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# Caching UAV-Enabled Small-Cell Networks

Nan Zhao*†, *Senior Member, IEEE*, F. Richard Yu‡, *Fellow, IEEE*, Lisheng Fan§, Yunfei Chen¶, *Senior Member, IEEE*, Jie Tang‖ (Corresponding Author), *Senior Member, IEEE*, Arumugam Nallanathan**, *Fellow, IEEE*, and Victor C. M. Leung††, *Fellow, IEEE*

*School of Information and Communication Engineering, Dalian University of Technology, Dalian, China

†School of Information Science and Technology, Qingdao University of Science and Technology, Qingdao, China

‡Department of Systems and Computer Engineering, Carleton University, Ottawa, Canada

§ School of Computer Science and Educational Software, Guangzhou University, China

¶School of Engineering, University of Warwick, Coventry CV4 7AL, U.K.

‖School of Electronic and Information Engineering, South China University of Technology, Guangzhou, China

**School of Electronic Engineering and Computer Science, Queen Mary University of London, London E1 4NS, U.K.

††Department of Electrical and Computer Engineering, the University of British Columbia, Vancouver, Canada

**Abstract**

Unmanned aerial vehicles (UAVs) can be utilized to provide flexible wireless access in future wireless networks, with larger coverage and higher transmission rate. However, the wireless backhaul for UAVs is usually capacity-limited and congested, and UAVs cannot operate for a long time due to the limited battery life. In this paper, a framework of caching UAV-enabled small-cell networks is proposed, to offload data traffic for the small-cell base stations via caching. In the proposed scheme, the most popular contents are stored at the local caches of UAVs in advance, which can be delivered to mobile users directly from the caches when required. Thus, the congestion of wireless backhaul can be alleviated, the energy consumption can be reduced, and the quality of experience can be improved.

*(Corresponding author: Jie Tang.)*

Based on this framework, several typical schemes of caching UAV-enabled small-cell networks are demonstrated, and the distributed caching strategy for UAVs is discussed. For illustration, a case study of interference management is also presented. Finally, several interesting research issues and challenges are discussed for caching UAV-enabled networking.

**Index Terms**

Distributed caching, quality of experience, small-cell networks, unmanned aerial vehicle (UAV), wireless backhaul.

## I. Introduction

*Unmanned aerial vehicles* (UAVs), also called drones, are expected to be utilized in a variety of civil services, e.g., disaster detection, medical rescue, wild animal tracking, etc., due to their decreasing cost and size. In addition, UAVs can also be exploited to provide flexible access and high-speed transmission in the future wireless networks [1]–[4]. When UAVs are utilized, the wireless connection can be established without fixed infrastructure. Thus, the communication coverage can be expanded and the transmission rate can be enhanced [5], [6]. In the next-generation wireless networks, small cells will be densely deployed to meet the rapidly increasing demand for data services. UAVs can be leveraged to improve the small cells coverage and boost capacity [7], [8]. In the UAV-aided small-cells, the UAV can be used as a mobile base station (BS) to help the small-cell BSs (SBSs) by offloading data traffic through wireless backhaul, especially in extremely crowded areas and times. However, there exist two fundamental limitations in UAV-enabled communications. First, UAVs are battery-limited [8] and thus, they cannot operate for a long time if the energy utilization is not properly scheduled. Also, the wireless backhaul that connects UAVs to the core network is capacity-limited, causing great energy consumption [2].

On the other hand, content-centric networking via *caching* is a promising technology for future mobile systems [9]. In small-cell networks using caching, the popular contents are stored at the caches of SBSs during off-peak times and thus, they can be transmitted to the small-cell users (SUs) directly during peak times without using the backhaul links [10], [11]. Traditionally, each single file is cached at a specific SBS. In [12], a novel decentralized caching scheme was proposed by separating each file into several segments cached at different SBSs without coordination. Through proper coding, the cached files in the decentralized scheme can be shared with more users at a transmission rate close to the centralized scheme [13], [14]. Another important issue of caching is the content cached at a specific SBS. This can be solved by using popularity analysis. Thus, caching at the edge of mobile systems is an effective method to alleviate the congestion of backhaul, reduce transmission latency, and save energy consumption.

The aspects of UAV and caching are often studied separately in the literature. In the existing UAV studies, recent advances in caching are largely ignored. Also, for caching, UAVs have not been used as its carrier. Nevertheless, when caching is harnessed, the data traffic can be delivered to the mobile users directly from the local caches at the UAVs to avoid the use of the wireless backhaul. Therefore, the pressure of wireless backhaul can be alleviated effectively with less energy consumption via caching in the small-cell networks with UAVs, which will no longer act as the bottleneck of transmission capacity between UAVs and mobile users.

In this article, we present a caching-UAV framework, in which UAVs with caches are planned to assist the SBSs to provide high-speed data transmission in small-cell networks. First, an overview of UAV-enabled networking is presented, and the motivation of caching UAV is introduced. The framework of caching UAV-enabled small-cell networks is proposed. Then, typical schemes of caching UAV-enabled small-cell networks are demonstrated in detail. The distributed caching strategy for UAVs is presented. As a case study, interference management for UAV-enabled small-cell networks is then presented. Finally, we point out some interesting research issues and challenges for caching UAV-enabled small cells.

