UAVs deployment in Heterogeneous Networks: enhancing video streaming QoE

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***Abstract*—In recent years, the use of UAVs (Unmanned Aerial Vehicles) to boost mobile networking technology performance is rising interest in the scientific community. UAVs can be used as aerial relays to be deployed in 4G/LTE networks. Small scale UAVs, such as quadrotors or small fixed wing drones, are able to carry a wide variety of sensors, actuators and communication equipments. Due to the increasing interest in this field, UAVs have become more and more affordable and even off-the-shelf quadrotor UAVs can carry $>1\,kg$ equipments in their structure. In parallel, the miniaturization of commercial femto cells results in the development of very lightweight network equipments. The combination of UAVs and cellular network equipments provides an interesting approach towards the enhancement of performance of a network. In our view, UAVs are seen as an additional service that can be provided in order to ensure a higher Quality of Experience for video streaming users. The work focuses on the study of a system model with specific parameters and constraints in order to embed a UAV functioning as an LTE micro-cell to perform user offloading and optimize the bandwidth usage of a macrocell during video streaming. The result is a new architecture, that can be framed as Heterogeneous Network.**

I. Introduction and Motivations

In modern cellular networks, the deployment of the Radio Access Network (RAN) is designed mainly based on predictions of long-term spatio-temporal distributions of the traffic load. Consequently, the fixed locations of the Base Stations (BSs) do not provide the necessary flexibility, coverage, or resources in unpredictable scenarios impacting the network performance. To alleviate this ineffectiveness, in 4G networks the paradigm of Heterogeneous Network (HetNet) was recently introduced [1]. The fundamental idea in HetNet is to distribute several Low Power Nodes (LPNs), such as micro-, pico- and femto-cells, relays and distributed antenna systems, under the wide umbrella coverage of a macro cell in order to bring resources to dead zones and increase the network capacity in high traffic areas. The introduction of HetNets in 4G systems, and specifically in LTE-Advanced, offers new opportunities in terms of capacity improvement, macrocell offloading, energy saving, and better coverage. However, HetNet-supported LTE systems are not able to face unexpected traffic demand peaks, for the rather rigid placement of the heterogeneous network elements is not flexible enough to follow the deviations of traffic geographical distribution from the long-term average, unless highly overprovisioning is offered by the RAN (often not a feasible solution). The inhomogeneity of traffic distribution, due to the unpredictable users arrivals, makes the network topology design even more challenging.

The recent years emerging technical and commercial interest in Unmanned Aerial Vehicles (UAVs) reflected in the academic research as well and numerous solutions, involving the deployment of drones (DR) in cellular networks [2], [3]. Nevertheless, these studies are still in their early stages and require further investigation. The innovative idea of using UAVs equipped with transceiver stations (drone-BSs) to assist ground wireless networks is receiving increasing interest [4]. Aerial base stations can provide a cellular network with the flexibility and agility necessary to its reconfiguration in problematic scenarios where the traffic demand is hard-to-predict or the capacity and the coverage can not be guaranteed. Examples of these cases include coverage of rural areas, assisting a congested macrocell, natural disasters, public events such as concerts or sport events, traffic jams [1], [4]. Furthermore, the size of a drone-cell, namely the coverage area relative to a drone-BS, can be adjusted by changing the UAV altitude, transmission power, and antenna directivity, providing more adaptability to unstable traffic loads and uneven users distributions.

Moreover, the optimization of the UAV flight plan introduces a clustering problem. Users, widely dispersed around the macrocell, usually tend to assemble around urban points of interest (e.g. a shop, a monument, a school). Therefore, considering the aggregate bandwidth of clusters and evaluating the density and distance from the macrocell are key parameters for the UAV battery lifetime.

