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D2D Communication Underlaying UAV-Enabled Network: A Content-Sharing Perspective

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Abstract: The last era has witnessed an unprecedented demand for digital content. To meet these rigorous demands, researchers have been busy developing content-sharing applications and services. The advancement in technology has aided this process. Unmanned aerial vehicles (UAVs) have gained a lot of attention in assisting cellular networks since they play a paramount role in disaster management, capacity enhancement, on-demand communication, and content dissemination. In this study, we consider content-centric UAV communication underlaid device-to-device (D2D) users. Different from the current research trends, this study considers clustering the D2D users (i.e., ground users) and UAV only deliver the requested content to the cluster heads. We considered the clustering approach since the UAV is an energy constraint device and the aim is to reduce the energy consumed by the UAV during the communication phase. Clustering the ground nodes will allow the UAV to communicate to only cluster heads as compared with a bigger group of users. Cluster heads are then responsible to forward the cached contents to their respective cluster members. A comprehensive performance evaluation of the proposed scheme was conducted by benchmarking it against state-of-the-art research works and considering various performance parameters such as throughput, energy consumption, and content delivery delay. The proposed scheme produced promising results for all parameters and against other research works as well.

Keywords: clustering; content distribution; UAV communication; D2D communication; energy consumption

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1. Introduction

Conventional cellular communications are mainly aimed at fixed terrestrial infrastructure such as ground base stations (BSs) and access points. The ever-increasing and highly diversified traffic demands of cellular communication have tested fixed terrestrial infrastructure to the limit. Therefore, to meet the current traffic demands, providing aerial connectivity has been considered an effective technique. Unmanned aerial vehicles (UAVs), helikites, and balloons are some examples of these aerial communication platforms [1–3]. Compared with other technologies, fast development and wide-range applicability have made UAVs the go-to solution for cellular networks. Utilizing UAVs as BSs promise to aid cellular networks and positively impact their performance parameters as well [4,5]. Recent research trends show that substantial research has been conducted relevant to UAV-enabled communication. UAVs can be deployed as stationary, quasi-stationary, and mobile BSs which can then be used for coverage extension, relaying, providing communication in disaster-hit areas, data collection missions, and content dissemination as well.

Content sharing dominates the cellular network's traffic. Modern and dominant applications including social media updates and data sharing, traffic monitoring, video creation of live events, and virtual reality all demand effective and aerial mobility-assisted solutions. These demands are tailor made for using UAV-enabled cellular communication systems. Most recently, device-to-device (D2D) communication is exploited for UAV-enabled networks as it offers novel solutions for content-centric and social-aware networks [6]. D2D enables the users in proximity to communicate with each other by reusing cellular resources. D2D can effectively distribute content in dense environments while maintaining the quality-of-service (QoS) of the network. Most importantly, a D2D underlaying the UAV network can be used to offload a particular set of tasks to nearby D2D devices; thus, reducing the load on the UAV. It helps in meeting the energy requirements of the UAV as well as the latency requirements of the network [7]. However, for this to work, D2D communication faces various challenges such as synchronization (especially where the UAV acts as the BS), interference mitigation, resource allocation, D2D channel estimation, air-to-ground link modeling, etc.

Numerous important tasks such as D2D channel estimation, fetching contents, and catching contents at a relay node are usually performed centrally which puts significant pressure on the conventional ground BS. In 6G, it is expected that millions of devices will be connected to cellular networks; therefore, BS-free and decentralized mechanisms are required. This study considers a UAV-enabled BS (UAV-BS), offloading the conventional BS, and distributing contents to the underlaid D2D users. Specifically, this study exploits clustering to provide the much-needed distributed mechanism for content distribution.

Despite all the benefits of UAV communication, there are several challenges as well. In particular, power and energy constraints and limited endurance. The existing designs for UAV-enabled communication consider delivering content to all the users in a particular area. In such a scenario, a communication link between the UAV and ground node (GN) needs to be maintained until the content transmission is successful for all the requestors. Due to the limited battery of UAVs, this sort of transmission can be possible only for a limited duration of time. Otherwise, service interruption may take place. Considering all these aspects of UAV communication, as opposed to the recent literature, this study considers a clustering approach to delivering content. We consider clustering the GN resulting in various clusters. Each cluster will be represented by a cluster head (CH). The UAV-BS communicates only to the CH; therefore, reducing the number of nodes it needs to communicate and maintain the connection, which saves energy, and as found by this study enhances the performance of content sharing as well.

The main contributions of this work are as follows.

- This research presents a comprehensive study on the utilization of clustering for content-centric networks targeted to be served by UAV-BS-underlaid D2D communication. This study is significantly different from the relevant literature since clustering has been under studied and conventionally either the UAV communicates to all the users in a given area or a hybrid approach is implemented where the UAV, BS, and D2D work together to deliver content.
- Though this article does not consider UAV trajectory planning, however, we introduce the concept of nested clustering to find a suitable stopping point for the UAV for content distribution.
- A comprehensive performance evaluation of the proposed scheme is presented considering various performance parameters such as energy consumption, network throughput, and content delivery delay. This study paints a promising picture for utilizing clustering in UAV-enabled scenarios for content delivery. This scheme is ideal for social events such as a football match in a stadium.
- A comparative study with state-of-the-art benchmarked schemes is presented as well. It is promising that all the considered performance parameters perform better than conventional and state-of-the-art schemes. Since the UAV only communicates with the CH, therefore, it is important to study the rates enjoyed by CH while downloading content from the UAV. To demonstrate a practical scenario, the height of the UAV is varied, and corresponding rates enjoyed by the CH were evaluated as well.

2. Literature Review

In this section, a detailed literature review is presented pertinent to UAV-enabled content distribution mechanisms. Extensive research works have targeted UAV-enabled communications and the following text explores the main ideas and key findings of these works while demonstrating the need of the proposed clustering approach for UAV-enabled content distribution.

Content-delivery/content-sharing infrastructure aims to reduce redundant transmissions by strategically placing content servers at various locations [8]. It helps in alleviating the burden on the central controller, reducing congestion, and maximizing bandwidth utilization. Initially, the whole emphasis of the research revolving around content delivery mechanisms was on optimal cache placement and proposing distributed architectures. Mobile nodes were communicating directly to content servers with wireless backhaul connections to central controllers. However, with the recent advances in UAV development technology, a paradigm shift has been observed considering UAVs as a befitting option for content distribution.

A comprehensive study regarding UAV-enabled wireless communication has been presented in [2]. Research challenges and various opportunities that UAVs bring to the world of wireless networks are detailed. Different applications and use cases of UAV-enabled communication are discussed as well. Further advancement in this field produced numerous research works deploying UAVs as aerial BSs [9–11].

UAV-enabled communication has been widely used for content distribution and sharing. Different mechanisms and content distribution architectures have been proposed in the literature [12]. Different approaches to content distribution can broadly fall into three categories: (i) centralized, (ii) decentralized, and (iii) hybrid [13]. The details of these approaches are summarized in Figure 1.

