Joint Path and Radio Resource Management for UAVs Supporting Mobile Radio Networks

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***Abstract*—In this paper we investigate the potential advantages of using a roaming Unmanned Aerial Vehicle (UAV) as base station of a mobile radio network deployed in a city. The design of the UAV dynamic trajectory and Radio Resource Management (RRM) strategies are combined, with the goal to improve the sum throughput of the network. The comparison between joint and separate aerial-terrestrial RRM is discussed. With respect to previous papers, we identified a cost function, used to define the UAV path, improving significantly the performance.**

***Keywords*-Radio Resource Management, UAVs, Mobile Networks**

I. Introduction

The long term evolution of 5G (the 5th Generation of mobile radio communications) is going to be shaped in the next few years. Future networks have to face new challenges: service requests from users and platforms of many different kinds, with very diverse requirements, and the domination of massive machine type communication. In urban environments, data traffic demand will increase significantly, mostly due to video uploads and downloads. As a result, the network will need to be able to adapt efficiently to traffic demand evolutions in space and time.

This flexibility can be achieved by moving infrastructure nodes as a reaction to the spatial and temporal variations of traffic. We assume in this work that the terrestrial network is supported by autonomous Unmanned Aerial Vehicles (UAVs, also denoted as drones); they carry radio equipment connected to the rest of the network through high capacity links [1]. They might be fully functional Base Stations (BSs), or simple relays extending the coverage of Terrestrial Base Stations (TBSs). See Fig. 1 for a pictorial representation of an UAV-aided mobile radio network comprising such aerial component. The UAVs will support the terrestrial mobile radio network through their ability to establish links with ground User Equipments (UEs) characterized by large Signal-to-Noise-Ratio (SNR), and the possibility to provide coverage and capacity where TBSs are ineffective.

Some researchers envision the possibility to use mesh topologies and multi-hop links, applying ad-hoc routing protocols to the UAV network. We believe that the ease of establishing Line-of-Sight (LoS) links towards the TBSs, and the need for ultra-reliable and low-latency connection to the core network, suggest to implement simpler approaches without inter-UAV links.

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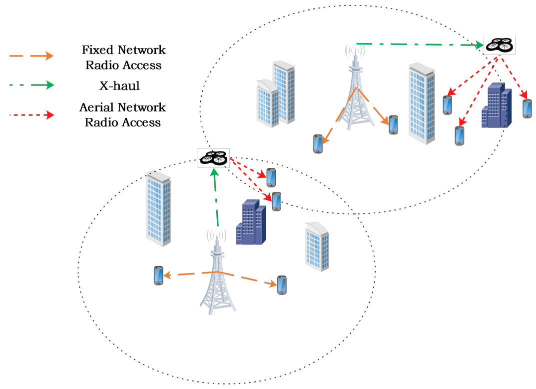

Fig. 1. An UAV-Aided Mobile Radio Network.

Most of papers dedicated to UAV-aided mobile radio networks analyze the optimal UAV placement, in static scenarios without mobility. Moreover, the issue of Radio Resource Management (RRM) is often not considered. Our work focuses on the opposite on the joint design of the UAV path and RRM. This requires the consideration of all aspects of network dynamic behavior: traffic evolution, radio resource assignment, the mobility of UEs and UAVs. In particular we focus on the provision of high throughput services to ground UEs having non stringent delay constraints. Video streaming is an example of application falling in this category. We show results obtained through dynamic simulations.

We define the dynamic trajectory of the UAVs through a heuristic approach which in previous papers of the same Authors has proven to provide evident improvements in terms of network throughput [1]; in this work we modify the approach to account for joint RRM, and discuss possible ways to achieve further improvements in performance, left for further work.

The rest of the paper is organized as follows. Sect. II discusses prior literature works. Sect. III describes the network model and the scenario considered. In Sect. IV we propose our approach to the joint definition of UAV path and RRM strategies. Numerical results and conclusions are presented in Sect. V and VI, respectively.

II. State of the Art

The Air To Ground (ATG) channel model has been analyzed in papers like [2].

As for RRM, [3] investigates optimal resource allocation mechanisms for IoT applications. In [4], scheduling for UAV-aided networks is addressed, with the aim of achieving the maximum system performance in terms of encounter rate and energy efficiency. [5] introduces a discussion on the integration of UAVs in the next generation of networks.