The rest of this article is organized as follows. In Section II, the framework of caching UAV-enabled small-cell networks is proposed. Then, some typical schemes of caching UAV-enabled small-cell networks are demonstrated in Section III, and distributed caching strategy for UAVs

TABLE I

SOME OF THE TYPICAL WORKS ON UAV-ENABLED NETWORKING

| **Year** | **Authors** | **Features and advantages** |
|---|---|---|
| 2016 | Y. Zeng, etc. [1] | Summary of architecture, channel characteristics, and design considerations |
| 2016 | L. Gupta, etc. [2] | Thorough survey of important issues in UAV networking |
| 2017 | D. He, etc. [3] | Security of UAV communications |
| 2016 | M. Mozaffari, etc. [4] | UAV with underlaid D2D Network |
| 2016 | Y. Zeng, etc. [5] | UAV-enabled relaying |
| 2017 | J. Lyu, etc. [6] | Placement optimization of UAVs |
| 2016 | V. Sharma, etc. [7] | UAV-enabled HetNets |
| 2016 | S. Koulali, etc. [8] | Energy consumption optimization |

are discussed in Section IV. In Section V, a specific case study of interference management for caching UAV-enabled networking is presented. In Section VI, some research issues and challenges are pointed out, followed by the conclusions and future work in Section VII.

## II. FRAMEWORK OF CACHING UAV-ENABLED SMALL-CELL NETWORKS

Plenty of research efforts have been devoted to the study of UAV-enabled networking, especially in the past two years, due to its promising performance and flexible utilization. Some representative works are listed in Table I[1]. We can observe that the research on UAV-enabled networking is developing rapidly [1], [2], and various works have focused on, e.g., security issues of UAV communications [3], coexistence of UAV with device-to-device (D2D) links [4], UAV-enabled relaying systems [5], optimal placement of UAVs [6], UAV-enabled heterogeneous networks (HetNets) [7], and energy consumption optimization [8], etc.

Although UAVs can help the conventional cellular networks achieve higher transmission rate with much wider coverage of wireless connection, owing to its flexible access and short-range line-of-sight (LOS) channels, there still exist some fundamental limitations in UAV-enabled networking, summarized as follows.

[1]Due to the space limitation, we cannot list all of them.

- *Wireless Backhaul Limitation:* UAVs can provide the data service for mobile users with the support of wireless backhaul links that connect them to the core network. Thus, the transmission rate achieved by the UAVs to the users is limited by the capacity of wireless backhauls, which are usually very congested during peak periods.
- *Battery Limitation:* UAVs cannot rely on fixed power supply. Instead, batteries should be carried to support their operation. Thus, the UAV communications are battery-limited, and energy-aware algorithms and schemes should be well developed to save energy for UAV-based networks.
- *Mobility Limitation:* The high mobility of UAVs will result in severe Doppler effect, which should be compensated. In addition, the high mobility of UAVs makes it difficult to estimate the channel state information (CSI) accurately, and the conventional coding methods of multiple-input and multiple-output (MIMO) cannot be effectively utilized.

Fortunately, the above wireless backhaul and battery limitations can be relieved through the method of caching. With caches mounted at UAVs, the popular contents can be cached during off-peak period in advance, and they can be picked up and transmitted to the mobile users directly from the local caches, when the wireless backhaul links are congested. Consequently, the pressure of wireless backhaul on UAVs can be effectively alleviated, and the transmission rate to the mobile users can be enhanced accordingly. In addition, when the contents are fetched from the caches of UAVs directly, instead of delivering from the wireless backhaul, the energy consumption can also be reduced significantly, due to the fact that caching can be established at off-peak times when the UAVs are recharging on the ground, through fixed energy supply instead of batteries. Thus, in this article, the framework of caching UAV-enabled small-cell networks is presented, as shown in Fig. 1.

In this figure, a cache is equipped at each UAV, which can be reloaded with popular contents either through wireless backhaul from the macrocell BS (MBS) as UAV 1 and UAV2, or through