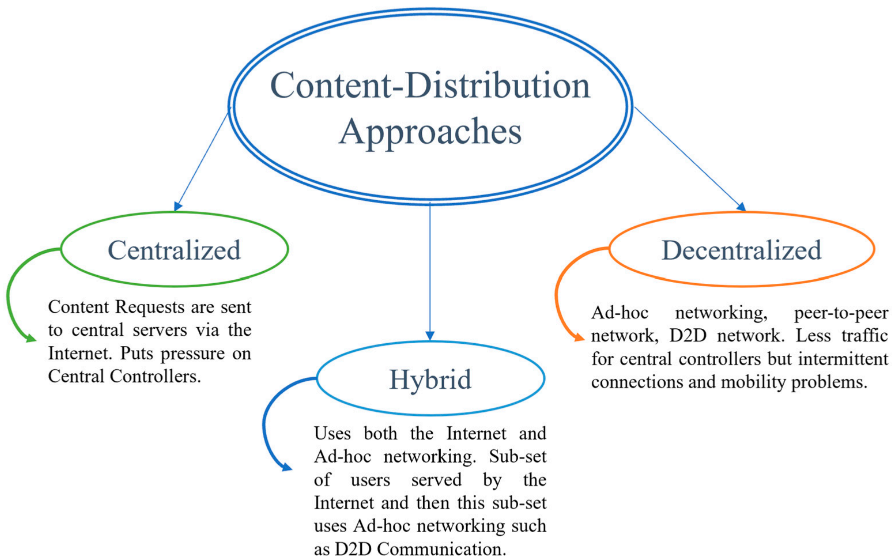

Figure 1. Summary of content distribution approaches.

Numerous research works have been dedicated to developing UAV-based content distribution schemes in heterogeneous networks (HetNets). A cache-enabled and UAV-aided content distribution scheme was proposed in [14]. It targeted mobility issues along with achieving energy-efficient solutions. The study presented in [15] proposed a content delivery architecture for a UAV-supported network. This work also targeted delivering content efficiently to mobile users.

A slightly different but effective approach has been taken by other researchers involving D2D communication with UAV-enabled caching schemes. This increased the efficiency of content distribution [16]. The introduction of D2D also enabled proposals of numerous distributed architectures. Typically, UAVs transmit contents to the selected GNs, which then employ D2D communication to share the contents with the rest of the users [17]. A similar approach has been taken in the work presented in [18], which aims to address the endurance issue of UAV-enabled communication. The authors proposed active caching of popular content at selected GNs so that devices can communicate with each other to share content via D2D communication.

Some research works have considered maximizing throughput of the UAV-enabled system as well. The maximization of D2D throughput for downlink UAV-aided communication was studied in [19]. The transmit power of UAV and D2D nodes were jointly studied. UAVs have also been used as a relay for an underlaid D2D communication system [20]. In this work, spectrum sharing between UAV and D2D users was considered with the constraint of maximizing the sum rate of the network.

One of the most recent studies conducted on maximizing the global energy efficiency of UAV-enabled communication networks is presented in [21]. This study jointly optimized the throughput as well as the energy consumption of the system. Cooperative communication among multiple UAVs has been studied as well [22]. In this study, UAVs network was integrated with VANET and a multimodal optimization scenario was considered for UAVs' geographical distribution and placement to aid the VANETs. UAVs are still popularly used for providing communication infrastructure to GNs in case of natural disasters [23]. In [23], UAVs' optimal placement is investigated to cover as many ground nodes as possible. Moreover, the optimal transmission power of the ground nodes is obtained through an iterative method as well.

The above-given literature suggests that caching has received significant interest for UAV-enabled communication systems. Despite all the advancements, this field has several challenges that are yet to be addressed. Practically, UAVs have limitations due to energy and power constraints and endurance issues [18]. The current standards of UAV-enabled communication require maintaining a consistent connection between the UAV and ground nodes for transferring the required content. The endurance problems might be a significant hindrance in completing the mission. Therefore, there is a need for a different scheme that requires communication only with a few nodes that can be obtained in a shorter period, requiring less energy. There are different approaches to solving this problem; however, we believe performing clusters of GNs and caching the requested contents on cluster heads (CHs) via an aerial UAV-BS serves the purpose. This is demonstrated in the results section as well. Once content is available with CHs, D2D communication can be utilized to share with the respective cluster members. There are several benefits to this scheme. Firstly, the UAV-BS will only be communicating with cluster heads and not all the nodes in a specific geographical area. Secondly, this scheme reduces the mission time and saves energy and power; therefore, addressing the endurance issue. It is clear from all the works mentioned above and presented in Table 1 that most of the relevant works have not considered clustering and an investigation is required to evaluate the performance of the UAV-enabled system when subjected to clustering.

Table 1. An Overview of Relevant and Recent Literature.

S#.	Published Research Works	Year	UAV—Content Provider	Clustering Approach
1	[18]	2018	Yes	No
2	[24]	2018	Yes	No
3	[25]	2019	Yes	No
4	[26]	2020	Yes	No
5	[27]	2020	Yes	No
6	[28]	2020	Yes	No
7	[29]	2020	Yes	No
8	[30]	2020	Yes	No
9	[31]	2020	Yes	No
10	[32]	2021	Yes	No
11	[33]	2021	Yes	No
12	[34]	2021	Yes	No

3. System Model

We consider a social gathering, such as a football game, where a considerable number of users are assembled in a stadium. These users are assumed to be interested in content sharing. It is assumed that the requested contents are cached at the UAV. The considered scenario is depicted in Figure 2.

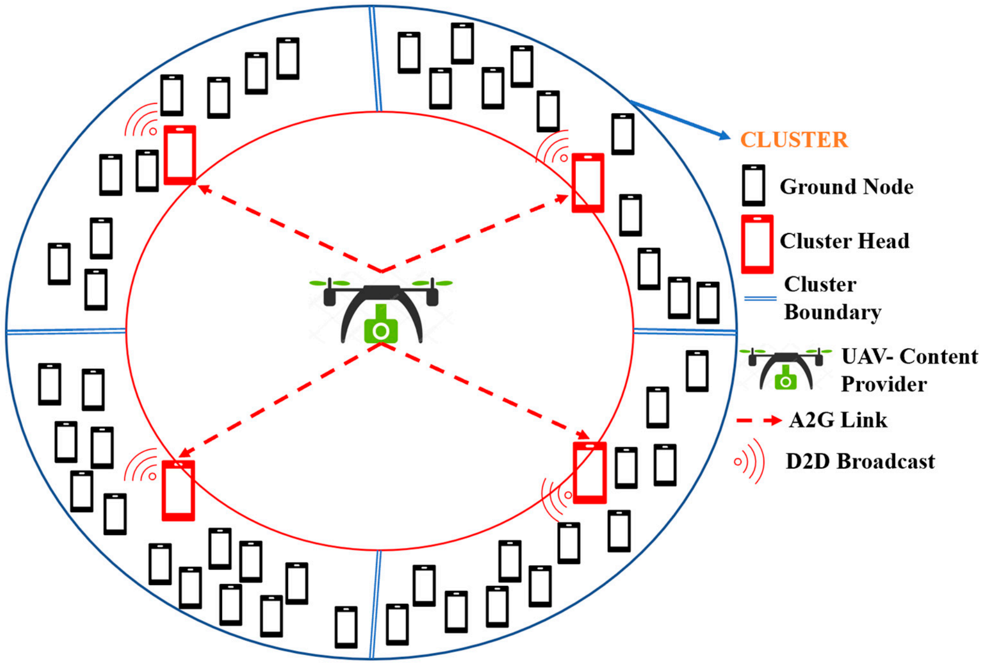

Figure 2. The system model considers a social event such as a football stadium. Ground nodes (users) are distributed in the stadium stands. The proposed scheme considers forming clusters, where each cluster is represented by a cluster head (shown as a red node in the figure). UAV-BS is the content provider, which directs them to the cluster head. Cluster heads then forward the contents to their cluster members using D2D links. The link between the UAV and cluster head is denoted by the air-to-ground (A2G) link, represented by a red dotted line.