Clusterization algorithms for UAV scenarios are introduced in [6]: the model considers one UAV per cluster. In particular, Authors study the optimal trajectory and deployment in IoT uplink communications to minimize the power transmitted by machine nodes and the energy consumed at UAV side. Moreover, the Authors in [7] obtain dynamic trajectories in 3D space to connect IoT devices in the scenario at their activation time. They jointly optimize the transmission power of machine nodes, the overall energy spent in movement and the choice of the next stop for each UAV. Other early results regarding UAVs in cellular networks can be found in [8]. Authors considered the maximization of downlink coverage in drone small cells by computing the optimal height and minimizing the transmit power. The impact of interference on deployment of multiple UAVs was discussed together with the wanted distance between them, to improve coverage performance. In [9], UAVs are used to carry relays; the model uses density and cost functions to calculate areas with higher demands and multiple UAVs are deployed depending on these functions. In [10], [11] new considerations are introduced about the usage of Radio Maps to drive UAVs, in order to exploit the effective environment dependent Path Loss (PL) to drive system performance. One of the early works about the integration of terrestrial infrastructure and aerial platforms is [12]. Authors analyze aspects such as radio access, backhaul links and coverage introduced by multiple drone-cells. However, they mainly focus on uplink machine type communication and do not consider a joint system resource management that includes trajectory design. [13] introduces a single frequency scenario where TBSs and one UAV operate together to serve underlying users, but the RRM techniques implemented in the terrestrial network work independently with respect to the aerial platform. Moreover, [14] studies user scheduling in the terrestrial network for non-orthogonal transmission in UAV relay networks. Potential interference is analyzed for both backhaul and UAV-UE link with the terrestrial network, and an interference avoidance solution is proposed.

Apart from very few exceptions, all these papers have been published in the last two years; the research field is very recent, and the topic is still addressed under simplistic assumptions. Moreover, there is no paper in the scientific literature addressing relevant issues like joint aerial-terrestrial RRM and combination of RRM with the dynamic path design for UAVs. In contrast, in this paper we introduce the impacts that dynamically defined trajectories and joint RRM between the terrestrial and aerial components of the network, bring to system performance. From this viewpoint, this work is very novel.

III. Network Model

A. Network Architecture

5G will rely on networking techniques like SDN (Software Defined Networking) and NFV (Network Functions Virtualization). An NFV Orchestrator will manage the overall network; SDN controllers will be responsible for resources at more local level. We assume (see Fig. 2) that the Mobile Architecture Network Orchestrator (MANO) will manage a UAV Network Controller (UANC) that will be responsible for i) the assignment of radio resources available on the UAVs, ii) defining their trajectories and missions. The UANC through the MANO will be aware of the ground user traffic, and how the TBSs are serving UEs. In particular, an assumption usually made in scientific literature is that the UANC has knowledge of the position of the ground users to be served by UAVs; moreover, we assume that the UANC is aware of the key performance indicators and the radio resources used in TBS-UE links.

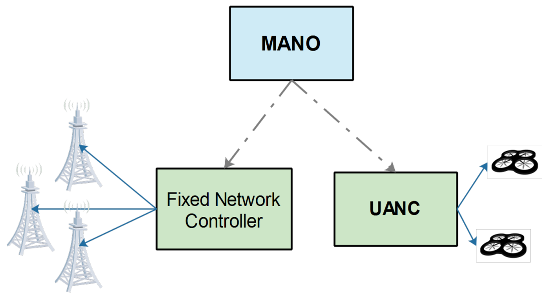

Fig. 2. Reference network architecture.

B. Traffic Model and Scenario

Services with stringent delay requirements cannot benefit from the aerial component of the network owing to the limited speed of UAVs. For this reason we focus on video streaming; the application requirements include a maximum waiting time (in the order of few seconds) before the streaming starts, and a minimum level of throughput. To evaluate the benefits introduced by the aerial component of the network, we will therefore measure the sum throughput, S, better defined later. We will focus on downlink streaming.

Most papers on UAV-aided mobile radio networks analyze urban environments, because spatial/time traffic variations can be very significant. Such scenario may include macrocells, and small cells. Some macrocell BSs, located on rooftops or towers, can act as UAV Homes; UAVs are normally parked in any Home (where batteries can be charged), and leave it only when required by the UANC, flying along trajectories optimized according to traffic needs. As a reference scenario, we consider an L by L urban area, with four TBSs per site and nine sites deployed on a regular square grid. We focus on a single UAV; its Home is located in the center of the scenario.