In this paper, we propose the use of a DR carrying an LTE micro-cell to enhance coverage and capacity of a LTE BS (macrocell) aiming at maximizing the Quality of Experience (QoE) of end users playing video streaming. The contribution of our work is the following: we consider a macrocell congested by subscribers trying to stream videos and, in order to reduce the BS workload, (1) we propose the exploitation of a clustering algorithm to group users (taking into account the drone-cell parameters, e.g., altitude of the drone, coverage area, LOS connectivity) to offload them from the ground station to the micro-cell carried by the drone. (2) Based on different strategies we adaptively identify the clusters of users that should be served by the drone while (3) maximizing both the network performance and the users QoE.

II. Related Work

The investigation of UAVs use to provide and strengthen mobile connectivity is a rather new branch of research, although in the last few years some remarkable works have

been published. Mozaffari et. al in [4] provide a study on the coverage performance of drone small cells and derive the optimal altitude for a single drone. A 3-D placement algorithm for drone cells with the goal of maximizing the revenue of the cellular networks was recently proposed [2]. In [5] it is shown that aerial network provisioning can be used for optimizing mobile networks in overload and outage scenarios. In this framework the UAVs, equipped with a cellular technology, are used to temporarily offload traffic into neighbor cells in 4G networks. A study on the optimal altitude of aerial platforms to provide maximum radio coverage on the ground was recently presented [6]. Comprehensive surveys on communication networks for UAVs and satellites are given in [7] and [8], analyzing which communication technology is most suitable to fulfill tasks and applications. In [9] an overview of UAV-aided wireless communications is provided, by introducing the basic networking architecture and main channel characteristics, highlighting challenges and new opportunities to be exploited. The framework proposed in [10] offers a statistical propagation model for predicting the air to-ground path loss between the aerial platform and the terrestrial terminal; this prediction is based on the urban environment properties. An analysis of the potential of using small UAVs as wireless relays for assisting cellular network operations is reported in [3]. This experimental study is reinforced with network analysis using both stochastic geometry and multi-cell simulations results. Bor-Yaliniz et al. presented a study on the utilization of low-altitude unmanned aerial platforms equipped with base stations in future wireless networks [1]. The authors demonstrated the 3-D placement of a drone-cell, depending on the drone's altitude, location, transmission power, antenna directivity, type of drone, and the characteristics of the environment.

As for the video streaming in cellular networks, in [11] techniques for providing video streams at assured QoE levels to mobile users served by a heterogeneous cellular network are investigated. The network is composed by micro and macro base stations and the authors define a resource allocation algorithm to offload a subset of users from the micro to the macro base station.

III. Proposed System Architecture

A HetNet is a communication network that adopts various types of access nodes. It can be defined as a network with composite interworking between macro base stations, characterized by a high transmission power ($5 - 40$ W), and small heterogeneous LPNs transmitting at $0.1 - 2$ W and providing covering ranges from tens of meters up to $1 - 2$ km. LPNs are distributed throughout the network macrocells in order to extend the system capacity in those sections characterized by a high traffic density or poor coverage.

A qualitative representation of the considered network architecture is reported in Fig. 1. The system consists of a macrocell covering a wide area comprising N terminals connected to the BS. The clients request video streaming contents from a video server with a minimum QoE to be respected. Our system leverages a DR to increase the performance of the HetNet and, ultimately, enhances the video streaming QoE of the end users. The benefits achieved by the exploitation of drones are diverse. As an example, drones can transport a small base station, specifically an LTE microcell, and acting

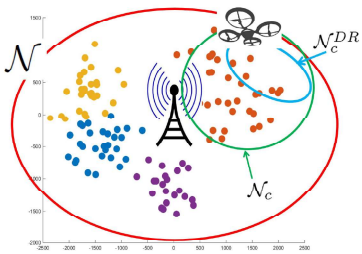


Fig. 1. Architectural model.

as a mobile access infrastructure node. The mobile microcell is initially located at the BS position, where both the drone's and the microcell's batteries can be recharged, and is moved around depending on the distribution of the users resources demand in the entire macrocell.