In this study, content-centric UAV-enabled communication is considered where a UAV-BS is used for the downlink transmission. Several works have used the content pre-loading concept where the UAV-BS is loaded with popular content [35–38] and then utilized for different missions, reducing the service delay and alleviating backhaul load. We believe that proactive caching both of the UAV-BS and CHs can significantly improve the performance of content sharing. There are two important reasons for considering the clustering scenario and allowing only CHs to communicate directly with the UAV-BS. The first reason is the file retrieval cost (FRC). It should be noted that ideally, well-separated nodes are well-suited for caching popular content [18] since the probability of getting a file from a nearby node increases as compared with directly going to BSs. Secondly, endurance issues always exist for UAV-enabled missions; therefore, reducing the communication time between the UAV and the GN can positively affect energy consumption.

It is assumed that random file requests are demanded by different clusters that are forwarded to the UAV-BS via the CH. This means that the mission time of a UAV is dependent on how fast it delivers the requested content to the selected CHs instead of responding to random content requests from all the users in a given geographical area. Hence, this operation saves energy for UAVs which is demonstrated in the results, shown later in this manuscript.

As represented in Figure 2, a UAV is dispatched to a football stadium to provide UAV-assisted downlink content transmissions. Moreover, following the standard and relevant literature [33], to alleviate the backhaul requirement, the UAV is assumed to have a sufficient cache to store popular content. When the requested content from a particular cluster is stored in the UAV's cache, it can directly transmit to the CH. D2D communication then takes over to deliver content to their CMs. The D2D communication with overlay spectrum sharing is considered; therefore, interference between D2D communication and cellular services is assumed to be eliminated. Without loss of generality, we model a 3D Cartesian coordinate system for UAV and D2D communication pairs. Ground users are assumed to be approximately stationary, so the coordinates of the ground node present in cluster B can be represented by gn_B = (xgn_B, ygn_B, 0) and gn_{CH} = (xgn_{CH}, ygn_{CH}, 0) represents the coordinates of a particular CH. Though the ground users are stationary, every simulation iteration randomly generates a new distribution that represents a practical scenario. The coordinates of the jth. UAV is represented by uav_j = ($x_{uav,j}$, $y_{uav,j}$, $z_{uav,j}$). Moreover, the distance between the ground node in cluster B and the jth UAV is represented by Equation (1):

$$d_{uav_j - gn_B} = \sqrt{\left(x_{uav,j} - xgn_B\right)^2 + \left(y_{uav,j} - ygn_B\right)^2 + \left(z_{uav,j} - zgn_B\right)^2} \tag{1}$$

which can be written as Equation (2),

$$d_{uav_j - gn_B} = \sqrt{\left(x_{uav,j} - xgn_B\right)^2 + \left(y_{uav,j} - ygn_B\right)^2 + h_{uav_j}{}^2} \tag{2}$$

where h_{uav_j} is the height of the jth UAV.

It is assumed that the UAV-BS has already cached the contents using resource blocks where resource blocks represent a time and frequency resource. These resource blocks are reused by the UAV-BS to deliver the content to CHs [32]. The signal-to-interference-plus noise ratio (SINR) between the jth UAV and kth CH can be written as:

$$SINR_{uav_j - CH_k} = \frac{p_{uav_j} d_{uav_j - CH_k}^{-\alpha_{uav_j - CH_k}}}{\sum_{U=1,\ U\neq j}^{N} \ p_{uav_U} d_{uav_U - CH_k}^{-\alpha_{uav_U - CH_k}} + \delta^2} \tag{3}$$

p_{uav_j} is the power of the jth UAV, $\alpha_{uav_j - CH_k}$ is the A2G path-loss exponent for the link between jth UAV and kth CH. The additive white Gaussian noise is represented by δ^2. The distance between jth UAV and kth CH is represented by $d_{uav_j - CH_k}$, whereas $\sum\limits_{U=1,\ U\neq j}^{N} \ p_{uav_U} d_{uav_U - CH_k}^{-\alpha_{uav_U - CH_k}}$ is the interference between other UAV transmitters and kth CH. Given that the transmission bandwidth is β_T, the transmission capacity denoted by T, can be written as:

$$\mathrm{T}_{uav_j - CH_k} = \beta_T \ log_2\left(1 + SINR_{uav_j - CH_k}\right) \tag{4}$$

Similarly, transmission capacity/rate can be determined for the D2D link between the CH and CM.

The throughput of the system depends on the aggregate rate achieved by all the users of the network. In the proposed scheme, two types of users exist in the system, CH getting content from the UAV-enabled BS and CMs getting content from the CH.

The achievable rate of the cluster member can be found as given in Equation (5) [6]:

$$R_{CM_M} = \beta_T \ log_2\left(1 + \frac{p_{CH_k} h_{CM_M - CH_k}}{N_0 \ \beta_T}\right) \tag{5}$$

R_{CM_M} is the achievable rate of the mth cluster member. p_{CH_k} is the transmission power of the kth cluster head. The channel gain between the kth cluster head and mth cluster member is represented by $h_{CM_M \ - CH_k}$. N_0 denotes the noise spectral density.

3.1. Energy Consumption

The UAV consumes energy during the following activities; flight, hovering, and communication. We focus on reducing the energy consumption of the UAV during communication (i.e., particularly content distribution).

The total energy consumption of the system during the downlink transmission of the contents is presented in Equation (6a). This equation and subsequent energy consumption calculations are adapted from [39]; however, they are modified as per the considered scenario:

$$E_S = E_{UAV-COMM} + E_{CH} + E_{CM} \tag{6a}$$

where;
$E_S = energy\ consumption\ of\ the\ system$
$E_{UAV-COMM} = energy\ consumed\ by\ the\ UAE\ for\ content\ transmission$
$E_{CH} = energy\ consumed\ by\ the\ cluster\ head$
$E_{CM} = energy\ consumed\ by\ the\ cluster\ members$

$$E_{UAV-COMM} = P_{uav} * t_{transmit} \tag{6b}$$

$P_{uav} = transmission\ power\ of\ the\ UAV$
$t_{transmit} = time\ taken\ by\ the\ UAV\ to\ transmit\ contents$

$$t_{transmit} = \frac{Content\ size}{\mathrm{T}_{uav_j - CH_k}} \tag{6c}$$

$$E_{UAV-COMM} = P_{uav} * \frac{Content\ size}{\mathrm{T}_{uav_j - CH_k}} \tag{6d}$$

Considering the above-mentioned equations, the total energy consumption can now be written as follows:

$$E_S = P_{uav} * \frac{content\ size}{\mathrm{T}_{uav_j - CH_k}} + \left(\frac{content\ size *\ P_{ch,rec}}{\mathrm{T}_{uav_j - CH_k}} + \frac{content\ size *\ P_{ch}}{R_{CM_M}} \right) + \sum_{\forall m} \frac{content\ size *\ \ P_{cm,rec}}{R_{CM_M}} \tag{7}$$

The second term in Equation (7) is the addition of two factors: energy consumed by the CH to receive the content from the UAV and energy consumed to transmit the content to cluster members. The energy consumed by the cluster members to receive the content is represented by the third term.

