In this way, all possible flight trajectories of the UAV in the optimization cycle can be known, so that the corresponding content delivery success times of these trajectories can be calculated. Finally, the trajectory with the highest number of successes is selected as the final trajectory for this cycle. The destination reached is the initial position of the next trajectory optimization cycle, and the trajectory of the next cycle is continued to be optimized according to the road conditions until all cycles are completed. The details are shown in Algorithm 3.

The algorithm has low complexity and can make decisions instantly with the knowledge of only the request of the vehicle user at the current moment, thus further reducing the request latency. However, the algorithm does not consider the fairness of users because it always chooses to serve the users that are optimal for the total objective function, potentially serving the same group of users for a longer period of time.

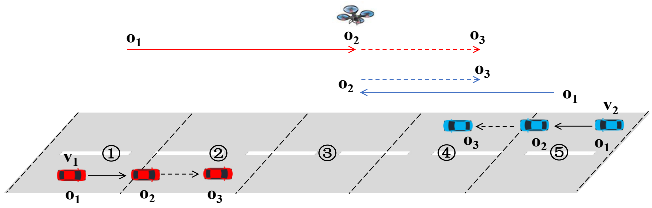

Figure 4. UAV trajectory

Algorithm 3. Greedy algorithm-based trajectory optimization algorithm

Input: cache decision for each node, length of time period T
Output: UAV's trajectory of time period

1. Divide the time period into trajectory optimization cycles
2. **For** nt =1 to NT do
3. List all the destinations that can be reached and generate the trajectory list Tra_{nt}
4. Calculate the number of times the trajectories can successfully deliver content in Tra_{nt} as of the current cycle
5. Select the trajectory with the highest number of successes.
6. **End For**

In summary, the joint cache and trajectory optimization algorithm first establishes the initial preference lists of RSUs and UAV for contents without considering inter-node effects, then optimizes the proportion of common contents cached by RSUs through an exhaustive method, and determines the caching decisions of each RSU and UAV through a preference-based exchange collaborative caching algorithm, and finally optimizes the UAV trajectory using a greedy algorithm-based trajectory optimization algorithm. The details are shown in Algorithm 4.

Algorithm 4. Joint optimization algorithm for UAV trajectory and node caching decision

Input: length of time period T
Output: cache decisions for RSUs and UAV, UAV's trajectory of time period T.

1. Create initial preference lists of RSUs and UAV for content
2. Initial caching of UAV according to preference list
3. **For** m = 1 to M do
4. **For** $CN_m^l = 1$ to CN_m
5. $x_m = CN_m^l / CN_m$
6. According to the preference list, the initial cache according to x_m, and calculate the time delay at this time, recorded in table D_{xm}
7. **End For**
8. The proportion corresponding to the smallest value in is chosen as the final proportion of R_m
9. **End For**
10. Optimize caching decisions with Algorithm 1
11. Optimize UAV's trajectory with Algorithm 2

---

4 Simulation Results

In order to evaluate the performance of the proposed algorithm, this chapter takes two road sections as example, uses SUMO to simulate the environment, and python to simulate the algorithm. The path loss exponent is $\alpha = 4$, the channel fading gain is $X = 10^{-2}$, the channel bandwidth is $B = 1.1MHZ$, the power of Gaussian noise is $P_n = -110dBm$, and other simulation parameters are shown in Table 2.

