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Optimal Design of 5G Networks in Rural Zones with UAVs, Optical Rings, Solar Panels and Batteries

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ABSTRACT We focus on the problem of designing a 5G network architecture to provide coverage in rural areas. The proposed architecture is composed of 5G Base Stations carried by Unmanned Aerial Vehicles (UAVs), and supported by ground sites interconnected through optical fiber links. We also consider the dimensioning of each site in terms of the number of Solar Panels (SPs) and batteries. We then formulate the problem of cost minimization of the aforementioned architecture, by considering: i) the cost for installing the sites, ii) the costs for installing the SPs and the batteries in each site, iii) the costs for installing the optical fiber links between the installed sites, and iv) the scheduling of the UAVs to serve the rural areas. Our results, obtained over a representative scenario, reveal that the proposed solution is effective in limiting the total costs, while being able to ensure the coverage over the rural areas.

Keywords: 5G, UAV-based networks, optical rings, cost minimization, optimization

1. INTRODUCTION

5G will be the dominant technology to provide wide area connectivity in the forthcoming years [1]. In order to provide extremely large throughput, coupled with low latency, new 5G equipment will be installed at selected sites. In general, 5G is expected to be initially installed in urban areas, where the Return on Investment (RoI) is guaranteed to the operator(s). On the other hand, rural zones are less appealing for installing 5G sites, due to the fact that the relatively low density of users is not able to generate a sufficient profit for the operator [2]. Hence, there is the imminent risk that rural zones will not be covered by 5G. Clearly, the lack of 5G deployments in rural zones will inevitably increase the digital divide for the users living in such areas [3].

To overcome such issues, in this work we study the design of a cheaper 5G architecture, where the 5G Base Stations (BSs) are carried on board of Unmanned Aerial Vehicles (UAVs). The exploitation of UAVs to provide radio connectivity is receiving considerable attention from the research community (see e.g., [4], [5], [6], [7]). However, the evaluation of the installation costs of UAV-based radio architectures, as well as a thorough comparison with traditional architectures, is still an open issue. To tackle this aspect, we formulate the problem of minimizing the installation costs of an UAV-based 5G architecture. More in detail, we consider the costs for installing a site, the costs for acquiring the radio equipment, the costs for placing the optical fiber links between the sites, the UAV costs, the costs for installing the Solar Panels (SPs) and the batteries on each site. We then target the minimization of the total installation costs, by ensuring the 5G coverage over a set of areas. To further reduce the costs, the proposed architecture is able to exploit the energy coming solely from the SPs and batteries. Results, obtained over a representative scenario, prove that the proposed architecture is able to notably reduce the costs compared to a classical solution, which instead assumes to provide radio connectivity by installing fixed 5G BSs.

2. UAV-BASED 5G ARCHITECTURE DESCRIPTION

We briefly review the UAV-based 5G architecture, based on the reference architecture of [2], [8]. In brief, we assume the deployment of a softwarized architecture, where the radio functionalities are decomposed into elementary blocks. In this context, the low-level functionalities are deployed on the dedicated HardWare (HW) carried by the UAV, while the commodity HW, hosting high-level virtual functionalities, is installed at ground sites. The decoupling between high-level and low-level functionalities allows to decrease the amount of HW carried by the UAV, and consequently to move the UAVs over the territory to cover selected areas. Finally, we assume that an area is covered by an UAV when the UAV reaches the central point of the area.

In order to provide the 5G connectivity, a maximum distance constraint needs to be ensured between the UAV covering the area and the site at which it is connected through a radio link. This is an essential condition to maintain the radio connectivity between the low-level functionalities flying on the UAV and the high-level ones placed at the ground sites [2].