The achievable rate of the CH is given in Equation (4). R_{CM_M} is the achievable rate of the cluster member given in Equation (5). The transmit power of the UAV and CH is denoted by P_{uav} and P_{ch}. $P_{ch,rec}$ is the power consumed by the cluster head to receive content from the UAV, whereas $P_{cm,rec}$ is the power consumed by the cluster members to receive content from the cluster head. All the values of these different parameters are taken from the standard literature, presented later in Section 5.

3.2. Content Delivery Delay

In this study, we follow the content delivery delay model presented in [27]. If the content is requested at time slot t, then according to [27], the content delivery delay $D(t)$ can be written as:

$$D(t) = backhaul\ delay(t) + transmission\ delay\ (t) + scheduling\ delay(t) \tag{8}$$

Since in this study it is assumed that the requested content is cached at the UAV, therefore, the *backhaul delay* will be zero. Equation (8) can be elaborated as:

$$D(t) = \frac{Content\ size}{\mathrm{T}_{uav_j - CH_k}(t)} + \frac{Content\ size}{R_{CM_M}(t)} + \sum\nolimits_{n=1}^{N} \left(\sum_{c=1}^{C} r_{g,c}(t) \right) L(t) \tag{9}$$

The first and second term in Equation (9) represents the *transmission delay* of the UAV and the CH, whereas the last term is the *scheduling delay*. $L(t)$ is the length of the time slot. Following other studies and 5G specifications, it is assumed to be 1 ms. $r_{g,c}(t)$ is the request of ground node g at time slot t to fetch content 'c'. 'N' represents the total number of users.

4. Clustering Mechanism

Clustering has been exploited for improving the performance of wireless networks [6,40–42]. It is shown in the literature that most of a cellular device's power is consumed during data transmission, so clustering offers a promising solution to not only optimize power consumption but also improve the energy efficiency of the network. It has been observed that clustering has been popularly used with D2D communication and other ad hoc networking scenarios. Clustering is believed to improve D2D caching efficiency and communication [42]. Therefore, we believe clustering can improve the performance of the D2D communication underlaying the UAV-enabled network as well. Most importantly, as shown in the results, it substantially reduces the energy consumption of the UAV, hence addressing the UAV's endurance issues.

In this study, we do not consider path planning; however, a calculated approach is utilized for UAV placement using the concept of nested clustering. First, the clustering algorithm (details of which can be found in Sections 4.1 and 4.2) was considered for selecting CHs among the ground nodes and then the re-application of the clustering algorithm takes place to optimize the placement of the UAV. This re-application takes chosen CHs and UAVs as the input. However, as opposed to the first step, the re-application of the clustering algorithm is only meant to optimize the placement of the UAV and not form any further clusters. In this case, the UAV is hard coded as the cluster head and the clustering algorithm only reduces the distance of the UAV to all the chosen CHs. It is important since all the CHs are fetching content directly for the UAV without involving any conventional BS.

We consider a social event, such as a football match in a stadium, similar to the scenario shown in Figure 2. It is assumed that content sharing service dominates the traffic. In this paper, we introduce the nested clustering (NS) concept that takes into account user clustering as well as user-UAV clustering. To the best of the author's knowledge, this approach has not been used in the literature. The following Figure 3 describes the underlying concept. The subsequent subsections define each of the clustering steps.

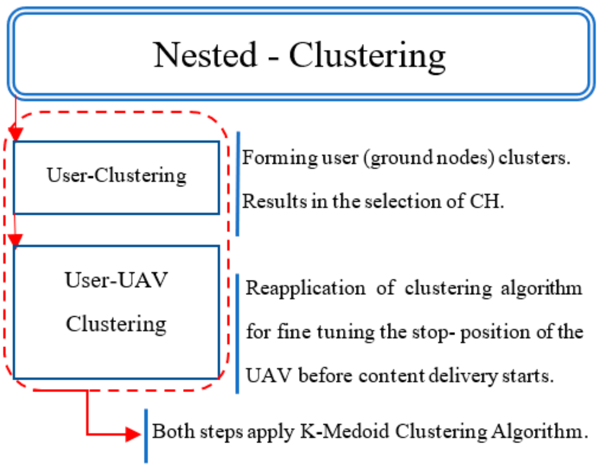

Figure 3. The nested clustering concept.

4.1. User Clustering

It was explained earlier that the idea is to address the endurance issue of UAVs and decrease the energy consumption of UAVs during the communication phase. Therefore, we proposed to use clustering so that the UAV only delivers content to the CHs, reducing the number of connections with ground nodes. To cluster the users, we employed the k-Medoids (KM) clustering algorithm as it represents one of the most popular partitioning algorithms that minimize the distance between nodes. The KM algorithm iteratively finds CHs and assigns the nodes (cluster members) to the nearest CHs. It should be noted that KM is given preference over k-means since the latter is sensitive to the outliers [43] and, secondly, the actual data point (node in this case) is selected as CH rather than a centroid which might not even represent an actual data point. As the users are closely packed inside a stadium, distance is the most significant metric for clustering in such scenarios. The KM algorithm uses Euclidean distance as the dissimilarity matrix between nodes and runs iteratively to minimize the distance and find clusters accordingly.

4.2. User-UAV Clustering: The One Cluster Case

Cluster heads are obtained once the user clustering process finishes (as described in the previous section). To efficiently distribute the content, the placement of the UAV is important. Therefore, we now reapply the clustering algorithm to find the best placement of the UAV according to the chosen CHs. In this case, best placement refers to finding the optimal placement based on the distance of the UAV from all the CHs. The KM algorithm is once again applied to minimize the distance between the UAV and the CHs. Since we are not interested to make further clusters, therefore, it is a special case of 'One Cluster'.

Once the first user clustering round ends, the user-UAV clustering round begins, and the UAV is randomly placed at a particular coordinate. The clustering algorithm is then applied to find an appropriate position—also known as a stopping point. The modified KM algorithm for the case of one cluster is detailed below:

Step 1:

Consider the inputs:

(i.) Node Locations (coordinates of all CHs and the UAV).
(ii.) Association of all nodes to only one cluster. (hard-code $k = 1$).

Step 2:

(i.) UAV is hard-coded to be the centroid (as opposed to randomly selecting a centroid).
(ii.) UAV is randomly placed at location U_l.