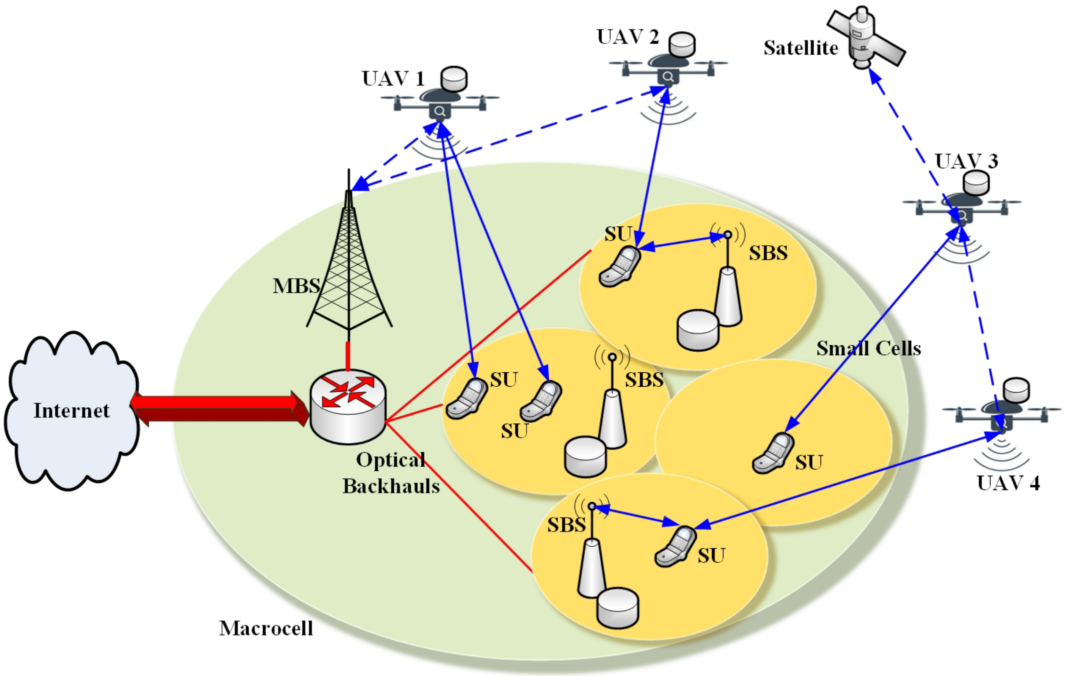


Fig. 1. Framework of caching UAV-enabled small-cell networks.

wireless backhaul from the satellite as UAV 3. As for UAV 1, it broadcasts the cached segments of the required content to two SUs in the same small cell, due to its high popularity. After that, the other segments of the content can be transmitted to these two SUs by the SBS. With regard to UAV 2, it helps the SBS offload data traffic from its local cache to the corresponding SU simultaneously. When UAV 3 is considered, it serves as the mobile BS for the small cell to provide data service via caching, i.e., no ground SBSs are available in this small cell. For UAV 4, it is located far from the MBS, and do not have access to the satellite either. Thus, it can download the popular contents from its neighbouring UAV 3 in a D2D manner, and provide data service to its serving SU accordingly. Therefore, caching UAV-enabled small-cell networks can be achieved in different ways, and some of the typical schemes will be presented in the next section.

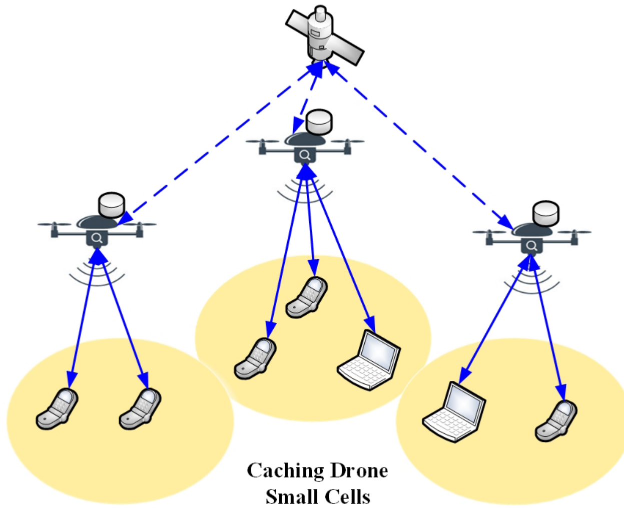


Fig. 2. Small-cell networks based on mobile UAV base stations without ground SBSs.

## III. Typical Schemes of Caching UAV-Enabled Small-Cell Networks

Some of the typical schemes for caching UAV-enabled small-cell networks are presented and analyzed in this section as follows.

### A. *Mobile Caching UAV Base Stations Without Ground SBSs*

In the first scheme, caching-enabled mobile UAVs act as BSs to serve the SUs, without deploying any SBSs on the ground, as shown in Fig. 2, which is also called drone small-cell networks [6]–[8]. Centralized caching strategy can be adopted in this scheme, due to the fact that each small cell is served by only one UAV without any SBSs. This scheme is suitable to recover the data service rapidly in the events of emergent accidents or disasters with no or damaged infrastructure, e.g., earthquake and fire. Thus, the UAVs cannot access to any BSs. Instead, they usually fetch the data traffic via the wireless backhaul from satellites or emergency communication vehicles.