We assume an HTTP-based video streaming, where the video sequence is encoded into multiple versions each at a different quality and characterized by its video rate. Then, each sequence is divided into small video segments of few seconds each and are addressed by an URL. These video fragments, encompassing one or more Group of Pictures (GOPs), are requested by the clients and sent to them via HTTP servers using the HTTP protocol. Throughout the paper, we will refer to video segments as "*chunks*". In the described architectural system, we propose three different bandwidth allocation strategies to offload users to the drone-BS. The serving infrastructure nodes are centrally coordinated so that an entire cluster of users, or a subset of them, can receive the video segments either from the fixed base station or from the drone. The bandwidth is adaptively allocated based on BS availability to transfer one or more video segments to the clients. This flexibility in resource allocation is able to increase the network performance while keeping the QoE under control. The architecture is characterized by specific constraints related to its subsystems. In addition to traditional HetNet requirements, the introduction of drones poses new limitations and challenges. The main constraints to be taken into account are: i) UAV's battery lifetime and motion dynamics; ii) cells capacity; iii) video streaming data rates; iv) requested QoE.

In more detail, the bandwidth required by each user for video chunk download depends on the chunk size, the video chunk playout duration τ and the spectral efficiency of the channel. The bandwidth $B^{(i)}$ (expressed in MHz) required at the application layer by a user i to download the chunk k is given by $B_k^{(i)} \approx \lambda_k^{(i)}/(\alpha \cdot \tau \cdot \eta_{(x_i,y_i)})$, where $\lambda_k^{(i)}$ is the video chunk size, $\alpha \in (0,1)$ is a factor accounting for overhead caused by retransmissions incurring at lower protocol layers, and $\eta_{(x_i,y_i)}$ is the spectral efficiency in [bit/s/Hz] achieved at the user's position (x_i, y_i) [11]. Given the bandwidth requested by the users, the BS evaluates the bandwidth to be allocated in order to meet the QoE constraint (in our case the average transmission delay). Several streaming strategies can be adopted at the application layer, ranging from optimized [12] to constant [13] target HTTP GET inter-arrival time. To this end, we refer to this latter streaming scheme, and we adopt the bandwidth allocation mechanism Dynamic Minimum Average Delay (D-MAD) proposed in [13]. This scheme computes the allocated bandwidth $\tilde{B}_k^{(i)}$ dynamically chunk by chunk and

jointly for all users. In case of bandwidth requests summing up to a value higher than available system bandwidth BW_s [Hz], the algorithm assigns resources in an optimal method, minimizing the average chunk delays of the users. When the D-MAD allocation scheme is considered, the chunk delay is calculated as:

$$\delta_k^{(i)} = \max\left\{\left(\frac{B_k^{(i)}}{\tilde{B}_k^{(i)}} - 1\right)\cdot\tau, 0\right\}. \quad (1)$$

IV. Drone Offloading Strategies

In our system, all the users connected to the base station are divided in clusters [1]. The proposed approach then follows two main steps. The first step aims at identifying a cluster to be served; i.e., in accordance to a Selection Method SM the drone selects the cluster presenting:

- SM_1: the minimum average CQI;
- SM_2: the maximum requested bandwidth to the BS;
- SM_3 the maximum number of users in the cluster.

Then, once a cluster is identified, users to be offloaded from the BS are selected as follows. Let us denote as $\mathcal{N}$ the set of users of cardinality N in the BS radio range. N_c is the number of users in the selected cluster c and $\mathcal{N}_c$ the set of these users. Besides we assume that in general only a subset of the cluster users, $\mathcal{N}_c^{DR}$ is offloaded to the DR (to have an example of the users sets see Fig. 1). We consider three different criteria to identify the set of cluster users $\mathcal{N}_c^{DR} \in \mathcal{N}_c$ that are offloaded to the drone, namely

- C_1: All the N_c cluster's users are served by the drone, i.e. $\mathcal{N}_c^{DR} \equiv \mathcal{N}_c$;
- C_2: Only the subset $\mathcal{N}_c^{DR}$ of cluster users having BS-related CQI below a threshold θ_{CQI} are served by the drone and the others remain connected to the BS;
- C_3: Only the subset $\mathcal{N}_c^{DR}$ users with bandwidth requests toward the BS greater then a threshold θ_{BW} are served by the drone and the others stay connected to the BS.

