Mobility-aware Probabilistic Caching in UAV-assisted Wireless D2D Networks

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***Abstract*—This paper investigates the problem of cache node placement and selection with the coexistence of unmanned aerial vehicles (UAVs) cache and device-to-device (D2D) cache in mobile networks. In recent years, caching popular content in UAV base stations has received growing interests as a promising solution to improve communication performances. With the agility and mobility features, the dynamic movement of cache-enabled UAV should be further designed to increase the cache-aided throughput. Different from the conventional caching approaches assuming ground users remain static, we consider the dynamic movement design of UAV to maximize the cache-aided throughput taking into account the movement of ground users. As the formulated optimization problem is NP-hard, we propose a mobility-aware probabilistic caching algorithm in which K-means clustering is utilized to obtain the partition of ground users. Simulation results show that the proposed algorithm notably outperforms the pure D2D cache scheme (without UAV caching) in different cases.**

***Index Terms*—Unmanned aerial vehicle base station (UAV-BS), device-to-device (D2D) communications, mobile edge caching.**

I. INTRODUCTION

Deploying small base stations using millimeter wave (mmWave) is a promising way to meet the high throughput and low latency demands of tomorrow mobile applications [1]. However, as networks are further densified, deploying high-speed backhaul for each small base station becomes infeasible considering the high cost [2], [3]. To alleviate the resulting backhaul congestion, mobile edge caching provides a feasible solution for service content delivery based on the observation that most of the data content are reusable [4]. In mobile edge caching, data in the cloud server can be cached in the proximate edge node, thereby reducing the duplicated content transmission. Also, popular content can be stored at the user equipments (UEs) and transmitted through device-to-device (D2D) links to save cellular resources.

Incorporating caching capability into unmanned aerial vehicles (UAVs) has been considered in recent works [5] by introducing the concept of using UAV as an aerial base station (BS) that can dynamically cache the popular content. Since the UAV-BSs are connected to the core network through the wireless backhaul, high popularity content data can be cached at the UAV-BSs during the off-peak-traffic hours to relieve the backhaul congestion [6]. Compared to the ground base station (GBS), UAV base station (UAV-BS) is preferable due to the following reasons. Flying at high altitude, UAVs can provide a high ratio of line-of-sight (LoS) connections toward ground users [7]. By changing the location of UAV-BS, blockage effect from buildings can be decreased. Also, with the ability to move autonomously, UAV-BS can be quickly deployed to aid communications and extend coverage, especially in those areas that are difficult to be served by an existing GBS.

The existing literature in [8]–[12] has studied a number of problems related to UAV-assisted wireless networks. Cache-enabled UAVs are proposed in [8] to serve ground users over licensed and unlicensed bands, whose goal is to maximize the number of users that have stable queues. In [9], a single UAV is dispatched to serve all the ground terminals. An optimal UAV trajectory is constructed to minimize the total dispatch time. The authors of [10] propose a deployment method of multiple UAV-BSs using machine learning techniques. In [11], the authors propose a simple circular trajectory design of a single UAV using a low-complexity algorithm, which aims to maximize the minimum average throughput of all users. However, the coexistence of UAV cache and D2D cache has so far drawn little attention. In [12], a joint design on the UAV trajectory together with the caching placement is considered in a combined UAV and D2D-based network, whereas the cache node selection was not considered and the movement of ground nodes was also ignored.

In this paper, we formulate a cache-aided throughput maximization problem by optimizing the trajectory of caching UAV-BS, while considering the movement of ground users. Due to the NP-hardness of the formulated optimization problem, a joint cache data access node selection and UAV-BS movement design algorithm is proposed. We show that the cache-aided throughput under the outage constraint can be significantly improved if the strategy to determine which cache node to access is carefully designed. The main contributions of this paper are summarized as follows:

- We propose a low complexity algorithm which com-

bines UAVs movement design and cache node selection to solve the cache-aided throughput maximization problem. With the aid of K-means clustering, the proposed algorithm is capable of partitioning ground users into different clusters and obtaining the UAV position.
- Our simulation results show that the proposed cache node selection strategy can achieve significant throughput enhancement compared to that of the pure D2D cache scheme.