When the mobile UAV BSs are utilized, they are more convenient to be deployed and relocated according to the specific requirements, compared to the conventional ground SBSs with fixed locations. However, there still exist some key disadvantages, due to the capability and battery

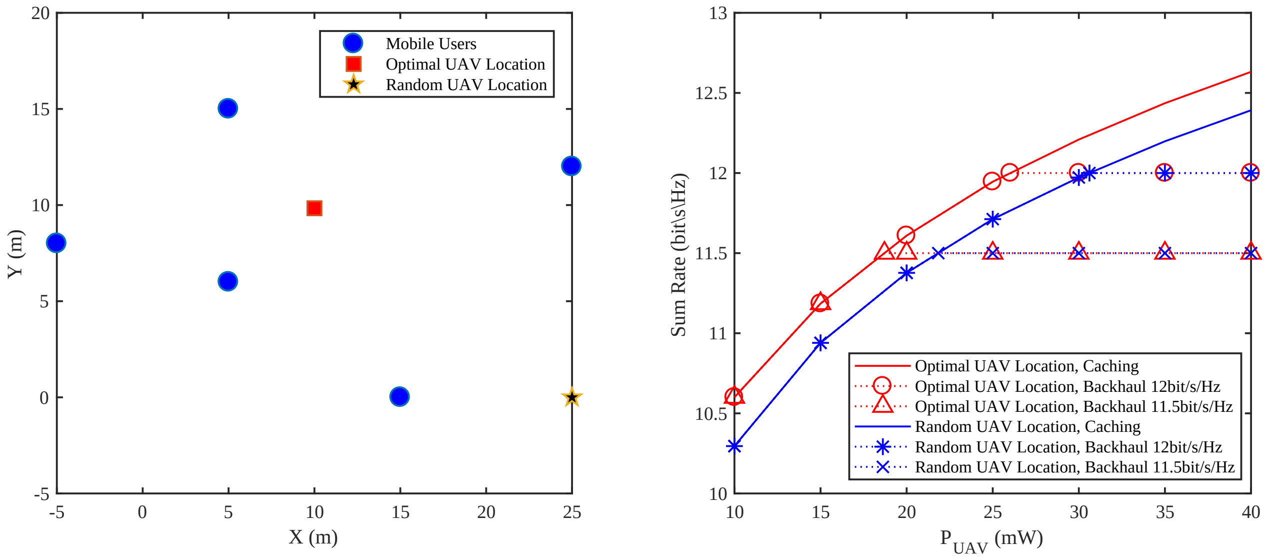


Fig. 3. Locations of the UAV BS and users in the horizontal dimension, and the sum rate comparison of the NOMA UAV network through caching or limited wireless backhaul.

limitations of UAVs. Especially, when plenty of SUs exist in each small cell, the UAVs will be overloaded. This consumes a large amount of energy. To solve this problem, storing the most popular contents at local caches of UAVs can alleviate the pressure of wireless backhaul, provide higher transmission rate, and reduce energy consumption. In addition, this scheme is not suitable for applications with fixed infrastructure and crowded users. In this case, the UAVs should only assist the ground SBSs to provide data service to the mobile users, which is the main focus of this article.

We further consider a single-antenna caching UAV BS that provides wireless service to 5 ground users via non-orthogonal multiple access (NOMA), as shown in Fig. 3(a). The UAV is deployed at a fixed height of 50 m, and the power of the background noise is set to -110 dBm. The location and transmit power of the UAV are jointly optimized to maximize the sum rate of users. In Fig. 3 (b), simulations are performed to compare the sum rate when the UAV is caching-enabled or the UAV can only obtain the required files through limited wireless backhaul. From the results, we can see that the sum rate of users served by the caching UAV increases with

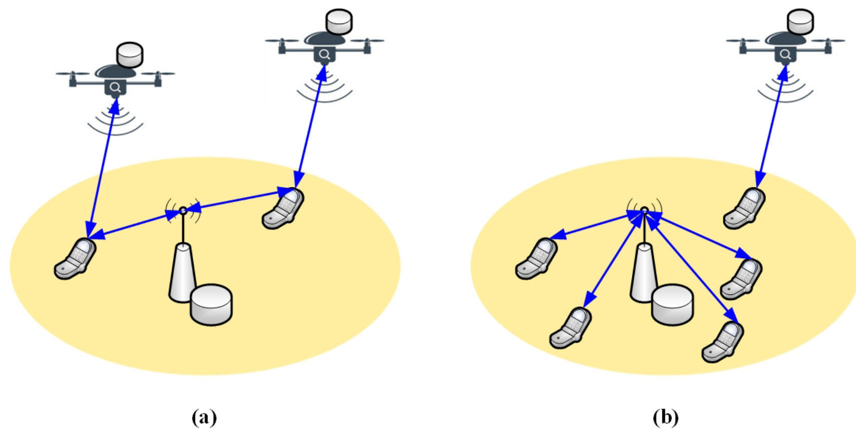


Fig. 4. Small-cell networks with caching UAV offloading. (a) Simultaneous service by SBS and UAV. (b) Separated service by SBS and UAV.

the transmit power, without the need of wireless backhaul. On the contrary, for the case without caching, the sum rate will not increase when it reaches the limitation of wireless backhaul, no matter how high the transmit power is. Thus, caching can help the UAV BS to achieve higher transmission rate and reduce the load of wireless backhaul.