Let us denote as B_{DR} the requested bandwidth for video streaming by using the drone, and B_{BS} the one requested when the BS is used. The bandwidth requests originated by the set of offloaded users derived in accordance to one of the $C_l,\ l = 1, 2, 3$ criteria are served by the drone. In more detail, for each chunk the DR bandwidth is allocated in accordance to D-MAD in [13] with N_c^{DR} offloaded users jointly allocated on an overall bandwidth of $BW_s = BW_{DR}$. The rest of the users in the set $\mathcal{N}\backslash\mathcal{N}_c^{DR}$ is served by the BS with $BW_s = BW_{BS}$.

The case when all users request the bandwidth to the BS, so no cluster users are served by the drone, is indicated as C_0, i.e., all the N users are served by the BS.

Based on the applied criterion, we compute the *i*-th user bandwidth requests $B_{DR_k}^{(i)}$ with respect to the drone micro-cell, allocate the overall drone bandwidth with D-MAD with $BW_s = BW_{DR}$, collect the assigned bandwidth $\tilde{B}_k^{(i)}$ and evaluate the *k*-th chunk delay experienced by the *i*-th user in accordance to Eq. (1). The remaining $N - N_c^{DR}$ users of the scenario are served by the base station using $BW_s = BW_{BS}$ and the bandwidth requests $B_{BS_k}^{(i)}$ with respect to the BS.[2]

V. Scenario Definition

To validate our approach we carried out numerical analysis using a simulation tool in Matlab. We considered a BS covering a hexagonal area spanning for $2.5\ km$. The BS serves video contents via HTTP streaming to a total of $N = 150$ users randomly distributed over its coverage area. We suppose that people tend to gather in specific areas in real life, rather than being uniformly distributed, therefore we model the aggregation behavior of the users as follows. We firstly generate 15 aggregation points and then extract the positions of the users as points uniformly distributed around the aggregation landmarks. Users are clustered in 4 clusters in accordance to a K-means algorithm simply based on their geographical coordinates in the plane. The streamed videos are taken from real traces in [14]. Five different videos are considered with the average encoding rates V_x, $x = 1, ...5$, in Table I.

We consider a scenario in which the drone flies at an altitude higher than the building height. Typical building height in urban area is about $20m$; thereby, without loss of generality, we consider the case of a drone flying in an urban area at an altitude $50\ m$, covering a circular area with a diameter of $500\ m$ on the ground, and experiencing a path loss described by a Non-Line-of-Sight Walfish-Ikegami model [15][3]. Once the attenuation A due to the path loss is known, the SNR at the receiver is calculated as $SNR = G \cdot P_{tx}/(A \cdot P_{noise} \cdot BW_s)$, where P_{noise} represents the power spectral density of the background thermal noise, BW_s the system bandwidth, P_{tx} the transmission power, G the antenna gain. The SNR value determines the Channel Quality Indicator (CQI) parameter $CQI = 1 + \frac{7}{13}(SNR_{dB} + 6)$ [11] ranging from 1 to 15, and ultimately determining the adopted coding/modulation scheme and the actual channel spectral efficiency.