Step 3:

Aim: Repeat until convergence

Objective: Minimize the distance between the UAV and all the CHs.

$$U_l(i) = \underset{1<k<K}{argmin} \sqrt{\left(x_{CH_k} - x_{uav_l(i)}\right)^2 + \left(y_{CH_k} - y_{uav_l(i)}\right)^2 + h_{uav_l(i)}{}^2} \quad (10)$$
$$i = 1, \ldots, I \text{ where } i \text{ represents the ith iteration.}$$

Step 4:

(i.) Update the position, U_l, of the UAV obtained in Step 3.
(ii.) UAV moves, from the initial random placement, to the new 'stop-position'.

5. Performance Evaluation

5.1. Simulation Setup

The simulation of the proposed scheme is conducted in MATLAB. We assume that all terrestrial links undergo independent and identically distributed (i.i.d.) Rayleigh fading together with a large-scale path loss with a path loss exponent. We consider a sports stadium such as a football or cricket stadium where users are gathered for a social/sports event. The users are uniformly randomly distributed in the stadium. A flying UAV-BS is considered for distributing the requested content. The ground nodes follow the KM clustering algorithm as explained in the previous section. The number of clusters formed for a particular user density is explained later. Various content sizes and user densities are considered for evaluating the performance of the proposed scheme. The size of content is uniformly distributed within the interval (1–5) megabytes, whereas the number of contents are varied from 10 to 40 with a step size of 5. The network throughput, UAV and network energy consumption, and content delivery delay are considered for performance evaluation. All the important simulation parameters are listed in Table 2. All the simulation parameters are taken directly from the relevant literature [33,44,45].

Table 2. Simulation Parameters.

Parameter	**Value**
Simulations	10,000
Stadium radius	400 m
Path loss exponent for D2D links	4
Path loss exponent for UAV-user	2.25
Path loss exponent for conventional BS ground users	3.25 (used for implementing Benchmarked II)
Noise power	−130 dBm
UAVs transmit power	23 dBm
D2D CH transmit power	23 dBm
Base station transmit power	43 dBm (used for implementing Benchmarked II)
Power required to receive data from UAV	1.8 Joules/s
Power required to receive data from CH	0.925 Joules/s
System bandwidth	5 MHz
Resource block bandwidth	180 KHz
Height of the UAV	100 m
Content size	Uniformly distributed within interval (1–5) Mb.
Number of Content	10, 15, 20, 25, 30, 35, 40.

5.2. Benchmarking

To evaluate the performance of the proposed scheme, two state-of-the-art works were selected for benchmarking.

The first scheme was proposed in [46] and is referred to as 'Benchmarked I' in this manuscript. This scheme is chosen since, similar to our work, this study considers content-centric networking, delivering content via UAV-BS and D2D communication. Moreover, [46] also targets optimizing the energy consumption of the UAV. However, this study does not consider making clusters.

The second scheme is presented in [47], referred to as 'Benchmarked II', which considers a hybrid approach where UAVs and D2D communication as well as ground BSs are utilized to deliver demanded content. To select the users for each delivery method, the user-associated problem is formulated, and a heuristic algorithm is proposed to solve the optimization problem. All the algorithm optimization parameters presented in this study are considered as is for benchmarking. This study also considers optimizing the energy efficiency of the hybrid network. The reason for selecting this scheme is that they consider each serving node i.e., UAV, BS, or D2D Transmitter as a CH and content requester as the cluster member. However, as opposed to this study, our work considers UAV to communicate only with a small number of CHs and there is no BS assisting the content delivery. The reason we do not involve BS in our work is to make the scheme decentralized in nature and provide offloading gains to conventional macro/micro/small-cell BSs.

5.3. Determining the Number of Clusters (k)

Several factors define the performance of a clustering algorithm. Among these factors, determining the value of '*k*' (i.e., the number of clusters to be formed) for a given node density is very important. Numerous research works arbitrarily choose the value of '*k*'; however, we believe a better selection of '*k*' leads to a better clustering solution. The literature reports a number of schemes (such as the Rand Index, Distortion Score, etc.) for evaluating the clustering results, i.e., the number of clusters to be formed [48]. This work considers using the Silhouette Index (SI) since it does not require training and can be readily applied to a given data set (randomly distributed users in our case). The 'SilhouetteEvaluation' function is available in MATLAB an can be utilized to determine the optimal number of clusters for a given node distribution. To read more details on SI, please refer to the work presented in [48].

To find the value of '*k*', user distribution becomes the input of the 'SilhouetteEvaluation', which is then evaluated against a number of clusters, and that value is selected which maximizes the SI. The complete process is depicted in Figure 4.

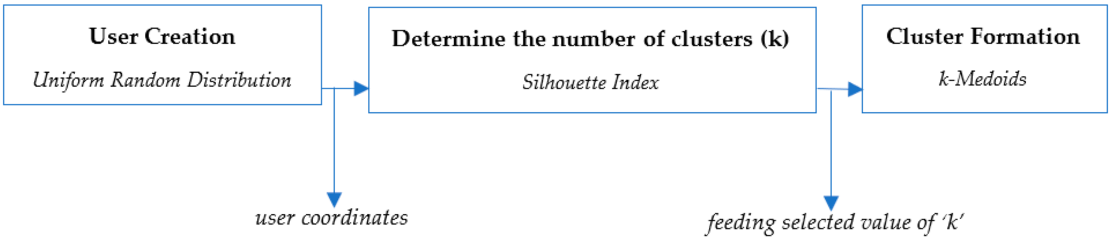

Figure 4. The process of determining the value of '*k*', the number of clusters.

An Example

Here we demonstrate the example of selecting the value of 'k' using SI. The result shown in Figure 5 considers three hundred users generated following uniform random distribution. The SI index was evaluated against thirty clusters. It is shown that SI is maximized at $k = 4$ (represented by a red arrow). Therefore, for such a user distribution, four clusters would be formed.

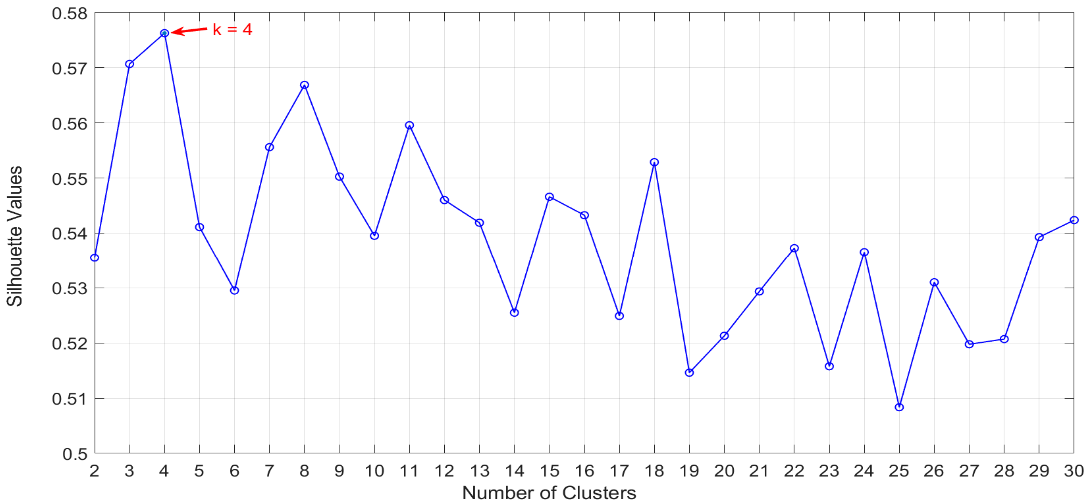

Figure 5. An example demonstrating the result of using 'SI' for determining the value of '*k*'.