In this context, UAVs will serve the UEs (denoted as Unsatisfied Users, UUs) that cannot be served efficiently by the TBSs. UUs are of three types:

- the number of radio resources assigned by the serving TBS is not sufficient,
- the TBS-UE link has low SNR,
- the TBS-UE link has low SIR (Signal-to-Interference-Ratio).

In most cases, the UUs are confined at the cell edges where normally SIR and SNR is smaller; therefore, the spatial distribution of UUs is not uniform and UAV trajectories will privilege cell borders. Fig. 3 shows an instance of the traffic distribution of UUs, obtained through an LTE-like simulator implementing the network scenario described above [1].

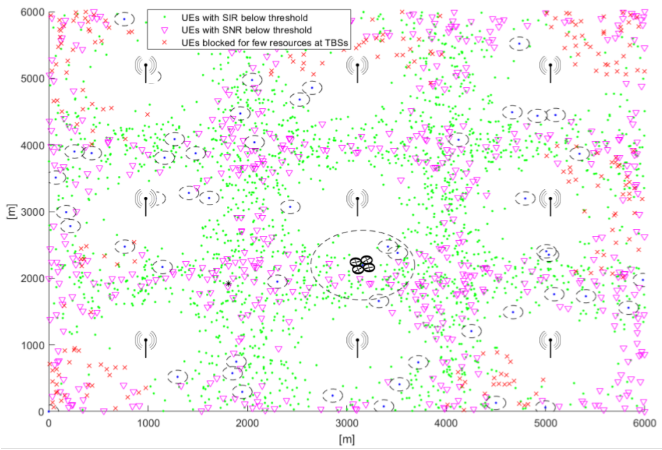

Fig. 3. Network scenario.

C. Air Interface and Radio Channel

For both the aerial and terrestrial air interfaces, we refer to the LTE standard over the 3.6 GHz frequency band, candidate for future 5G service provision in cities.

Most papers in the literature assume that UAVs are equipped with a directional antenna pointing towards the ground, with a fixed aperture angle α. Assuming an ideal antenna without side lobes and with constant gain, the area covered by the BS carried by the UAV (denoted hereafter as footprint) under uniform propagation conditions is a circle of radius $r = h \cdot \tan\alpha$, where h is the drone height. Many works assume that the UAV antenna gain depends on α as $G_\alpha = 29000/(\alpha)^2$. We add to such gain 3 dB, to account for a minimum level of gain even when α is very large. The larger is the UAV height, the larger is the footprint and the number of UUs that can be served by the UAV. On the other hand, setting h, the larger is α, the larger is the footprint and the smaller is the antenna gain.

TBSs serve ground users through a radio channel affected by the typical impairments of urban environments, like fading and

TABLE I
SYSTEM PARAMETERS

L	6000 m	*Squared area side*
λ_u	10 arrivals/s	*Arrival requests per second*
N_{SC}	50	*Total amount of SCs*
$P_{tx,TBS}$	43 dBm	*TBSs transmit power*
$P_{tx,UAV}$	9 dBm	*UAV transmit power*
$P_{tx,SC}$	33 dBm	*SCs transmit power*
$G_{tx,TBS}$	12 dB	*TBSs transmitter gain*
N_0	$4{\cdot}10^{-20}$ W/Hz	*Bilateral noise density*
h	140 m	*UAV altitude*
α	120 $[degrees]$	*UAV radiation angle*
r_{SC}	100 m	*SCs coverage radius*
$f_{c,TBS} = f_{c,UAV}$	3.6 GHz	*Single carrier frequency on TBSs and UAV*
$f_{c,SC}$	10 GHz	*Carrier frequency of SCs*
$R_{b,mn}$	30 kb/s	*Bit rate per subcarrier*

shadowing. The propagation exponent of the terrestrial to user links, β_t, equals 3.6, while the shadowing standard deviation, σ_t, is 6 dB. On the opposite, the UAVs can serve users on the ground through a LoS link. Most papers in scientific literature use an ATG channel model that is based on two states: LoS and Non-LoS. The probability of LoS, P, depends on the angle θ between the terrain and the line connecting the UAV to the UE; the larger is θ, the closer to one is P. In this paper, the power loss of aerial links is computed using the ATG model proposed in [2].