### *B. Caching UAV offloading for SBSs*

For networks with fixed infrastructure, the caching UAVs can help SBSs offload data traffic to SUs as shown in Fig. 4. In the scheme, the SBS and UAVs can provide data services in a complementary way, and the pressure of both the SBS and UAVs can be relieved. In addition, with the help of proper caching, the overload of the wireless backhaul for UAVs can be reduced significantly, the energy consumption can be saved, and thus the quality of experience (QoE) of SUs can be improved. The proposed caching UAV offloading scheme for SBSs can be categorized according to Fig. 4 as follows.

*(1) Simultaneous Service by SBS and UAV:* When there are not so many SUs in the small cell, UAVs can help the SBS offload data to the SUs simultaneously, as shown in Fig. 4(a). In this mode, the overload of SBSs is not very high, and it can support wireless connection to all the

SUs in the small cell. Some selected popular contents are divided into segments via distributed caching strategy, some of which are cached at the SBS, while the others are cached at the UAVs. When a certain cached content is required by a specific SU, all of its segments are delivered to this SU, from both the SBS and a corresponding UAV, simultaneously.

*(2) Separated service by SBS and UAV:* In the cases when there exist plenty of SUs in the small cell with only a few UAVs, the network is congested and the SBS cannot support the data transmission tasks for all the SUs at the same time. In this scenario, some of the SUs are served by the SBS at each time slot, and the other ones are served by the UAVs, as shown in Fig. 4(b). Specially, the popular contents are divided into segments and cached partially at the SBS and UAVs in advance. When they are required by the SUs, their segments can be organized to transmit by the SBS and UAVs separately at different time slots.

## IV. Distributed Caching Strategy for Caching UAV-Enabled Networking

To make the caching of the SBS and UAVs more efficient and to guarantee the performance of caching UAV-enabled small-cell networks, the caching strategy of the SBS and UAVs should be well designed. Through dividing each popular content into segments and caching them at the SBS and UAVs in a distributed way as shown in Fig. 5, more contents can be cached partially at each UAV, and thus, more requirements of SUs can be covered by the SBS and each UAV through caching.

In Fig. 5, assume that 1 SBS and 3 UAVs are providing data services for 6 SUs. These 6 SUs require 6 files, $A$, $B$, $C$, $D$, $E$ and $F$, respectively, which are all cached at the SBS and UAVs in a distributed manner. Each file is divided into 12 segments, 6 of which are cached at the SBS and 2 of which are cached at each UAV, due to the fact that the cache at the SBS is larger than that at the UAV. Nevertheless, the UAVs can serve the users simultaneously, and thus the total size of caches at these UAVs can catch up with that at the SBS. The SBS can only allow

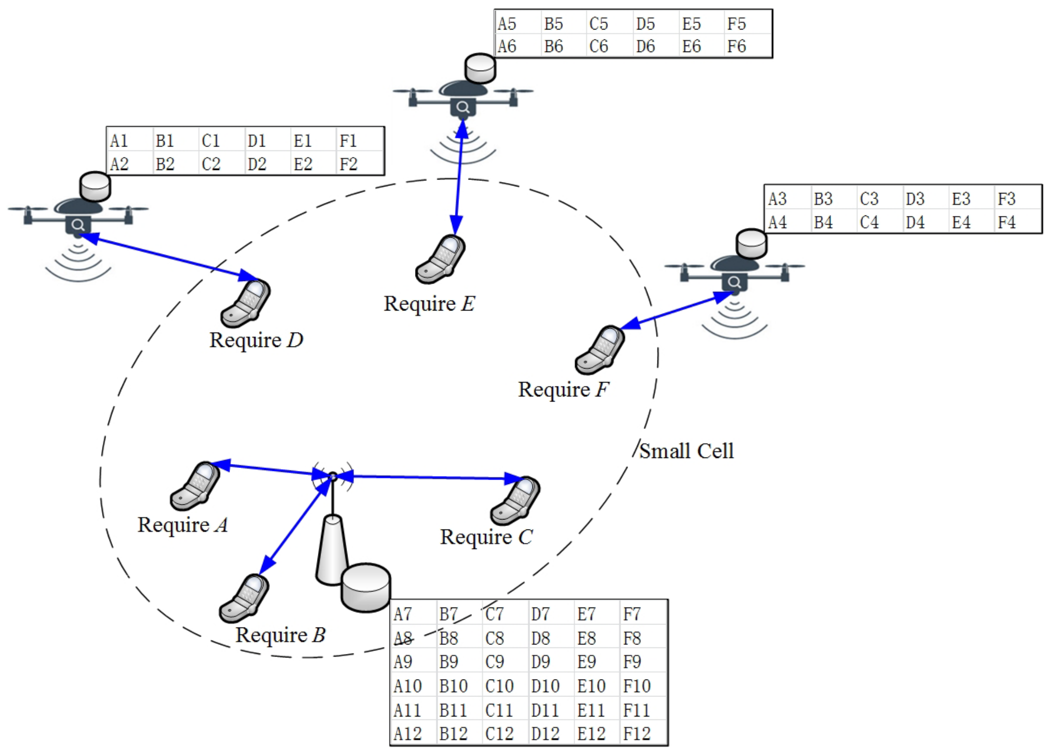


Fig. 5. Demonstration of distributed caching for UAV-enabled small-cell networks.