In order to analyze the performance of the different schemes, the QoE metric is defined as the average-per-chunk delay. Here we consider 20 runs and for each run the delay $\delta_k^{(i)}$ of Eq. (1) is averaged over the overall number of chunks and on different set of users under the l-th C_l criterion. Thus, the average has been computed as:

$$\overline{\delta}^{(\mathcal{S})}(C_l) = \sum_{i\in\mathcal{S}}\sum_{k}\frac{\delta_k^{(i)}}{n_c\cdot|\mathcal{S}|} \quad (2)$$

considering the overall number of chunks n_c and the users' set $\mathcal{S}$ of cardinality $|\mathcal{S}|$. Different sets of users have been considered, namely, i) all the cell users in $\mathcal{N}$; ii) selected cluster drone offloaded users in $\mathcal{N}_c^{DR}$; iii) selected cluster BS served users, in $\mathcal{N}_c\backslash\mathcal{N}_c^{DR}$; iv) out of cluster users in $\mathcal{N}\backslash\mathcal{N}_c^{DR}$.

[1] In this work the clustering scheme is based on a K-means with an arbitrary K; clustering optimization is left for future works.

[2] Notice that $B_{DR}^{(i)}$ depends on the CQI computed as a function of the SNR to the drone, while $B_{BS}^{(i)}$ depends on the CQI computed as a function of the SNR to the BS.

[3] Specifically, in the simulations we adopt the following Walfish-Ikegami model parameter settings: building height of 20m, average road width equal to 20m, distance between building 36m, receiver height 1.5m, road orientation w.r.t. the radio path 10 degrees

TABLE I. SIMULATION PARAMETERS.

Parameter	Value
Average drone speed (Km/h)	30
UAV power usage/capacity/battery voltage	13.0 A/17.33 Ah/22.2 V
Flight time (min)	30
Fly height (m)	50
Permanency time in the coverage range (s)	60
Cell radius (Km)	2.5 (BS), 0.5 (DR)
Receiver node power/sensitivity (dBm)	-97.5 / -107.5 dBm
Maximum TX power (dBm)	43 (BS), 36 (DR),
Antenna gain (dB)	13 (BS), 10 dB (DR),
Operating frequency (GHz)	2.1
Bandwidth (MHz)	$BW_{BS} = 35$, $BW_{DR} = 5$
Number of different videos	5
Number of chunks per video	$n_c = 1200$
Video encoding rates [Mbps]	V_1= 1.08 V_2=1.33 V_3=1.35 V_4=1.19 V_5=1.17

Furthermore, for each run, the ratio between the overall average delay achieved in the BS+DR configuration and the overall average delay achieved using only the BS has been calculated. Namely, the Average Delay Reduction Factor (ADRF) is defined as:

$$ADRF(C_l) = \frac{\overline{\delta}^{(\mathcal{N})}(C_l)}{\overline{\delta}^{(\mathcal{N})}(C_0)},\ l = 1, 2, 3 \tag{3}$$

where $\mathcal{N}$ denotes the set of all the users.

The main parameters used to set up the simulations are reported in Tab. I.

VI. SIMULATION RESULTS

We analyze the effects of the 4 different offloading criteria C_l as a function of the SM that can be applied to select the cluster where users are served by the DR.

To simulate this scenario, 10 users are randomly generated around each one of the 15 central points. The users are then clustered according to their locations using a K-means algorithm with 4 clusters. The thresholds for offloading in case of C_2 and C_3 criteria are set to $\theta_{CQI} = 10$ and $\theta_{BW} = 1800\ kHz$, respectively.

Snapshots of the scenario resulting from a simulation run for all three SMs are reported in Fig. 2. We can notice some key differences of the criteria: the CQI-based SM_1 criterion basically seeks for the farthest cluster, with users experiencing bad channel conditions; the BW-based SM_2 accounts jointly for the channel quality and the application layer bandwidth requests; the population based one, SM_3, is the simplest and fastest criterion, that requires minimal knowledge about the user characteristics. Criterion SM_2 maximally relieves the BS from bandwidth requests but requires maximal knowledge about the user characteristics, including the actual throughput rate. The SM_1 criterion represents a trade-off among simplicity, prior knowledge and efficacy in reducing the bandwidth requests to the BS.