In particular, the computation of SNR and SIR characterizing both TBS-UE and UAV-UU links follows Eqs. (1, 2):

$$SNR_{m,n} = \frac{P_{r\{m,n\}}}{2 \cdot N_0 \cdot B_{subc}} \quad (1)$$

$$SIR_{m,n} = \frac{P_{r\{m,n\}}}{\sum_{i=1}^{N_{TBS}} P_{r\{i,n\}}} \quad (2)$$

where $c_{m,n}$ equals 1 whenever subcarrier set n is assigned to UE m otherwise it is set to 0. N is the total amount of subcarriers and B the total bandwidth. Then:

$$X_{m,n} = \min(SNR_{m,n}, SIR_{m,n}) \quad (3)$$

Finally, the computation of throughput gained from each properly served UE (which is the same for UAV-UU and TBS-UE links) is made through Eq. (4):

$$T_m = \frac{B}{N} \sum_{n=1}^{N} c_{m,n} \log_2(1 + X_{m,n}) \quad (4)$$

The parameter values adopted for simulation purposes are defined in Table I and II.

IV. UAV PATH AND RADIO RESOURCE ASSIGNMENT

A. Trajectory Design

As shown earlier, few papers address the optimal design of UAV paths. The dynamic trajectory of UAVs should be defined according to a number of factors: the position of UUs,

TABLE II
RADIO ACCESS PARAMETERS AND USER REQUIREMENTS

Subcarrier spacing	15 kHz
Number of subcarriers per PRB	12
Maximum capacity, C_{max}	100 Mb/s
Time slot interval	0.5 ms
Frame time duration	10 ms
TBSs bandwidth	20 MHz
Small cells bandwidth	1.74 MHz
Reuse factor	1
Minimum throughput required per user, Thr_{min}	10 Mb/s
Traffic data size per UE	25 MB
Maximum waiting time for video download	24 s
Range of speed for walking users	0 - 1.5 m/s
SNR_{min}	10 dB
SIR_{min}	3 dB

their traffic requirements, the residual energy available on the UAV, etc. In this paper we refer to the approach used in [1], considering all factors above. However, we modified the way we account for them.

Assume the UAV is located in Q (x, y, h) at a given instant t, when a new direction of flight has to be chosen. The MANO sends the updated information on UUs, their traffic demand, and radio resources assigned by TBSs, to the UANC. Based on this:

- the UANC groups the UUs in K clusters [1];
- for each cluster ($i = 1, \ldots, K$), the centroid is computed;
- for each centroid ($i = 1, \ldots, K$), a cost function, C_i, is computed (see later);
- the centroid having smallest cost function is selected (its distance from Q is denoted as d_c);
- the UAV starts flying in the direction of the chosen centroid along a segment travelled during a time interval d_c/v, where v is the UAV speed;
- during its flight, the UAV serves all UUs covered by its footprint.

The cost function in this paper is based on the same factors included in [15]. However, one more factor has been added and its expression has been modified as follows.

$$C_i = F_d \cdot F_\delta \cdot F_W \cdot F_S \cdot F_E \cdot (1 + B) \tag{5}$$

where:

- $F_d = \frac{d_i}{d_{max}}$; d_i is the distance between Q and the i-th centroid, d_{max} is the maximum of all values of d_i limited to a maximum range R;
- $F_\delta = \frac{\delta_i}{\delta_{max}}$; δ_i is the average distance between UUs in cluster i and its centroid, δ_{max} is the maximum of all values of δ_i over all K clusters;
- $F_W = \frac{W_i}{W_{max}}$; W_i is the number of RRUs already used by the TBSs inside the UAV footprint when the UAV is above the i-th centroid, and W_{max} is the maximum among all values of W_i;
- $F_S = \frac{S_{min}^{(cl)}}{S_i^{(cl)}}$ considers the estimated sum throughput that will be obtained when the UAV will be above centroid i, $S_i^{(cl)}$ (see later); $S_{min}^{(cl)}$ is the minimum sum throughput achievable in the current set of K clusters;
- $F_E = \frac{E_i}{E_{max}}$; E_i is the energy that the UAV will spend to reach the i-th centroid at constant speed v [16], computed as $E_i = \frac{d_i}{v}(c_1 \cdot v^3 + \frac{c_2}{v})$, and E_{max} is the maximum among all values of E_i;
- the term $(1 + B)$ provides spatial fairness.