The rest of this paper is organized as follows. In Section II, we present the system model and problem formulation. Then, the probabilistic caching with K-means based UAV-BS movement algorithm is proposed in Section III. In Section IV, we present simulation results to evaluate the effectiveness of the proposed algorithm. Finally, conclusions are given in Section V.

II. System Model and Problem Formulation

As illustrated in Fig.1, we consider a cellular downlink network including the following types of links: (a) aerial-to-ground (A2G) link, (b) D2D link and (c) ground-to-ground (G2G) link. For the A2G links, we consider UAV-BS transmission using the mmWave frequency band. The time horizon of UAV-BS is discretized into M equal time units, indexed by $m \in \{1, 2, ..., M\}$. We denote Δ as the duration of the maximum transmission. In practice, Δ should depend on UAVs' flight time constraints.

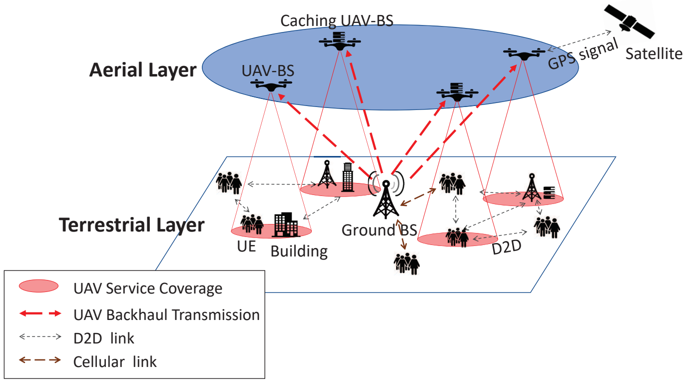

Fig. 1. The considered mobile network architecture integrating UAV-BS caching and D2D caching.

A. User Mobility Model

A Gauss Markov mobility model is adopted here as the user mobility model [13], which considers the previous speed and direction in each time step. The following equation is used to calculate the speed and the direction of the i_{th} ground users:

$$G_{m,i} = \alpha G_{m-1,i} + (1-\alpha)\bar{G} + \sqrt{(1-\alpha^2)}G^N \quad , \tag{1}$$

$$\Theta_{m,i} = \alpha \Theta_{m-1,i} + (1-\alpha)\bar{\Theta} + \sqrt{(1-\alpha^2)}\Theta^N \quad , \tag{2}$$

where $G_{m,i}, \theta_{m,i}$ denotes the speed and the direction of the i_{th} user in the m_{th} time index, respectively. α is a value between 0 and 1, indicating the degree of randomness with respect to the speed and direction for a time period. $\bar{G}$ and $\bar{\Theta}$ represent the average speed and direction, respectively. G^N and Θ^N are random variables chosen independently from a Gaussian distribution with zero mean and unit variance.

B. Channel Model

Since the amount of service request is relatively small compared to the amount of download data content, we only consider the downlink transmission in the following. The path loss of LoS and non-line-of-sight (NLoS) links is modeled according to the log-normal shadowing model by choosing specific channel parameters [5], which is given by:

$$l_{m,k}^{\text{LoS}}(s_{m,k}, u_{m,i}) = l_{FS}(d_0) + 10\mu_{\text{LoS}}(d_{m,ki}) + \chi_{\sigma\text{LoS}} \quad , \tag{3}$$

$$l_{m,k}^{\text{NLoS}}(s_{m,k}, u_{m,i}) = l_{FS}(d_0) + 10\mu_{\text{NLoS}}(d_{m,ki}) + \chi_{\sigma\text{NLoS}} \quad , \tag{4}$$

where $s_{m,k}$ denotes the position of the k_{th} UAV-BS and $u_{m,i}$ denotes the i_{th} user's position. $d_{m,ki}$ represents the distance from the k_{th} UAV-BS to the i_{th} user in the m_{th} time index. $l_{FS}(d_0) = 20\log(d_0 f_c 4\pi/c)$ is the free-space path loss at the reference distance d_0. The terms $\chi_{\sigma\text{LoS}}$ and $\chi_{\sigma\text{NLoS}}$ are the random variables which have normal Gaussian distribution.