In the following analysis we consider only the SM_1 selection method. In Figure 3 we present the scatter plot of the per-run average delay vs the corresponding CQI on different set of users and under different criteria. Specifically, in Fig. 3(a) in green we plot the delay averaged over the n_c chunks and on the set $\mathcal{I}$ of all the users when no user is offloaded. Besides, we show the average delay over different users' subsets, namely the cluster users served by the DR (blue) and the out-of cluster users (red). In Figures 3(b)-(d) we show in green the corresponding average delay when drone offloading is performed by using the $C_1 - C_3$ criteria, respectively. Notice that in Fig. 3(c)-(d) referring to case C_2 and C_3 we further distinguish between DR served cluster users, still in blue, and BS served cluster user, in black. The offloading architecture systematically improves the performance in terms of average delay for all the $C_1 - C_3$ criteria. Still, the criteria require an increasing knowledge of the users characteristics, ranging from users location to the knowledge of the application layer user bandwidth. We recognize that C_1 does not distinguish between different users in the cluster, C_2 offloads and improves the performance of the low CQI users, C_3 accounts for the requested bandwidth. In medium load conditions, which is the case addressed in Fig. 3, the average delays $\overline{\delta}^{(\mathcal{N})}(C_l),\ l = 0, 1, 2, 3$ over all the runs yields mean values of $0.438, 0.154, 0.150, 0.162$, respectively. Thereby, the C_2 criterion offers interesting performance. In high load conditions this performance ranking changes, as discussed in the following.

TABLE II. MEAN VALUE OF THE AVERAGE DELAY $\overline{\delta}^{(\mathcal{I})}(C_i)$ FOR DIFFERENT NUMBER OF USERS.

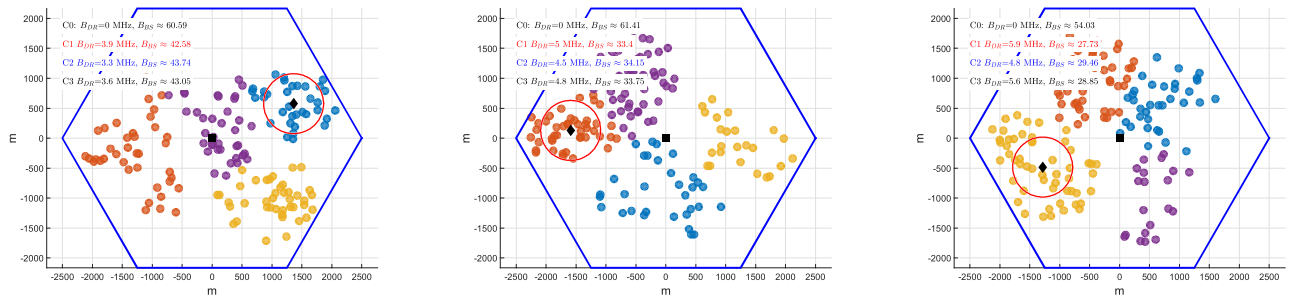
N	BS C_0	BS+DR C_1	BS+DR C_2	BS+DR C_3
150	0.6782	0.23543	0.24525	0.2401
120	0.37586	0.14607	0.14754	0.15695
100	0.14523	0.041321	0.04001	0.042024

In Fig. 4 we finally plot the $ADRF$ defined in Eq. (3). We recognize that the maximum performance improvement is found for offloaded bandwidth approximating the drone bandwidth, as shown in Fig. 4(a), as well as for sufficiently populated clusters, as noticeable in Fig. 4(b). This confirms the intuitive conjecture that the cluster formation can aim at achieving suitably populated clusters exploiting the majority of the drone bandwidth.

Finally, in Table II we show some results referred to different number of users. A great advantage is always found by the drone offloading; still we observe that the offloading criteria differently perform depending on the overall cell load. We can notice that for low load (low N) both the C_2 and C_3 attain a performance improvement; this occurs without overloading the DR bandwidth. On the contrary when the load is high, the C_1 criterion better relieves the BS.