In addition, time is discretized in Time Slots (TSs). In each TS, coverage over the territory has to be ensured, i.e., each area is covered by exactly one UAV. In each TS, an UAV can either: i) cover an area, or ii) recharge itself at a ground site. Each site provides at each TS an amount of power to the UAV(s) attached to it. This

$$\min \left[\sum_{s \in S} (C_B N_B^s + C_{SP} N_{SP}^s + C^s y^s) + C_D N_D + \sum_{(s,s') \in E} C_F^{s,s'} f^{s,s'} \right] \quad (1)$$

$$\sum_{s \in S} \sum_{d \in D} G_{s,a} x_{d,a}^s(t) = 1 \quad \forall a \in A, t \in T \quad (2)$$

$$\sum_{s \in S} r_{d,s}(t) \leq 1 \quad \forall d \in D, t \in T \quad (3)$$

$$r_{d,s}(t) \leq y^s \quad \forall s \in S, t \in T, d \in D \quad (4)$$

$$x_{d,a}^s(t) \leq y^s \quad \forall s \in S, a \in A, t \in T, d \in D \quad (5)$$

$$z_{d,a}(t) = \sum_{s \in S} x_{d,a}^s(t) \quad \forall d \in D, a \in A, t \in T \quad (6)$$

$$\sum_{a \in A} z_{d,a}(t) + \sum_{s \in S} r_{d,s}(t) = 1 \quad \forall d \in D, t \in T \quad (7)$$

$$\sum_{s \in S} G_{s,a} r_{d,s}(t) \geq z_{d,a}(t-1) \quad \forall d \in D, t \in T, a \in A \quad (8)$$

$$E^s(t) = \sum_{d \in D} r_{d,s}(t) E_R^d + E_F^s y^s \quad \forall s \in S, t \in T \quad (9)$$

$$B^s(t) \leq B_{MAX} N_B^s \quad \forall t \in T, s \in S \quad (10)$$

$$B^s(t) \geq B_{MIN} N_B^s \quad \forall t \in T, s \in S \quad (11)$$

$$B^s(t) \leq B^s(t-1) + E_{SP}(t) N_{SP}^s - E^s(t) \quad \forall t \in T \quad \forall s \in S \quad (12)$$

$$B^s(1) = B_{MAX} N_B^s \quad \forall s \in S \quad (13)$$

$$N_B^s \leq N_B^{MAX} y^s \quad \forall s \in S \quad (14)$$

$$N_{SP}^s \leq N_{SP}^{MAX} y^s \quad \forall s \in S \quad (15)$$

$$\sum_{d \in D} \sum_{a \in A} z_{d,a}(1) = \frac{N_D}{2} \quad (16)$$

$$\sum_{d \in D} \sum_{s \in S} r_{d,s}(1) = \frac{N_D}{2} \quad (17)$$

$$\sum_{s' \in S : (s',s) \in E} f^{s',s} + \sum_{s' \in S : (s,s') \in E} f^{s,s'} = 2y^s \quad \forall s \in S \quad (18)$$

$$\sum_{(s,s') \in E} f^{s,s'} \leq \mid \bar{S} \mid -1 \quad \forall \bar{S} \subset S \quad (19)$$

amount of power comes from the SPs and batteries that are installed in each site. Clearly, the amount of power coming from the SPs depends on the hour of the day, as well as the day of the year. We also assume that each site consumes an additional amount of power to keep powered on the commodity HW and the optical equipment. The installed sites are then connected by means of optical fiber links, by assuming a ring topology. The connection with the rest of the Internet is provided by other links which originate from the installed sites (not considered in this work).

Given this architecture, we then target the problem of limiting the number of installed sites, SPs, batteries, UAVs and optical fiber links in order to minimize the total installation costs, while ensuring the coverage of the areas in each TS. In addition, the installed sites are selected from a set of candidate sites, as commonly assumed during the network planning phase.

3. PROBLEM FORMULATION

Let us denote the following sets: i) A set of areas to be covered, ii) S set of candidate sites, iii) D set of available UAVs, iv) T set of TSs, v) E set of candidate links among the candidate sites.

For each candidate site $s \in S$ and for each area $a \in A$ to be covered, we introduce the matrix G, whose elements are Boolean parameters. More in depth, $G_{s,a}$ is equal to 1 if an UAV connected to site s is able to cover area a (0 otherwise). We denote the cost of one battery, the cost of one SP and the cost of one UAV as C_B, C_{SP}, and C_D, respectively. For each site s we denote with C^s the cost for installing the site s and with $C_F^{s,s'}$ the cost for installing the optical fiber link $(s, s') \in E$ between sites s and s', respectively. $N_D = \mid D \mid$ is the number of available UAVs. We denote with N_B^{MAX} and with N_{SP}^{MAX} the maximum number of batteries and the maximum number of SPs that can be installed in one site, respectively. E_R^d is the energy consumption for recharging UAV d. E_F^s is the fixed energy consumption of site s needed to keep powered on the commodity HW and the optical equipment. $E_{SP}(t)$ is the power produced by one SP at time t. We also introduce minimum and maximum battery levels, denoted with B_{MIN} and B_{MAX}, respectively.