The probability of the LoS link is related to the elevation angle ϕ_t between the UAV-BS and the user, which is given by [5]:

$$Pr(\text{LoS}) = \frac{1}{1 + Xe^{-Y(\phi_t - X)}} \quad , \tag{5}$$

where X and Y are constants depending on the environment and $\phi_t = h_{m,k}/(s_{m,k} - u_{m,i})$. $h_{m,k}$ denotes the height of the k_{th} UAV-BS in the m_{th} time index. The probability of the LoS connection depends on the density and height of the buildings. For example, an urban area has dense buildings that cause a lower LoS probability, whereas a rural area exists a higher LoS probability. In summary, the total path loss is expressed as

$$PL_{total} = Pr(\text{LoS}) \times PL_{\text{LoS}} + Pr(\text{NLoS}) \times PL_{\text{NLoS}} \quad , \tag{6}$$

where the probability of NLoS is $Pr(\text{NLoS}) = 1 - Pr(\text{LoS})$.

C. Cache Model

To optimize the throughput performance at the caching devices, the popularity of cache content should be considered. We use Zipf's law to model the relationship between the content popularity and the cache probability. Assume a finite content category with $f_i \in \{f_1, f_2, ..., f_N\}$ which represents the i_{th} popular file. The probability of i_{th} file to be cached in the edge node is given by

$$p_i = \frac{i^{-\beta}}{\sum\limits_{j=1}^{N} j^{-\beta}} \quad , \tag{7}$$

where β is the popularity factor. A larger value of β indicates the total data are more concentrated. Then, the sum of p_i can be used to calculate the probability that the user connects to a GBS:

$$P_{\text{ground}} = \sum_{i=1}^{N} p_i \cdot 1 \ . \tag{8}$$

The cache hit probability of the UAV-BS is defined as the probability that the required content of a user is cached by a nearby UAV-BS. We use the Poisson Point Process (PPP) to model the distribution of UAV-BSs and ground users. Therefore, the UAV-BS cache probability can be expressed as follows

$$P_{\text{hit,i}}^{\text{UAV}} = 1 - e^{-\pi(1-\rho)\lambda_u q_i R_u^2} \ , \tag{9}$$

where λ_u is the density of UAV-BSs, q_i is the size of the i_{th} data content, and R_u is the coverage radius of UAV-BSs. After summing each user's UAV-BS cache probability, we can obtain the total UAV-BS cache probability:

$$P_{\text{hit}}^{\text{UAV}} = \sum_{i=1}^{N} p_i (1 - e^{-\pi(1-\rho)\lambda_u q_i R_u^2}) \ . \tag{10}$$

Similarly, the D2D cache hit probability can be expressed as

$$P_{\text{hit,i}}^{\text{D2D}} = 1 - e^{-\pi(1-\rho)\lambda_d q_i R_d^2} \tag{11}$$

and

$$P_{\text{hit}}^{\text{D2D}} = \sum_{i=1}^{N} p_i (1 - e^{-\pi(1-\rho)\lambda_d q_i R_d^2}) \ . \tag{12}$$

D. Transmission Model

Now we provide the throughput calculation for the considered system. The cache-aided throughput performance can be calculated as

$$T_a = q_i \times S^a \times P_{suc,i}^a \ , \tag{13}$$

where q_i denotes the amount of data received by the i_{th} user. The term S^a denotes the probability of serving node selection with a $\in \{0, 1, 2\}$ and $P_{suc,i}^a$ is a successful transmission probability, which will be calculated in Section III. A. We consider the following two node selection strategies for the ground user.