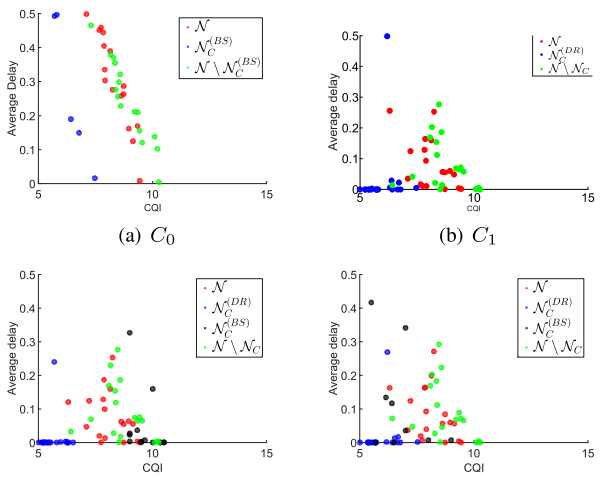
VII. CONCLUSIONS

In this paper we consider an Heterogeneous Network where a UAV is used as mobile LTE micro-cell performing user offloading and optimizing the bandwidth usage of a macr-ocell during video streaming. After dimensioning of the UAV cell, we consider a video streaming service offered to all the users, and partition the users into clusters within the drone coverage area. Then, we analyze the impact of offloading the cluster user generated bandwidth requests on the drone, by considering different methods for selecting the cluster to be served by the drone and different criteria for selecting the offloaded users within cluster. We show that, even though independent allocation of the DR and BS bandwidths is suboptimal in principle, offloading yields significant improvement as far as



(a) SM_1: Minimum CQI (b) SM_2: Maximum bandwidth (c) SM_3: Maximum number of users

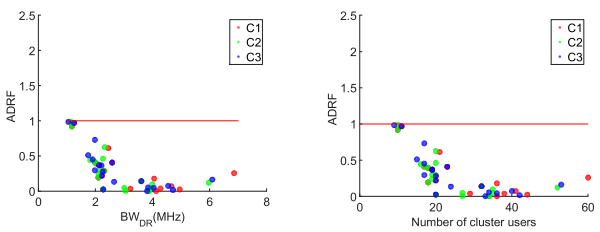
Fig. 2. Different scenarios resulting from the three cluster selection methods SM; comparison of the resulting bandwidths (expressed in MHz) requested to the DR (B_{DR}) and to the BS (B_{BS}) as for the 4 offloading criteria. Scenario (a) C0: B_{DR}=0, B_{BS} ≈60.59, C1: B_{DR}=3.9, B_{BS} ≈42.58, C2: B_{DR}=3.3, B_{BS} ≈=43.74, C3: B_{DR}=3.6, B_{BS} ≈43.05; Scenario (b) C0: B_{DR}=0, B_{BS} ≈61.41, C1: B_{DR}=5, B_{BS} ≈33.4, C2: B_{DR}=4.5 MHz, B_{BS} ≈34.15, C3: B_{DR}=4.8, B_{BS} ≈33.75; Scenario (c) C0: B_{DR}=0, B_{BS} ≈54.03, C1: B_{DR}=5.9, B_{BS} ≈27.73, C2: B_{DR}=4.8, B_{BS} ≈29.46, C3: B_{DR}=5.6, B_{BS} ≈28.85.



(a) C_0 (b) C_1

(c) C_2 (d) C_3

Fig. 3. Average delay versus CQI per run for different offloading criteria.



(a) ADRF vs B_{DR} (b) ADRF vs N_c

Fig. 4. Average delay versus CQI per run for different offloading criteria.

the drone serves clusters characterized by bad channel quality and selectively offload users within the served cluster. Future work will be dedicated to: i) combine the clustering and the cluster selection mechanisms with a suitable offloading criteria; ii) plan the drone flight under a trajectory constrained by the drone battery and fly characteristics but optimized in order to achieve an high offloading gain.

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