the transmission to 3 SUs due to its limited capability, and each UAV is communicating with a single SU at each time slot. Therefore, the SBS and 3 UAVs can cooperatively transmit the segments of these files to the SUs directly from their local caches. Assume that two segments can be delivered to each SU during each time slot, either by the SBS or a certain UAV, and thus, the transmission of all these 6 files to their corresponding SUs can be finished within 6 time slots. In the system, the UAVs can move flexibly, and they can fly close to the served SU to provide high-quality transmission. Using the above method, each UAV can provide data service to all the SUs. On the contrary, only one SU can be served by each UAV in the conventional centralized caching strategy. In addition, although the required file of each SU should be fetched from all the UAVs and the SBS cooperatively, the missed segments can be transmitted by other terminals through the backhaul as a backup, when some of the UAVs cannot be connected or even damaged.

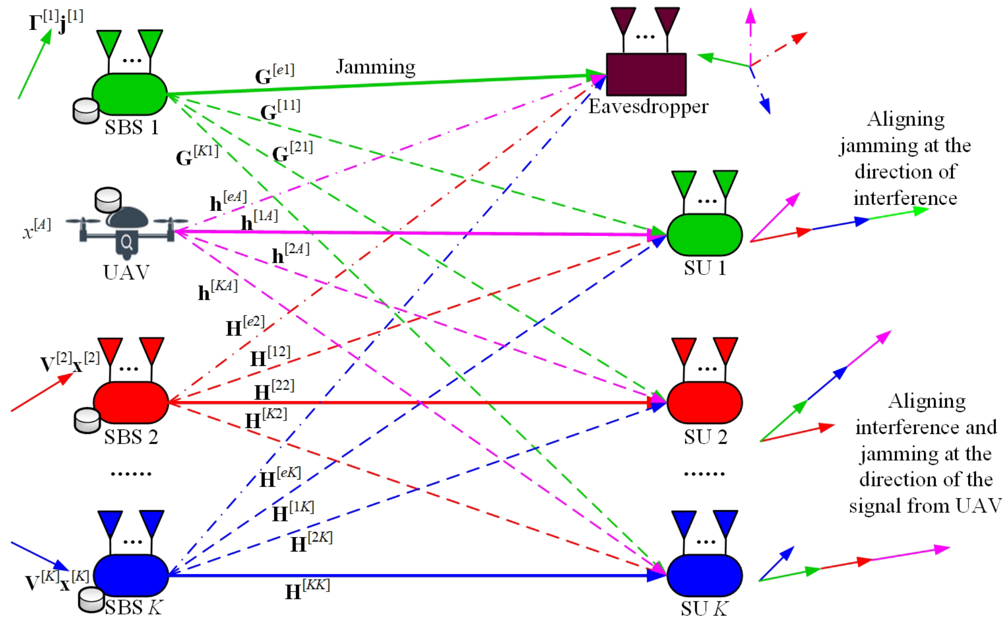


Fig. 6. A case study of interference management for caching UAV-enabled small-cell networks.

There also exists a special case of this distributed caching strategy, in which scalable videos are provided to the SUs in small-cell networks. Each video is divided into a base layer (BL) and an enhancement layer (EL). When an SU requires only fundamental viewing quality, only the BL should be transmitted to it. When the SU requires high-quality video to watch, the EL should also be transmitted to this SU in addition to BL. Therefore, the BL segments can be cached at the SBSs, with the EL segments cached at the UAVs. The UAVs should only transmit the EL segments to the SUs when required, and the data traffic of UAVs can be alleviated with lower energy consumption.

## V. A Case Study of Interference Management

An important issue for caching UAV-enabled small-cell networks is how to manage interference among small cells effectively. Several methods can be adopted for interference management, and we present a case study that exploits interference alignment (IA) to achieve this [15], as illustrated in Fig. 6.