- **UAV-first Strategy**: In this strategy, the ground user first attempts to connect to the UAV-BS. If failing to successfully receive the required data, the ground user will seek to connect the D2D node. Otherwise, the ground user can only be served by the GBS. We use a $= 0, 1, 2$ to represent the connection with $\{\text{UAV-BS}, \text{D2D}, \text{ground}\}$, respectively. Hence, we have

$$S^a = \begin{cases} P_{\text{hit,i}}^{\text{UAV}} \ , & a = 0 \ , \\ (1 - P_{\text{hit,i}}^{\text{UAV}}) P_{\text{hit,i}}^{\text{D2D}} \ , & a = 1 \ , \\ (1 - P_{\text{hit,i}}^{\text{UAV}} - (1 - P_{\text{hit,i}}^{\text{UAV}}) \times P_{\text{hit,i}}^{\text{D2D}}) \ , & a = 2 \ . \end{cases} \tag{14}$$

- **D2D-first Strategy**: Different from the UAV-first strategy, the D2D-first strategy first seeks to connect with the nearby D2D node. If failing, it switches to the UAV connection mode. Otherwise, it connects to the GBS. We use a $= 0, 1, 2$ to represent the connection with $\{\text{D2D}, \text{UAV-BS}, \text{ground}\}$, respectively. Similarly, we have

$$S^a = \begin{cases} P_{\text{hit,i}}^{\text{D2D}} \ , & a = 0 \ , \\ (1 - P_{\text{hit,i}}^{\text{D2D}}) P_{\text{hit,i}}^{\text{UAV}} \ , & a = 1 \ , \\ (1 - P_{\text{hit,i}}^{\text{D2D}} - (1 - P_{\text{hit,i}}^{\text{D2D}}) \times P_{\text{hit,i}}^{\text{UAV}}) \ , & a = 2 \ . \end{cases} \tag{15}$$

III. PROBLEM FORMULATION AND PROPOSED METHOD

A. Problem Formulation

The successful transmission probability $P_{suc,i}$ is used as a performance indicator based on signal-to-noise ratio (SNR) to select the cache node. We consider $P_{suc,i}^a = Pr[\gamma_i > \eta_a]$, where $a \in \{0, 1, 2\}$. Let γ_i denotes the SNR of the i_{th} user, which can be expressed as

$$\gamma_i = \frac{P_a |h_k|^2}{10^{PL_{\text{total}}/10} \sigma^2} \ , \tag{16}$$

where P_a denotes the transmit power of the cache node, $|h_k|^2$ is the Rayleigh fading channel gain, and d_i is the distance between the user and the serving node. Given this equation, we can derive $P_{suc,i}^a$ as

$$\begin{aligned} P_{suc,i}^a &= \mathbb{P}[\gamma_i > \eta_a] \\ &= \mathbb{P}[\frac{P_a |h_k|^2}{10^{PL_{\text{total}}/10} \sigma^2} > \eta_a] \\ &= \mathbb{E}_{d_i}[\exp(-\eta_a 10^{PL_{\text{total}}/10} \sigma^2 / P_a)] \\ &= \int_0^\infty r \cdot \exp(\frac{-\eta_{\text{a}} 10^{PL_{\text{total}}/10} \sigma^2}{P_a}) dr \ . \end{aligned} \tag{17}$$

Since we consider the Rayleigh fading channel model, $P_{suc,i}^a$ can be interpreted as the complementary cumulative distribution function (CCDF) of the exponential distribution.

Our objective is to maximize the total throughput from all the users without violating the SNR constraints. Given a cache strategy, we can obtain S^a according to (14) or (15). Based on (17) and (13), the optimization problem can be formulated as

$$\max_{s_{m,k}} \sum_{i=1}^{N} T_{\mathrm{a}} \tag{18a}$$

$$s.t. \quad 0 \leq x_{m,i} \leq X_{\max} \tag{18b}$$

$$0 \leq y_{m,i} \leq Y_{\max} \tag{18c}$$

$$\sum_{i=1}^{N} q_i^a \leq M_a \tag{18d}$$

$$\sum_{\mathrm{i}=1}^{N} C_i^a = 1, C_i^a \in \{1,0\},\ 1 \leq \mathrm{i} \leq N \tag{18e}$$

$$\gamma_i \geq \eta_a, \text{if } \mathrm{C}_i^a = 1\ . \tag{18f}$$

B. Probabilistic Caching with K-means based UAV-BS Movement

Due to the integer association constraint in problem (18e), it is in general hard to obtain the analytical solution for this non-convex optimization problem. Clearly, the optimal movement of UAV-BSs should take the users' position into consideration [14]. Since the path loss is dominated by the distance between the user and the UAV, the first step is to find the initial UAV position. Based on the considered system architecture, K-means cluster algorithm is applied since it can achieve the minimum distance from a centroid to each user [15], [16]. Our scheme aims to provide the best solution to serve the users by receiving the users' coordinate position. Different from the traditional method in which the trajectory is determined in advance (i.e., offline), the UAV-BS trajectory in our scheme is dynamically adjusted in an online fashion.