Table 2. Simulation parameters

Parameter	Value
The number of common content	50
The number of local content	15
The parameter of Zipf Distribution	0.7
The transmission power of vehicle (mW)	200
The transmission power of RSU (mW)	2000
The transmission power of UAV (mW)	200
The communication radius of vehicle (m)	50
The communication radius of RSU (m)	150
The communication radius of UAV (m)	100
The length of lane (m)	500

Figure 5 and Figure 6 give the variation of request delay and request success rate for vehicle users with different content sizes. It can be seen that as the size of the transmitted content increases, the average delay of the vehicle increases and the request success rate decreases. Compared with the literature [16], the strategy proposed in this paper has lower average request latency and higher request success rate. This is because although the strategy proposed in literature [16] cites UAV for assistance and also optimizes its caching policy and flight trajectory, it does not consider the impact of geographic location on vehicle user requests or inter-vehicle communication, which makes the edge node cache redundancy higher and the network load larger. In contrast, this paper optimizes the caching decision based on the user request characteristics and the mobility of the caching nodes to have better performance. Compared with the strategy using probabilistic caching according to popularity, the strategy in this paper has smaller average delay and higher request success rate because it considers collaborative caching optimization of nodes in the vehicular network to reduce the redundant caching of content. In terms of complexity, the complexity of this paper is $o(K(B - CN_k^c) \cdot rep_{\max})$. Since [16] does not consider the geographical location of the content and does not have to optimize the caching ratio of the local content of the RSU, the complexity is slightly less than this paper. For the strategy using probabilistic caching according to popularity, the complexity of the caching part is low, which is less than the complexity of this paper, but the performance is poor.

Figure 7 and Figure 8 show the average delay and request success rate versus vehicle user density for different content sizes. When the content size is constant, the average delay decreases and the request success rate increases with increasing vehicle density. This is because the density of vehicle users is related to speed, that is, the higher the vehicle density, the lower the vehicle speed, the longer the vehicle is in contact with other cache nodes, and the lower the probability of communication interruption. At the same time, vehicle users have a certain caching capacity, so as the density of vehicle users increases, the probability of vehicles obtaining content through other vehicles increases, which reduces the average delay and improves the request success rate.

Figure 9 and Figure 10 show the relationship between the average delay and request success rate with vehicle user density under different conditions of content quantity, where the total content quantity refers to the sum of the common content quantity and the local content quantity of all road sections. When the number of contents is constant, the average delay gradually decreases and the request success rate gradually increases with the increase of vehicle density; when the vehicle density is constant, if the amount of content increases, the average request delay will increase, and the request success rate will decrease accordingly. This is because the cache capacity of the cache node is limited, and the more the number of contents, the more diverse and scattered the user’s requests, which will lead to a lower success rate of requests and an increase in request latency.

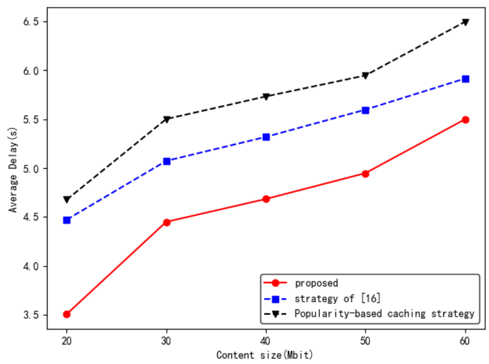

Figure 5. The relationship between the Average Delay and content size

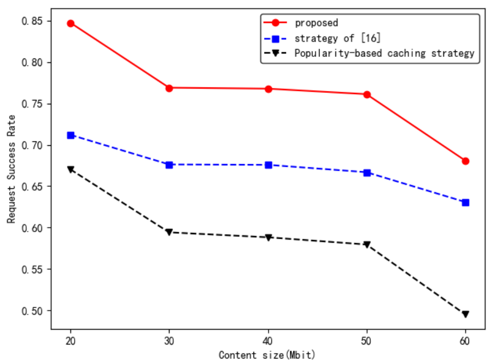

Figure 6. The relationship between the Request Success Ratio and content size

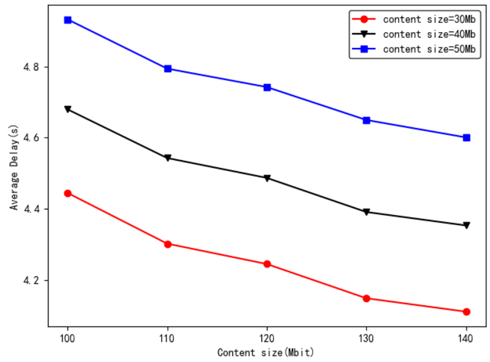

Figure 7. The relationship between Average Delay and vehicle density for different content sizes