The sum throughput S is defined as the sum over all interested UEs, $S = \sum_j T_m$, of the throughput they perceive when served by a TBS or the UAV; for the m-th user, throughput, reported in Eq.(4). Note that the factor F_E takes into account that the UAV spends energy and has a limited lifetime. However, the simulated scenario takes into account a time of operation of 30 minutes; professional drones having this endurance already exist, and it is expected that in the coming years the available technology for UAVs will still improve.

In summary, apart from the term $(1 + B)$, the cost function described above is the product of a number of factors taking values between 0 and 1. These factors were chosen to jointly reduce energy consumption and improve efficiently sum throughput. The UAV will take the direction identified by the lowest among all K costs; as long as the factors F_i are closer to zero, the i-th centroid has higher chance to be chosen.

The approach defined above will determine a UAV path made of segments of different lengths. They are travelled by the UAV at constant speed v, and height from the ground h. Indeed, these two parameters should be subject to optimization (in combination with the choice of the antenna aperture angle α), as they will significantly affect network performance. Paper [15] shows that optimal values of α are very large, and that the optimum of h lies between 100 and 140 m in a scenario like the one of this work.

B. Radio Resource Management

As far as the radio resource pool used by the aerial network component to serve the ground users is concerned, there are several options.

The simplest approach is to assume that the UAV serves the UUs using orthogonal frequency bands with respect to the TBSs. We are not interested here in this simple scenario with neither reuse nor interference. We consider the case where TBSs and UAVs use the same Radio Resource Unit (RRU) pool. At each scheduling instant, all TBSs decide through a Round Robin algorithm which camping users to serve, if they met the minimum requirement of SNR and SIR, having the whole RRU pool at disposal. Then, the UANC is made aware of each RRU set already used by any TBS to serve any UE. The UAV, while serving the UUs, should select the set of RRUs that will minimize mutual interference with the underlying terrestrial network.

As long as RRM is separate between the aerial and terrestrial components of the network, the solution proposed in [13] represents the optimal choice; the UAV uses at any instant only those RRUs that are not assigned by the TBSs to the UUs located in its current footprint (which is known by the UANC). Under the assumption of an ideal antenna, the UAV transmission has no impact on ground receivers outside the footprint; inside it, no UE is using the RRUs used by the UAV. Therefore, interference is completely avoided; the UAV is re-using some of the RRUs assigned by the TBS within its cell. In such situation, the UAV will provide additional contribution to the network throughput, and no interference. On the other hand, the availability of RRUs strongly depends on the footprint area covered by the UAV: if the radius is small enough (e.g. 100 m), it is more likely that a large number of RRUs used by TBSs remains out of the drone coverage and then is still available for reuse at the UAV side. The opposite is true when the footprint is larger. For this reason, a trade-off is necessary [15].

However, there is margin for further improvement. Let us assume that RRM is performed jointly by the terrestrial and aerial components. For any UE that can be served by both the TBSs and the UAV, the optimal choice is made. The advantage in this case is that there might be situations where a UE in the footprint of the drone will be served with much higher SNR by the UAV, even though it might have been served (with lower throughput) by the TBS. In this case, the network might decide to switch the UE's serving node from the TBS to the UAV, freeing the TBS of respective RRUs usage; however, this means that these RRUs can be re-used by the UAV for the new UU, avoiding interference. The contribution of the UAV to network throughput is expected to be larger with respect to the case of separate RRM.

A further consideration is related to latency. The separate RRM does not include any sort of feedback to the terrestrial network, therefore the TBS scheduler activity is not delayed or impacted by the UAV operation. The situation may be different when using joint RRM, but only for those UEs that change the serving node: in fact, in this case the network may issue an handover in favour of the UAV to serve the selected users.

C. Joint Trajectory Design and RRM

It is worth noting that the choice of the cost function reported above, includes the consideration of the expected number of radio resources that will be available in the cluster to be visited next, through the factor F_W. According to the RRM technique used in this paper, the number of RRUs available in each cluster is variable depending on how many UEs are served by the TBSs in the UAV footprint. Therefore, the design of the UAV trajectory is performed accounting for the specific type of RRM strategy envisaged for the network; in other words, the UAV trajectory is RRM-dependent.

Nevertheless, one step further might be taken, by joining the decision on the next direction with the RRU assignment. This is left for future investigation.

V. Numerical Results

Numerical results are obtained through a dynamic LTE-like simulator described in [1], with parameters set as in Tables I and II.