It should be noted here that various user densities are considered for evaluating the results; therefore, the value of '*k*' will be calculated for each user density using the same SI index as explained above.

5.4. Results

5.4.1. Network Throughput

In this section, we present the network throughput performance and the comparative study with the benchmarked schemes. Two different network throughput results are presented, one against the number of contents and the other against the number of users.

For the result presented in Figure 6, as adapted by the relevant and standard literature [32,49], the size of the content is varied following uniform distribution and lies within the interval (1–5) megabytes. The result shows that the proposed scheme performs better than the benchmarked schemes. It should be noted that the proposed scheme considers forming clusters and clustering has reportedly produced throughput gains [6]. However, clustering has not been thoroughly studied in the context of UAV-enabled content distribution. The results of Figures 6 and 7 show that introducing clustering in such a scenario is beneficial. Moreover, since users exist in a confined space in a sports stadium, D2D communication provides a favorable transmitting scenario (better channel conditions among users). It is encouraging to observe that as the number of contents increases beyond 25, in Figure 6, the difference between the proposed and the benchmarked schemes increases significantly.

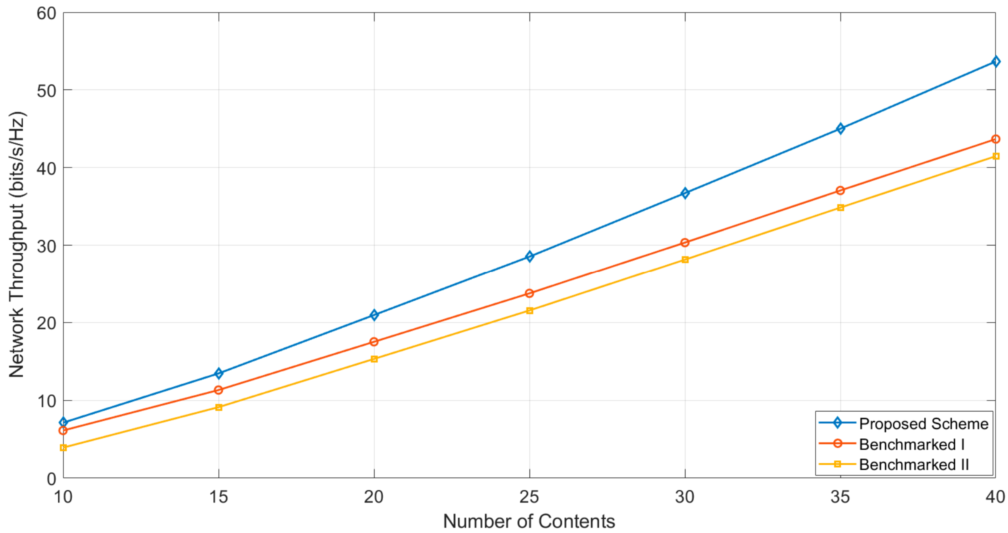

Figure 6. Network throughput V/S number of contents.

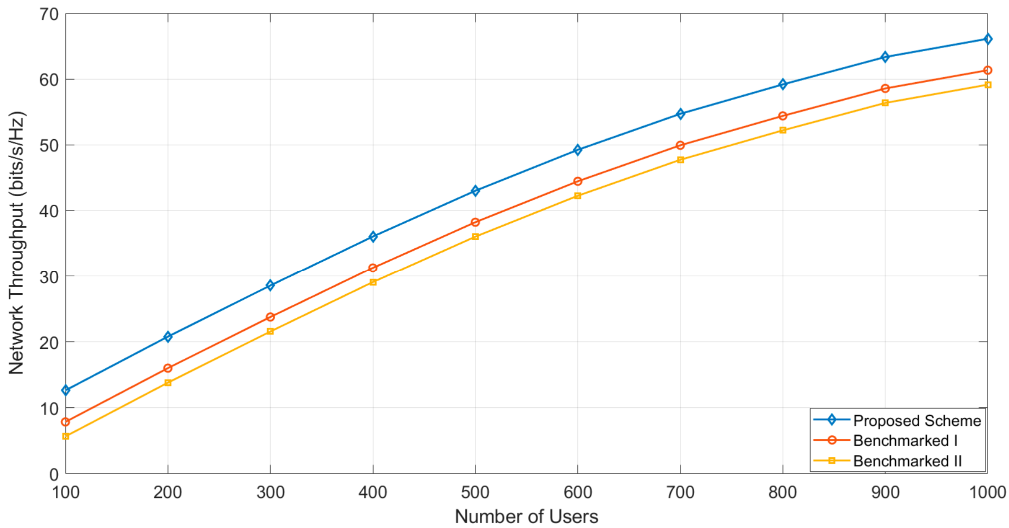

Figure 7. Network throughput V/S number of users.

Figure 7 presents the result of network throughput variation against the number of users. We can see a similar trend that the proposed scheme outperforms both of the benchmarked schemes. Since interference increases as the number of users increase while the bandwidth of the system remains the same, the network throughput will plateau after a particular user density. At the user density of one thousand users, the percentage difference in the network throughput between the proposed scheme and Benchmarked I is approximately 23%.

5.4.2. Average Rate of the Cluster Heads V/S Height of the UAV

In the proposed scheme, the UAV is responsible to transmit content to the CHs; therefore, we believe it is important to understand the variation of the rate (in terms of bits/s) enjoyed by the CHs as the height of the UAV is varied. In Figure 8, we observe that the average rate enjoyed by the cluster heads significantly depends on the height of the UAV. The average rate increases towards a maximum value and then decreases. In a nutshell, both low and high altitudes present a problem for obvious reasons of variation in channel conditions. Therefore, selecting an appropriate altitude for successful transmission is important.