The K-means algorithm is composed of two parts: initialization and iteration. For the initialization part, we need to determine the k cluster centers $\{\mu_1, \mu_2, ..., \mu_k\}$. In this step, we randomly choose a position to be the cluster center. Next, for the iteration part, we assign each of the users to its nearest cluster center μ_k. That is, the set of the k_{th} cluster C_k is defined as

$$C_k = \{n | k = \arg\min_{k} ||x_n - \mu_k||^2\}\ . \tag{19}$$

After that, we recompute the new cluster center μ_k until the iteration error less than a threshold ζ. The final center of the cluster μ_k can be calculated as

$$\mu_k = \frac{1}{|C_k|} \sum_{n \in C_k} x_n\ . \tag{20}$$

Given the UAV-BS trajectory, we can evaluate the throughput performance of each user. If we use the UAV-first strategy, the first step is to check whether the user can connect to the UAV-BS. We set a UAV connection threshold η_{UAV}. If the received power $r_{i,j}^{\mathrm{UAV}}$ is larger than η_{UAV}, we set $c_i^{\mathrm{UAV}} = 1$, which means that the i_{th} user connects to the UAV-BS. Otherwise, the D2D link should be considered. Similar to the UAV part, we compare the received power $r_{i,k}^{D2D}$ with the D2D connection threshold η_{D2D}. If $r_{i,k}^{D2D}$ is larger than η_{D2D}, we set $c_i^{\mathrm{D2D}} = 1$, which means that the i_{th} user connects to the nearby D2D node. In case that $c_i^{\mathrm{UAV}} \neq 1$ and $c_i^{\mathrm{D2D}} \neq 1$, the user can only connect to the GBS. The detailed procedures of the proposed scheme with the UAV-first strategy are given in Algorithm 1. On the other hand, in case of using the D2D-first strategy, the SNR of D2D links should be estimated before that of UAV links. That is, the statements from line 4 to 8 and 9 to 12 in Algorithm 1 are interchanged.

Algorithm 1 Cache Node Selection with K-means based UAV-BS Movement Design (UAV-first strategy)

```
Input: User position matrix $P_n$; Number of clusters K
Output: Communication link a $\in \{0,1,2\}$.
 1: while $m \leq M$ do
 2:     Use K-means to derive the centroid of clusters $[S_1, S_2, ... S_K]$, where $S_i$ is the position of the $i_{th}$ UAV-BS at the current time index $m$.
 3:     while $i \leq N$ do
 4:         while $j \leq K$ do
 5:             Use the distance between the user and the UAV-BS $||u_{m,i} - s_{m,j}||$ to derive the path loss $PL_{i,j}^{\mathrm{UAV}}$ from (6).
 6:             Calculate the user SNR $\gamma_i$ from (16).
 7:             Compare the user SNR $\gamma_i$ with the SNR threshold $\eta_{\mathrm{UAV}}$. If $\gamma_i > \eta_{\mathrm{UAV}}$, set $c_i^{\mathrm{UAV}} = 1$, which means that the connection between the $i_{th}$ user and the $j_{th}$ UAV-BS is available.
 8:         end while
 9:         if $c_i^{\mathrm{UAV}} \neq 1$ then
10:             while $k \leq N$ do
11:                 Use the distance between each user $||u_{m,i} - u_{m,k}||$ to derive the path loss $PL_{i,k}^{\mathrm{D2D}}$ from (6).
12:                 Calculate the user SNR $\gamma_i$ from (16).
13:                 Compare the user SNR $\gamma_i$ with the SNR threshold $\eta_{\mathrm{D2D}}$. If $\gamma_i > \eta_{\mathrm{D2D}}$, set $c_i^{\mathrm{D2D}} = 1$, which means that the connection between the $i_{th}$ user and the $k_{th}$ D2D node is available.
14:             end while
15:         end if
16:     end while
17:     Determine the connection link according to $c_i^{\mathrm{UAV}}$ and $c_i^{\mathrm{D2D}}$.
18: end while
19: return a;
```

IV. Simulation Results

In this Section, we evaluate the throughput performance of the proposed cache scheme. Comparisons of different cache strategies are provided to gain useful insight into the design of a throughput-optimal mobile network system.