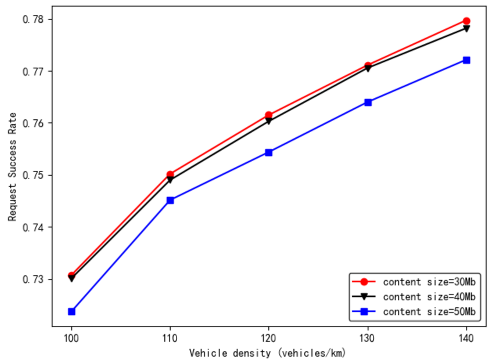

Figure 8. The relationship between Request Success Ratio and vehicle density for different content sizes

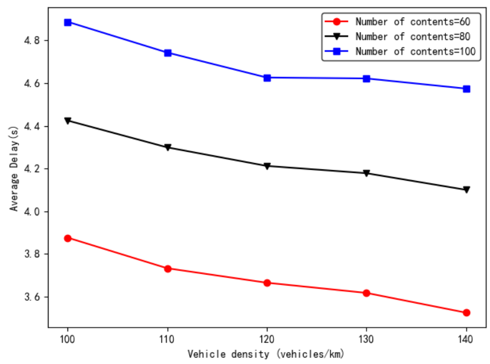

Figure 9. The relationship between Average Delay and vehicle density for different content quantities

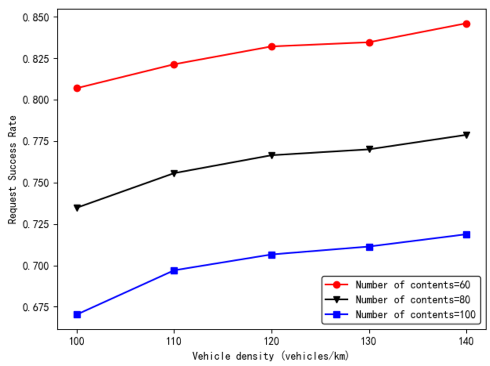

Figure 10. Relationship between Request Success Ratio and vehicle density for different content quantities

5 Conclusion

In this paper, we propose a geolocation-based UAV-assisted caching strategy. We consider the impact of geographic location on requests from vehicle users and classify the content into local content and common content according to the request characteristics of users, and then combine the mobility of caching nodes to develop different caching decisions for different types of content. Meanwhile, in addition to traditional RSUs, UAV and vehicles are also used as cache nodes in this paper, and detailed delivery decisions are formulated for the large variety of cache nodes in in-vehicle networks, and the optimization problem of minimizing the average request delay is established. Finally, in order to solve the problem, a joint optimization algorithm for UAV trajectory and node caching decision is designed to jointly optimize the caching ratio of RSU, the caching decision of nodes and the flight trajectory of UAVs. The simulation results show that the strategy in this paper can effectively reduce the average request latency and improve the request success rate. In addition, we believe that the problem of applying multiple UAVs for caching in VANET is also worth investigating. One of our next works is to design such new caching strategy.

Acknowledgment

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Biographies

Ting Gong is currently pursuing the master's degree in telecommunication engineering with the Nanjing University of Posts and Telecommunications, Nanjing, China. Her research interests are in the area of mobile communication

Qi Zhu received the bachelor's and master's degrees in radio engineering from the Nanjing University of Posts and Telecommunications (NUPT), Nanjing, China, in 1986 and 1989, respectively. She is currently a Professor with the School of Telecommunication and Information Engineering, NUPT. Her research interests include wireless networks, Internet of Things, green communication, and mobile edge computing.