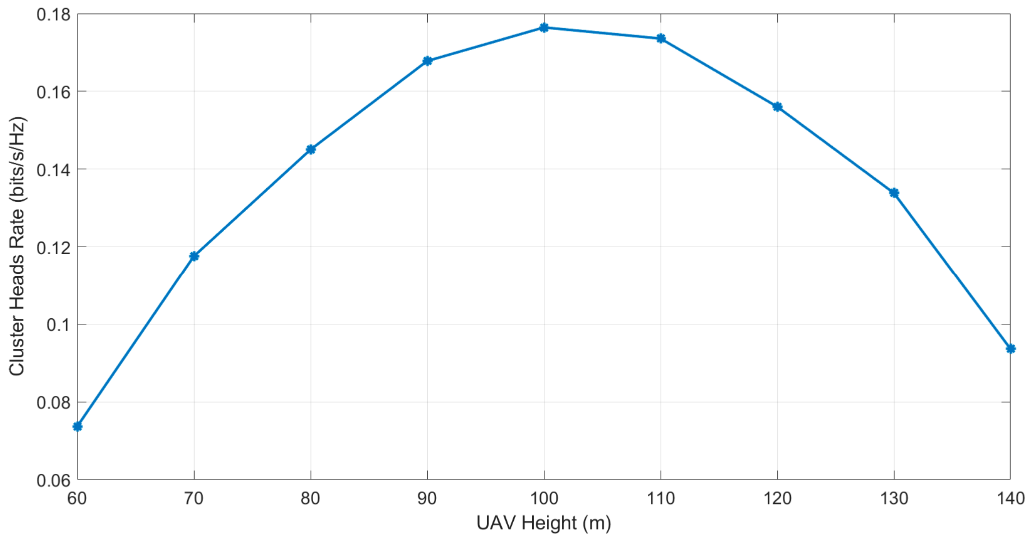

Figure 8. Variation in the cluster heads average rate as the UAV height changes.

5.4.3. Energy Consumption

This is an important result as it directly targets the aim of this study. The idea is to reduce the energy consumed by the UAV during the communication phase.

Here we present two sets of results: one showcasing the performance of the proposed scheme compared with the conventional scheme (Figures 9 and 10) and the second with the benchmarked scheme. It should be noted that Figures 9 and 10 demonstrate the energy consumption of the UAV only, whereas Figure 11 presents the energy consumption of the network.

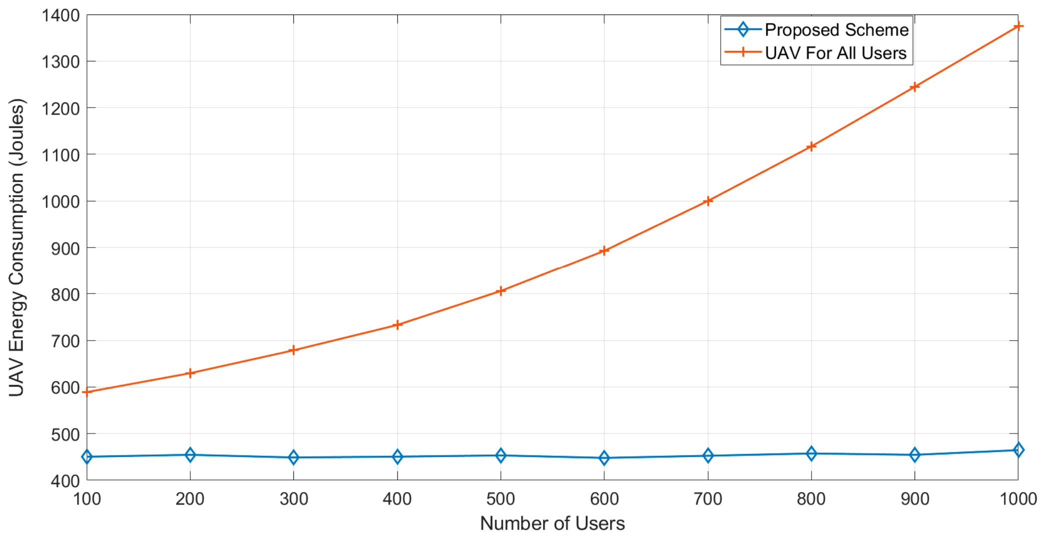

Figure 9. UAV energy consumption V/S number of users.

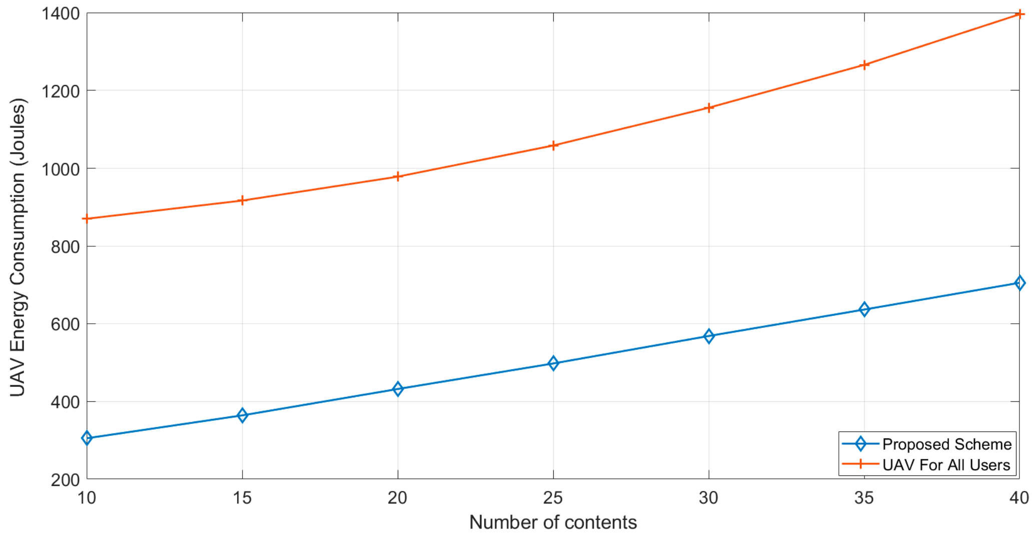

Figure 10. UAV energy consumption V/S number of contents.

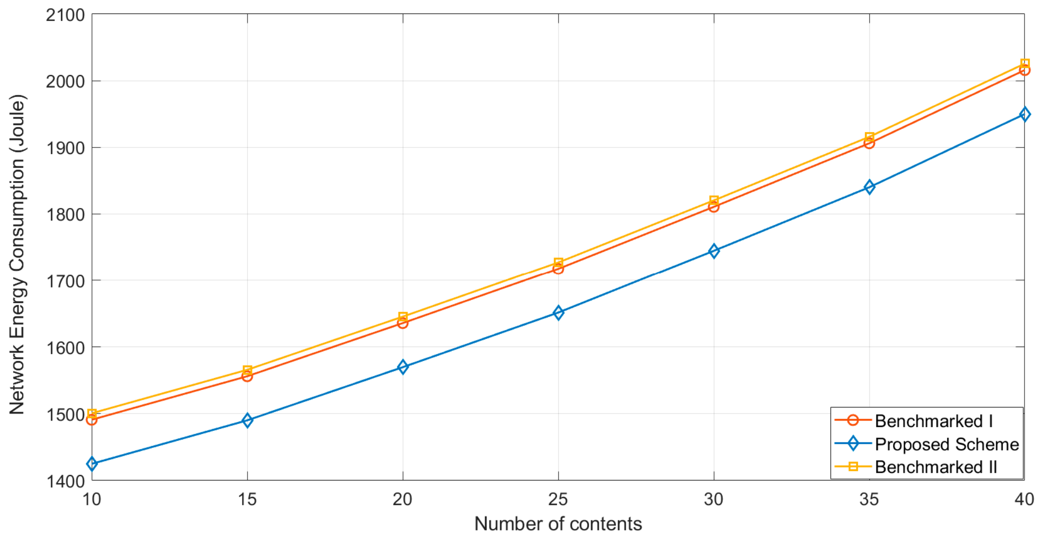

Figure 11. Network energy consumption V/S number of contents.