We consider the topology as shown in Fig. 1 with a single GBS located at the center. We simulate a cellular network

TABLE I
Simulation Parameters

Descriptions	Notations	Value
UAV-BS density	λ_{UAV}	5 per km^2
User density	λ_{UE}	500 per km^2
UAV-BS height	H	60 m
GBS link carrier frequency	$f_{c,\text{GBS}}$	2.1 GHz [5]
D2D link carrier frequency	$f_{c,\text{D2D}}$	2.1 GHz
UAV-BS link bandwidth	B_{UAV}	2.16 GHz [5]
GBS link bandwidth	B_{GBS}	10 MHz [5]
D2D link bandwidth	B_{D2D}	10 MHz
UAV-BS transmit power	P_{UAV}	20 dBm
GBS transmit power	P_{GBS}	40 dBm
D2D transmit power	P_{D2D}	8 dBm
Free-space reference distance	d_0	5 m
UAV-BS transmit power	P_{UAV}	20 dBm
Shadowing random variables	$\chi_{\sigma_{\text{LoS}}}, \chi_{\sigma_{\text{NLoS}}}$	5.3, 5.27
Environment dependent constant	X, Y	11.9, 0.13
Path loss exponent	α	2
Noise power	N_0/B	-174 dBm/Hz

with more than 100 mobile users uniformly distributed among a geographic area of size 1×1 km^2. The UAV-BS links are operated in mmWave band with carrier frequency $f_{c,\text{UAV}} = 38$ GHz and bandwidth $B_{\text{UAV}} = 2.16$ GHz. The UAV and D2D SNR threshold are set to be -95 dB and -109 dB, respectively. The simulation environment is developed in MATLAB 2018b.

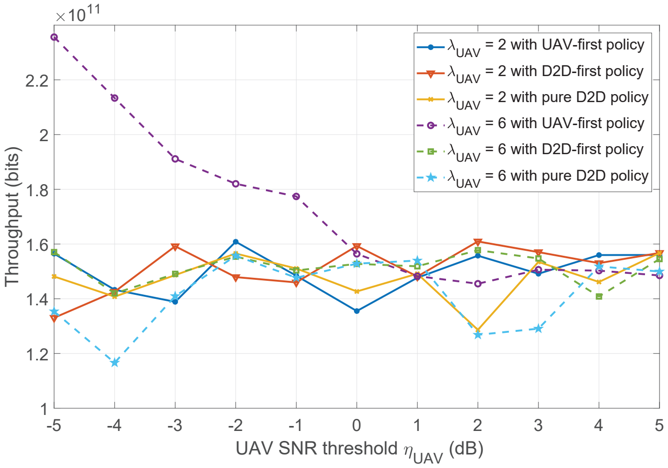

Fig. 2. Throughput performance comparisons with different UAV SNR thresholds.

Figure 2 shows the throughput performances with different UAV SNR thresholds. It is observed that increasing the UAV SNR threshold has a significant effect on the throughput performances for the UAV-first strategy with $\lambda_{\text{UAV}} = 6$. For the remaining cases, the impact of the SNR threshold on the throughput performances is not obvious. This may be caused by the following reasons. First, the users that having a large distance to UAV-BS tends to be served by D2D nodes or the GBS. This is especially likely to happen in case that UAV-BSs are insufficient. Therefore, the advantage of UAV to provide throughput gain is diminished. Second, there is no significant difference between the D2D-first strategy and the pure D2D strategy (without UAV). This is because both of the GBS and D2D communications are operated in the same carrier frequency band. Although the GBS has a relatively large transmit power, D2D nodes are possibly in close proximity, resulting in similar throughput performances.