### A. Secure Caching UAV-enabled Small-Cell Networks via IA

Assume that there are $K$ small cells with $K$ SBSs, and one active SU exists at the specific frequency band of each small cell. One single-antenna UAV with caching is considered to provide data service together with SBSs. Without loss of generality, we assume that the UAV provides data service to the 1st SU. A passive eavesdropper also exists trying to grab the information transmitted by the legitimate SBSs and UAV. When the transmission is performed, severe interference will appear among SUs if not properly managed. IA is exploited to cooperatively design the precoding matrices of the 2nd to the $K$th SBS. Specifically, at the 1st SU, the interference from other SBSs should be constrained into a certain subspace, which can be eliminated perfectly by its decoding matrix $\mathbf{U}^{[1]}$ to recover the information from UAV, i.e., $\mathbf{U}^{[1]}\mathbf{H}^{[1k]}\mathbf{V}^{[k]} = \mathbf{0}$, $k = 2, 3, \ldots, K$. $\mathbf{H}^{[kj]}$ is the channel matrix from the $j$th SBS to the $k$th user. At the 2nd SU to the $K$th SU, the interference from other SBSs should be aligned at the direction of the signal from the UAV to recover its transmitted information, i.e., $\mathbf{U}^{[k]}\mathbf{h}^{[kA]} = \mathbf{0}$, $\mathbf{U}^{[k]}\mathbf{H}^{[kj]}\mathbf{V}^{[j]} = \mathbf{0}$, $k = 2, 3, \ldots, K$, $j = 2, 3, \ldots, K, j \neq k$, where $\mathbf{h}^{[kA]}$ is the channel vector from the UAV to the $k$th user. Thus, the interference among the $K$ SUs can be perfectly eliminated by properly designing the precoding and decoding matrices according to IA. In addition, as the 1st SU is served by the UAV, the 1st SBS is idle. To fully utilize the resource, jamming signal is generated by the 1st SBS to combat with the eavesdropping, without affecting the legitimate transmission, i.e., $\mathbf{U}^{[k]}\mathbf{G}^{[k1]}\mathbf{\Gamma}^{[1]} = \mathbf{0}$, $k = 1, 2, \ldots, K$, where $\mathbf{G}^{[k1]}$ is the channel matrix from the 1th SBS to the $k$th user and $\mathbf{\Gamma}^{[1]}$ is the precoding matrix for the 1st SBS.

### B. Discussions

In the proposed scheme above, the interference-free transmission can be achieved in the caching UAV-enabled small-cell networks, with the legitimate security guaranteed, when enough antennas are equipped at each node according to the feasibility conditions of IA. The interference management of caching UAV-enabled small-cell networks can also be achieved by other methods, e.g., the optimization of beamforming matrices of each SBS according to the specific objective function, and we just present a case study by means of IA. Besides, due to caching the popular contents at the SBSs and UAV, some multicast channel may appear when the same popular content is required by different SUs. In this case, the network topology will become simpler and the IA scheme should be redesigned specifically according to the caching status [10]. Furthermore, when the users can be served by several caching UAVs, more SBSs can be utilized to generate jamming signal or go to sleep mode. However, the interference management will become more intractable due to the single antenna at each UAV. Last, some future research should be directed to establish deeper relationship between caching and IA for the UAV-enabled small-cell networks.

## VI. Open Research Issues and Challenges

Although some fundamental aspects on caching UAV-enabled small-cell networks have been addressed in this article, there are still some open research issues and challenges that should be addressed in the future.

**Optimal Caching Strategy:** Although the caching strategy for UAV-enabled small-cell networks is analyzed in Section IV, it is very important to improve the caching efficiency and guarantee the transmission performance. In the distributed caching strategy, how to divide the popular content into segments and how to manage the distributed caching among UAVs and SBSs, are essential issues in local caching to improve the performance. Besides, the caching performance can also be enhanced by the coding method [12], which is similar to network coding, i.e., to transmit the hybrid information by processing the segments of different contents. For the video-streaming contents, the maximum distance separable (MDS) coding can be applied to guarantee the caching efficiency.

**Popularity Analysis:** One key challenge of UAV-enabled small-cell networks is to predict the most popular contents for the local SUs according to their usual habits and thus, determine which contents should be stored within the limited local caches at the UAVs. Although it has been reported that big data analytics can be utilized to solve this problem, e.g., deep reinforcement learning, it is still difficult to perform popularity analysis fast enough for a tremendous amount of information, or to update the caching contents of the UAVs timely. In addition, how to control the caching process of UAVs, by a certain control center or in a self-organized way, is also important to achieve in practical systems.

**Communication Security:** Secure communication is a critical factor to guarantee the normal operations of caching UAVs [3]. First, UAVs may carry some sensitive information, which should not be eavesdropped. Also, UAVs are vulnerable to attack, which will affect their proper operation or even cause accidents. In the case study of Section V, the threat of eavesdropping in the caching UAV-enabled small-cell networks is tackled by the artificial jamming signal. However, there exist many other potential attacks that make caching UAVs unsafe and unstable, e.g., adversarial jamming, GPS spoofing, WiFi attack, etc., which all should be well researched in the future.

**Energy Saving:** Energy consumption is another challenge for UAV-enabled communications, due to the battery limitation [8]. Caching can help UAVs alleviate the congestion of wireless network, and thus save the energy effectively. In addition, in the case study of Section V, the energy aspect is also considered, e.g., one antenna mounted, no complicated coding, etc. Nevertheless, there is still a long way ahead to save energy and prolong operational time for UAVs. First, the transmitted power should be adaptive according to the requirements of SUs to minimize the energy consumption. Then, the energy-aware deployment and operation should be well designed. Besides, energy harvesting techniques should be fully utilized to replenish UAVs, such as the solar energy.