The result presented in Figure 9 shows the comparison of the proposed scheme with a conventional scheme where all the users are served by the UAV (termed as UAV for all users in Figure 9). In this context, all users means the users selected to be served for the UAV mission. This does not mean all users of a cell or given geographical area.

This result demonstrates the significance of the study as the UAV consumption remains approximately the same even if the number of users increases since the UAV only communicates with CHs. In the case of a conventional scheme where the UAV is serving all the users, then energy consumption increases significantly. This is quite evident from Figure 9.

The result of Figure 10 shows that if more contents are demanded, then more energy will be spent by UAVs for distribution. Even in this case, a significant difference exists between the proposed scheme and the conventional scheme.

It is understood that the energy consumption of the whole network, as opposed to just the UAV energy consumption presented in Figure 9, would increase even for the proposed scheme. It is demonstrated in the result of Figure 11 for various number of content requests. On the network level, energy consumption does not seem to differ significantly; however, still, the proposed scheme consumes approximately 4% less energy.

5.4.4. Content Delivery Delay

Heterogeneous and real-time service requests are expected in a content-centric network and hence content delivery delay is an important performance parameter. Here, we present two results, showing the content delivery delay corresponding to the increasing number of users and contents. Both results (shown in Figures 12 and 13) indicate that the proposed scheme has a better delay performance. Both results indicate that the performance gap is not substantial at lower user densities and with a lesser number of contents however, it increases with the increase in both parameters. When the requested contents are 40, the proposed scheme has reported approximately 11% less delay in Figure 12 compared with the second-best scheme. The delay performance improves even further when the content delivery delay is plotted against the number of users. At a user density of one thousand, the proposed scheme experiences approximately 18% less delay compared with the second-best scheme.

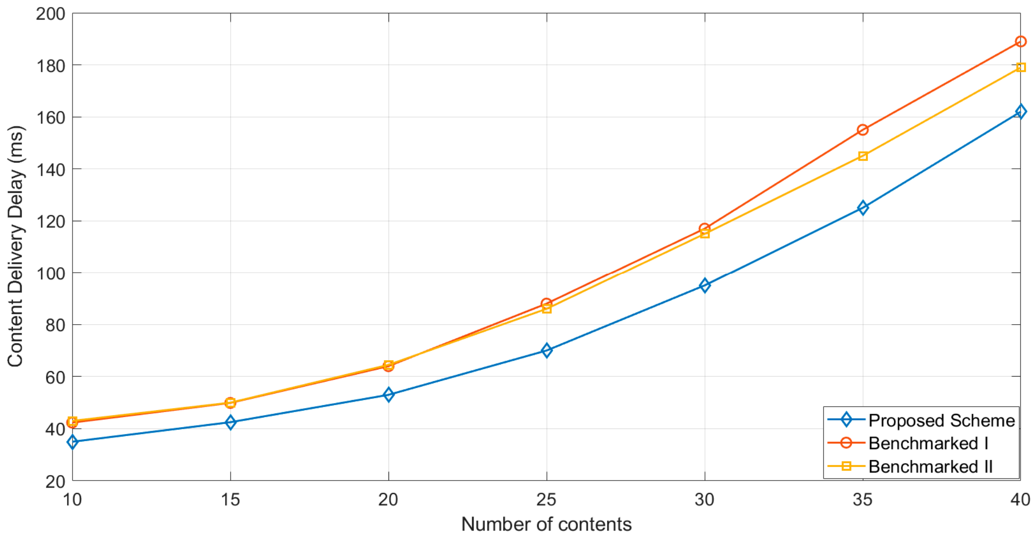

Figure 12. Content delivery delay V/S number of contents.

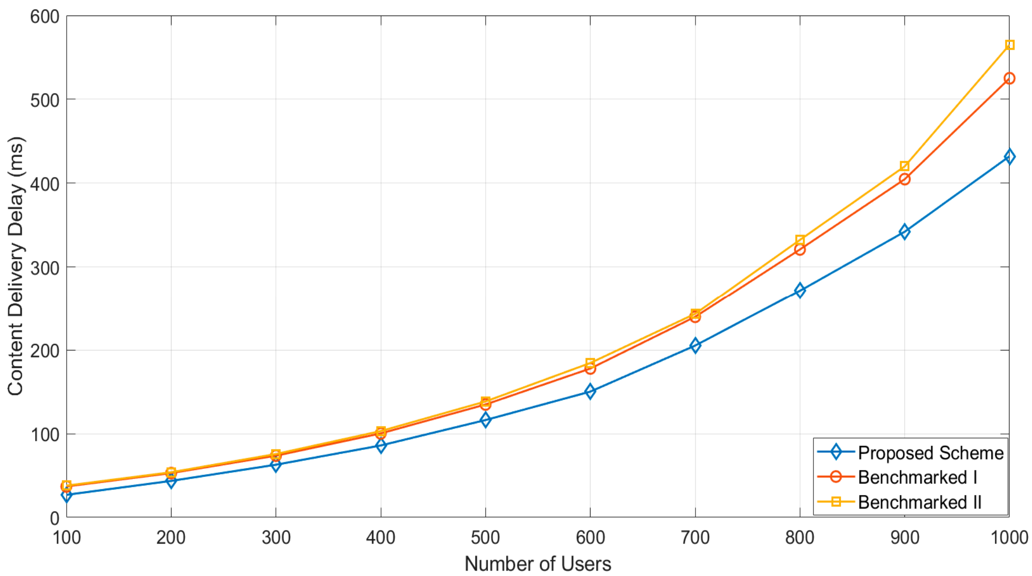

Figure 13. Content delivery delay V/S number of users.

It is interesting to observe the performance of the benchmarked schemes. The rest of the results (network throughput and energy consumption) show that the Benchmarked I scheme outperformed the Benchmarked II scheme. However, when it comes to the delay performance, it is clear in Figure 12 that as the number of contents increases beyond 25, Benchmarked II performs better. However, in case of the result presented in Figure 13 considering various user densities Benchmarked I scheme is performing slightly better at higher user densities.

6. Conclusions

The research revolving around designing efficient content delivery mechanisms has advanced considerably. Technological advancements have brought UAV-enabled solutions closer to cellular networks specifically targeting content delivery applications. However, the energy and battery constraints present a major obstacle to implement UAV-based communication systems. UAVs consumes energy while flying, hovering, and communicating. This study aimed at reducing the energy consumed by UAVs during the communication phase. For this purpose, we explored the clustering concept for ground nodes. As a result of clustering, the UAV only distributes content to the chosen cluster heads and then the cluster heads are responsible to distribute the content to their respective cluster members. The results demonstrate that clustering presents a profound solution for content delivery, providing better results for throughput, energy consumption, and content delivery delay. A comprehensive comparative study of the proposed scheme with the classical and state-of-the-art schemes was presented and the proposed scheme was found to perform better.

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