We then introduce the decisional variables of the problem. Variables y^s $\forall s \in S$ take value 1 if candidate site s is installed (0 otherwise). Variables $x_{d,a}^s(t)$ $\forall d \in D, a \in A, s \in S, t \in T$ take value 1 if UAV d connected to site s covers the area a at TS t (0 otherwise). Variables $r_{d,s}(t)$ $\forall d \in D, s \in S, t \in T$ take value 1 if UAV is recharging on site s at time t (0 otherwise). Variables $z_{d,a}(t)$ $\forall d \in D, a \in A, t \in T$ take value 1 if UAV d covers area a at time t (0 otherwise). Variables $f^{s,s'}$ $\forall (s, s') \in E : s \neq s'$ take value 1 if the optical link between s and s' is installed (0 otherwise). Moreover, we introduce four sets of non-negative variables: the continuous variables $E^s(t)$ $\forall s \in S, t \in T$, storing the energy consumption of site s at time t, the continuous

(a) Equipment Costs

(b) Locations of the candidate sites / centers of the areas

(c) Links installation costs $C_F^{s,s'}$ among all the possible site pairs

Parameter	N_D	E_R^d	E_F^s	B_{MAX}	B_{MIN}	N_B^{MAX}	N_{SP}^{MAX}
Value	20	0.2 [kWh]	1 [kWh]	2.4 [kWh]	0.72 [kWh]	50	100

(d) Parameters Setting

Figure 1: The Frascati Scenario

variables $B^s(t)\ \forall s \in S, t \in T$, storing the battery level of site s at time t, the integer variables $N_{SP}^s\ \forall s \in S$, representing the number of SPs installed on site s and the integer variables N_B^s representing the number of batteries installed on site s.

The problem formulation, reported in Eq. (1)-(19), simultaneously models: i) the covering problem of a set of areas in a set of TSs by means of a set of UAVs, ii) the location problem to select the set of installed sites in order to recharge the UAVs, iii) the sizing problem for the SPs and the batteries in each installed site, and iv) the design problem of the optical links. The objective function in Eq. (1) is the sum of all the considered costs. Eq. (2) imposes that each area in each TS must be covered by exactly one UAV. Constraints (3) and (4) guarantee that at each TS each UAV can be recharged in at most one site among the installed ones. Constraint (5) are logic constraints guaranteeing that the UAVs can be connected only to activated sites. By means of constraints (6) and (7) the binary variables $z_{d,a}(t)$ are defined. In this way, each UAV is forced to cover an area or to recharge at a ground site in each TS. Constraint (8) guarantees that the selected site for recharging in a given TS is compatible with the area covered in the previous TS and vice-versa. The energy consumption of each activated site in each TS is expressed in (9) as the sum of the energy used to recharge the UAVs and the fixed energy consumption of the site. Constraints (10) and (11) guarantee that the battery level in each TS on each installed site is between the minimum and maximum levels. The battery level of a given activated site in a given TS is expressed in (12), i.e., at most equal to the sum of the battery level of the previous TS, plus the energy produced by the SPs minus the energy consumption in the current TS. Constraint (13) forces the initial battery level of each activated site to be equal to the maximum level. In each installed site the number of installed batteries and SPs must be at most equal to the maximum values, as guaranteed by constraints (14) and (15), respectively. At the first TS, a subset of UAV is assumed to cover the areas (16), and the complement of this subset is placed at the ground sites (17). In this work, we assume that the number of UAVs is equal to the double of the number of areas. In this way, half of the UAVs can be used to cover the areas. Finally, constraints (18) and (19) ensure the ring topology among the installed sites, based on the ring constraints of [9].