**Interference Management:** Interference is always a key issue for wireless networks, which is also true regarding to the caching UAV-enabled small-cell networks [10]. In Section V, we provide a case study of interference management for UAV-enabled small-cell networks, which exploits IA to achieve it. Nevertheless, many other interference management techniques can also be adopted, for example, we can design the precoding and decoding matrices directly to optimize the performance. Besides, through properly caching, the network topology can be reduced, and the interference management will also becomes easier to achieve. When interference management is considered for UAVs, an essential principle is not to require UAVs to handle it, instead, interference management can be performed by the ground SBSs with high capability and sufficient energy supply.

**Joint Optimization:** When designing caching UAV-enabled small-cell networks, we should not only consider the caching and transmission, but also involve the optimization of locations and trajectories for UAVs, due to the mobility. Thus, the locations or trajectories of UAVs should be jointly optimized with the strategies of caching and communication, which is difficult to be solved. This joint optimization problems for the caching UAV-enabled small-cell networks will become a prospective research direction in the future.

## VII. Conclusions and Future Work

Two latest techniques, UAV and caching, have been combined to improve the performance of small-cell networks in this article. Specially, the most popular contents can be cached at the UAVs during the off-peak period, which can be fetched directly to help the SBSs provide data traffic for SUs at peak time. Thus, the overload of wireless backhaul for UAVs can be relieved via caching, the energy consumption can be reduced, and the QoE of SUs can be improved. In this article, we first presented an overview of UAV-based networking, to introduce the framework of caching UAV-enabled small-cell networks. Then, several typical schemes of caching UAV-enabled small-cell networks were demonstrated. In addition, the distributed caching strategy for UAVs were presented, followed by a case study of interference management for UAV networking using IA. Finally, some research issues and challenges on caching UAV-enabled small-cell networks were pointed out. Future work is in progress to address these research challenges.

## VIII. Acknowledgments

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## BIOGRAPHIES

Nan Zhao [Senior Member, IEEE] (zhaonan@dlut.edu.cn) is an associate Professor at Dalian University of Technology, China, and also a cooperative professor at Qingdao University of Science and Technology, China. He received the Ph.D. degree in information and communication engineering in 2011, from Harbin Institute of Technology, Harbin, China. He received the IEEE Communications Society Asia Pacific Board Outstanding Young Researcher Award in 2018. He is an Editor for IEEE Transactions on Green Communications and Networking.

F. Richard Yu [Fellow, IEEE] (richard.yu@carleton.ca) is a Professor at Carleton University, Canada. His research interests include connected/autonomous vehicles, security, and wireless. He serves on the editorial boards of several journals, including Co-Editor-in-Chief for Ad Hoc & Sensor Wireless Networks, Lead Series Editor for IEEE Transactions on Vehicular Technology, and IEEE Transactions on Green Communications and Networking, IEEE Communications Surveys & Tutorials. He is a Distinguished Lecturer and the Vice President (Membership) of the IEEE Vehicular Technology Society.

Lisheng Fan (lsfan@gzhu.edu.cn) is a Professor of School of Computer Science at the Guangzhou University, Guangzhou, China. He has co-authored more than 50 technical papers in the areas of wireless networks and mobile systems. His current research interest include the wireless big data, machine learning, mobile computing and networking.

Yunfei Chen [Senior Member, IEEE] (Yunfei.Chen@warwick.ac.uk) received his B.E. and M.E. degrees in electronics engineering from Shanghai Jiaotong University, Shanghai, P.R.China, in 1998 and 2001, respectively. He received his Ph.D. degree from the University of Alberta in 2006. He is currently working as an Associate Professor at the University of Warwick, U.K. His research interests include wireless communications, cognitive radios, wireless relaying and energy harvesting.

Jie Tang [Senior Member, IEEE] (eejtang@scut.edu.cn) received the B.Eng. degree from the South China University of Technology in 2008, the M.Sc. degree from the University of Bristol in 2009, and the Ph.D. degree from Loughborough University, in 2012. He is currently an associate professor at the South China University of Technology, China. His research interests include green communications, NOMA, 5G networks, SWIPT, heterogeneous networks, cognitive radio and D2D communications.

Arumugam Nallanathan [Fellow, IEEE] (a.nallanathan@qmul.ac.uk) has been a professor of wireless communications at Queen Mary University of London since September 2017. He was with King's College London from 2007 to 2017, and the National University of Singapore from 2000 to 2007. His research interests include 5G wireless networks, Internet of Things, and molecular communications. He received the Best Paper Award at IEEE ICC 2016. He is an IEEE Distinguished Lecturer. He was a Web of Science Highly Cited Researcher in 2016.

Victor C. M. Leung [Fellow, IEEE] (vleung@ece.ubc.ca) is a Professor of Electrical and Computer Engineering and holder of the TELUS Mobility Research Chair at the University of British Columbia, Vancouver, Canada. He has co-authored more than 1200 technical papers in the areas of wireless networks and mobile systems. Dr. Leung is a Fellow of the Royal Society of Canada, the Canadian Academy of Engineering and the Engineering Institute of Canada.