Figure 4 shows the throughput gain achieved as a function of UAV speed, where the throughput gain in percentage, G, is computed following Eq. (6):

$$G = \frac{S_{UAV}}{S_{tot}} \tag{6}$$

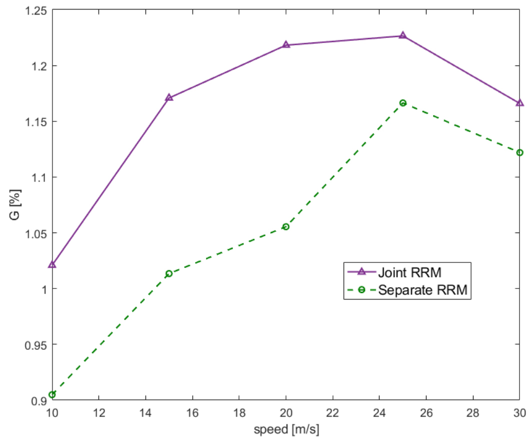

Fig. 4. Throughput gain with varying UAV speed.

The terms S_{UAV} and S_{tot} represent the sum throughput achieved by the UAV, and by the terrestrial network only, respectively. In the analysis of values assumed by G, it has to be considered that they are obtained from a single UAV in a large network (see Table I).

In the figure, the lowest curve represents the outcome achieved through the first separate RRM solution mentioned in Sec. IV-B. On the opposite, the uppest curve is obtained by implementing a joint RRM decision between aerial and terrestrial network, as mentioned before. As expected, the second case provides better performance results in terms of throughput gain. In fact, in this solution RRUs are scheduled taking into account and comparing the different downlink channel conditions. Moreover, both curves show the same behavior when varying drone speed. As its value increases, performance results increase as well. This happens because the UAV is able to reach UUs in a faster way. However, when speed is larger, the UAV is not able to satisfy the user application requirements, as it flies away before the video is fully downloaded. For this reason, a maximum in the curves is present and a tradeoff value to set for speed must be applied.

The comparison between the two curves shows that the maximum does not change with the RRM strategy used. Whatever the value of UAV speed, joint RRM provides a significant improvement in gain with respect to separate RRM. Moreover, it is worth noting that in previous papers of the same Authors where exactly the same settings were used, the gain is always lower [1]; the choice of the new cost function significantly increases the performance improvement achieved through one UAV in this scenario.

Figure 5 shows performance outcome while enlightening the influence of energy consumed. The total energy spent is computed as the previously mentioned E_i. The two parameter values c_1 and c_2 featuring the drone's mechanical

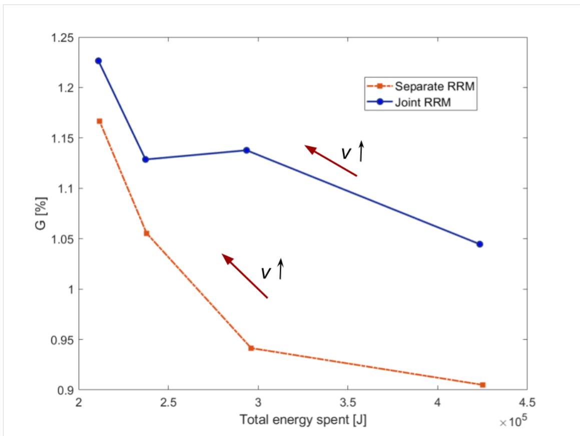

Fig. 5. Throughput gain with varying energy consumed.

characteristics are set as $c_1 = 9.26 \cdot 10^{-4}$ and $c_2 = 2250$, as in [16]. Authors state that the minimum energy spent is obtained for a drone speed of 30 m/s, and the same behaviour applies in this scenario. Therefore, with this speed not only the energy consumption is less, but also the network improves in performance in terms of throughput gain. Thus, higher speeds for the UAV are preferable with respect to low velocity of 10-15 m/s.

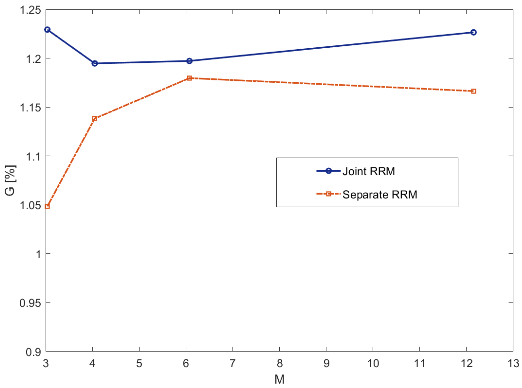

Fig. 6. Throughput gain while varying M.