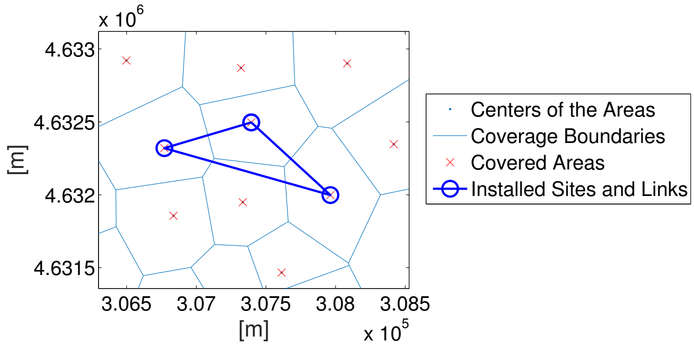
4. SCENARIO AND RESULTS

We consider a rural area in Frascati (Italy), whose main parameters are reported in Fig. 1. In addition, we set to 1 each entry $G_{s,a}$ if the distance between site s and area a is at most equal to 900 [m]. Moreover, we consider a TS duration of 1 [hour], for a total period T equal to 1 month. Finally, we set $E_{SP}(t)$ in accordance to the data used in [8] for the Frascati location during the month of June.

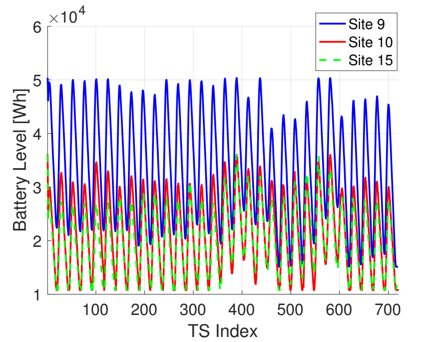
We then run the proposed optimization problem on the considered scenario. Fig. 2 reports the obtained results. We first analyze the obtained costs and the installed equipment, as reported in Tab. 2(a). Interestingly, the optimal solution includes a subset of three sites, which are connected through a minimum cost ring. In addition, the total installation costs of the sites and of the optical links dominate over the costs of SPs, batteries and UAVs. Overall, the total costs of the UAV-based 5G architecture is around 400 [k€]. On the other hand, we have estimated that a solution requiring the installattion of a fixed 5G site in each area, and connecting the 5G sites with the ring minimizing the link costs, costs more than 1000 [k€] (without considering the costs of SPs and batteries). Therefore, we can claim that the UAV-based solution is very cost-effective. Fig. 2(b) reports then an aerial view of the locations of the areas, the coverage boundaries of each area (which are computed as a Voronoi tessellation), the set of installed sites and links, and the covered areas. The installed sites tend to be located in the center of the scenario, where it is easier to reach each area. In addition, each area is always covered by one UAV. Finally, Fig. 2(c) reports the evolution of the battery levels for the installed sites over the considered set

	Equipment Types					Total Costs
	Sites	Optical Links	Batteries	Solar Panels	UAVs	
Cost [k€]	$\sum_s C^s y^s =$ 120	$\sum_{s,s'} C_F^{s,s'} f^{s,s'} =$ 167.02	$\sum_s C_B N_B^s =$ 7.65	$\sum_s C_{SP} N_{SP}^s =$ 20	$C_D N_D =$ 86	400.67
Installed Equipment	$\sum_s y^s = 3$	$\sum_{s,s'} f^{s,s'} = 3$	$\sum_s N_B^s = 51$	$\sum_s N_{SP}^s = 25$	$N_D = 20$	

(a) Detail of costs and installed equipment



(b) Installed sites and covered areas



(c) Battery level evolution for the installed sites

Figure 2: Results obtained over the Frascati scenario

of TSs. From the figure, we can see that all the sites present a clear day-night fluctuation, due to the following reasons: i) during the day, the batteries are charged up to a maximum value, thanks to the energy coming from the SPs, and ii) during the night, the battery levels tend to decrease due to the recharge of the UAVs and the site consumption.

5. CONCLUSIONS

We have targeted the problem of minimizing the total costs of an UAV-based 5G architecture, which is able to provide coverage for a set of rural areas. We have considered the sites installation costs, as well as the costs of SPs, batteries, UAVs, and the optical ring among the installed sites. We have then scheduled each UAV flight in order to either cover an area or to recharge the UAV at the ground site. Our results indicate that the total costs can be greatly reduced compared to the case in which a fixed 5G deployment is assumed. As next step, we aim to solve the problem for larger instances, as well as introducing the constraints to evaluate the 5G channel capacity.

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