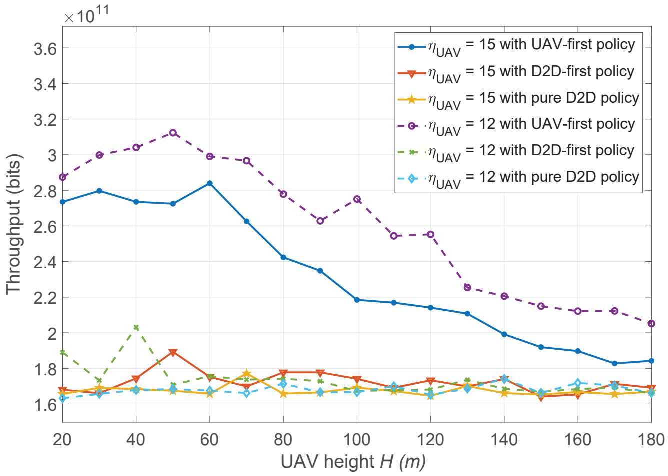

Fig. 3. Throughput performance comparisons with different UAV heights.

Figure 3 shows the relation between the UAV height and throughput performances. Not surprisingly, the UAV height has a significant impact on the performances using the UAV-first strategy. UAV at the height of 40 m to 60 m yields the largest throughput, which is the optimal trade-off between LoS link and path loss. The performances of the D2D-first strategy is similar to the pure D2D strategy in case of large user density. The user is more likely to retrieve the data from nearby D2D nodes compared to that from UAV-BSs.

In addition, Fig. 3 illustrates that a low UAV SNR threshold value leads to high throughput performances. The UAV-first strategy with $\eta_{\text{UAV}} = 12$ dB outperforms that with $\eta_{\text{UAV}} = 15$ dB by 30%. This is reasonable since a lower threshold will result in more users connecting to UAV-BSs.

From Fig. 4, we can observe that the total throughput served by the GBS increases as the density of users increases. The same phenomenon is observed for different UAV densities. For example, using the UAV-first strategy with $\lambda_{\text{UAV}} = 9$ per km^2 increases the total throughput about 100% compared to that with $\lambda_{\text{UAV}} = 3$ per km^2 in case that $\lambda_{\text{user}} = 300$ per km^2.

Moreover, we also find that different user densities will lead to different degrees of influence on the throughput in the UAV-first strategy. This confirms the necessity of cache-enabled UAVs, especially for dense urban areas. Based on the obtained results, the service provider can determine which caching strategy to use according to the user density and the corresponding traffic demand.

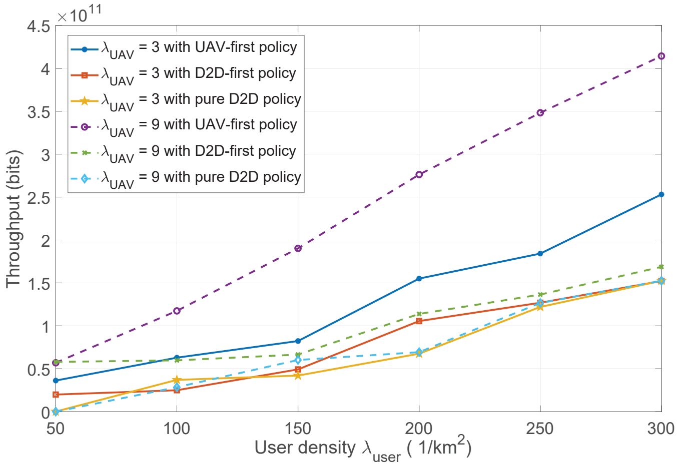

Fig. 4. Throughput performance comparisons with different user densities.

V. Conclusion

In this paper, we investigated the joint cache node selection and UAV-BS movement problem, which aims to maximize the total cache-aided throughput in a combined UAV and D2D cache network. A probabilistic caching with K-means based UAV-BS movement design scheme was proposed to deal with the formulated non-convex optimization problem. Simulation results demonstrated significant performance gains of the proposed scheme as well as the necessity of deploying cache-enabled UAVs in wireless D2D caching networks. In future work, we will exploit a more general model that considers the resource allocation among multiple UAVs.

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