In Fig. 6 the performance gain is shown with respect to another parameter, M, that is the average number of UUs present inside a cluster. This value is dependent on the total number of clusters, K, chosen as input for the clusterization algorithm. The curve related to a separate RRM is more dependent on this parameter, where for a larger number of users inside each cluster, the throughput gain increases (variations in G below 0.01% are considered as negligible due to statistical reasons). Therefore, for this case it is more advantageous to drive the UAVs through bigger clusters. However, for what concerns the aforementioned joint RRM, the performance gain obtained is almost equal for different values of M. Then, the clusterization algorithm appears to be more robust. In fact, the difference in performance gain while changing parameter M is small: the slight modifications are probably due to the realistic high randomness present in the scenario.

We conclude the analysis by understanding the different roles of every fraction in the new cost function.

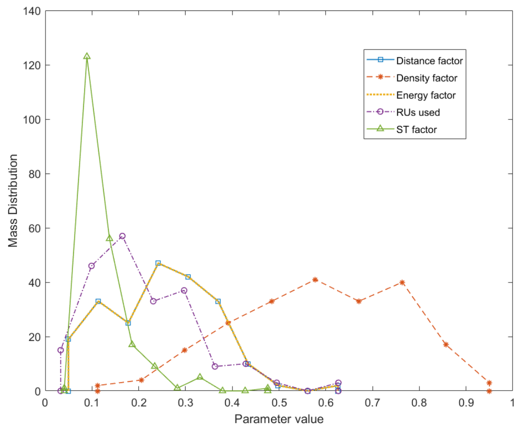

Fig. 7. Probability mass distribution of the different factors in the cost function.

We analyzed the behavior of both, factors F_i of the cost function and weighted C_i averaged costs throughout a simulation.

The mass distribution obtained for each factor F_i is shown in Fig. 7. Clearly, some factors have a distribution that is quite different than the others; as a result, the role of each factor is rather different. One possibility to overcome this problem would consist in using different exponents, ϕ_i, applied to the different factors F_i. This might provide some degrees of freedom to be properly used for optimizing system performance. This is left for further work.

However, we can infer from Fig. 7 that the most impacting factor between the five is F_S, i.e. the ST factor. Its values are mostly close to 0, then it drives the product to smaller costs. On the contrary, F_δ has values closer to 1, thus affecting less the overall cost. The other factors behave in a similar way, having then comparable weighs. Finally, F_S is the factor mostly shaping the mass distribution of the cost function.

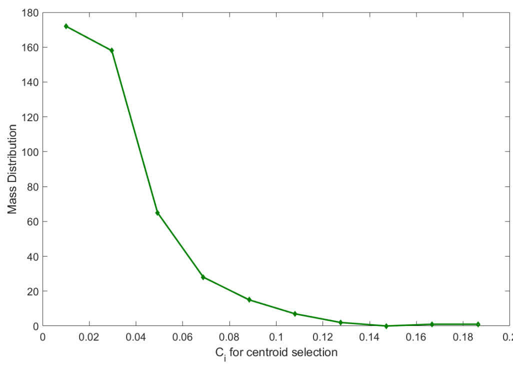

Fig. 8. Probability mass distribution of obtained C_i.

Figure 8 shows the mass distribution of the obtained costs to compare for the best centroid selection, during a simulation run. Most values are very small, showing that the path is chosen by the algorithm based on minimal differences among cost values. This suggests that there is margin for further improvement.

VI. Conclusions

This paper has proposed a new expression for the cost function used to determine the UAV path, with respect to [15]. Moreover, the role of joint aerial-terrestrial RRM has been emphasised. The two facts together bring to a significant performance improvement with respect to [15].

The cost function introduced in this paper has been generated according to a heuristic approach. No one ensures that a better way to define its expression does not exist. Five factors driving the cost function have been identified based on the drone hardware and mechanics, as energy and distance, and the final scope on performance, as ST, user density and RRUs availability. Finally, the impact of each factor is analysed and performance results of the system are encouraging. The analysis of the distribution of values for the different factors combined in such expression, might bring to interesting considerations related to the possibility to give different weights to the factors, e.g. through some (different) exponents. This is left for further works.

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