Efficiency/Off Grid Operation

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Abstract In order to be deployed in scenarios where the power grid is not available and/or not reliable, the 5G technology has to face several challenges, which are related to its costs and its energy-efficiency. These issues particularly emerge in rural and low-income areas, where the operators are not keen to deploy the same 5G infrastructure originally designed to serve urban zones, due to low Return On Investment (ROI) rates, as well as in emerging countries in which the power grid is not reliable. In this chapter, we face the efficiency and the off grid operation of a 5G network, by: i) defining a 5G architecture based on Unmanned Aerial Vehicles (UAV) and Large Cells (LCs), ii) analyzing the CAPital EXpenditures and OPex EXpenditures of the aforementioned architecture, iii) evaluating different strategies for the reduction of the costs during the design phase, iv) introducing the energy-efficient management of an UAV-based network, v) considering the introduction of renewable energy sources. Results, obtained over several case studies, demonstrate that an efficient 5G off-grid architecture can be deployed, with a positive impact to the connectivity of the users living in rural and low-income areas; the introduction of renewable energy sources allows also the off-grid operation in emergency situations.

1 Introduction

One of the peculiar aspects of 5G is its possibility to improve the cost/energy efficiency compared to pre-5G solutions, as well as the possibility of working in

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Table 1 Comparison of a classical 5G Urban Scenario with Rural and Low-income Ones [1]

	5G Urban Scenario	**5G Rural Scenario**	**5G Low-income Scenario**
Service Type	HD Video, HD Streaming, Tactile Internet, IoT	HD Video, Emergency Service, e-Health, e-Learning	Basic Connectivity, Emergency Service, Delay Tolerant, e-Health, e-Learning
Network Constraints	Maximize Bandwidth, Minimize Delay, Coverage	Coverage, Guaranteed Bandwidth	Coverage
Energy Sources	Power Grid	Power Grid, Renewable Sources	Unreliable Power Grid and/or Renewable Sources
Monthly User Subscription Fee	Pay per bandwidth	Same as standard urban users	Low
Business Model	Return on Investment	Subsidized by the government	Subsidized by the government
Required Network Flexibility	High	High	High
User Mobility	Pedestrian, Vehicular, High Speed Vehicular	Pedestrian, Vehicular	Pedestrian, Low Speed Vehicular

scenarios where the connection to the power grid is not available or not reliable. These two requirements emerge in particular in rural and low-income areas, where the pre-5G networks are currently being not (or not sufficiently) deployed, due to relatively low Return On Investment (ROI) rates for the operators and in emerging countries in which the power grid is not reliable. Tab. 1 reports a comparison among a classical 5G urban scenario, a 5G rural scenario, and a 5G low-income scenario. Focusing on the service type, people living in rural zones are willing to receive a service comparable to the one available in urban areas; this includes services like High Definition (HD) video and good connectivity. In addition, specific services for the rural areas, including emergency services, e-Health and e-Learning, may be required. On the other hand, people living in low-income zones are subject to basic connectivity service requests (rather that HD ones), due to the fact that the adopted devices in these zones mainly include smartphones rather than (expensive) smart TV and/or personal computers/laptops. On the other hand, an emergency service is very important for such zones, which may be coupled with e-Health and e-Learning activities. In addition, delay tolerant services may be required in the low-income scenario. Given the requirements in terms of service type, the 5G network constraints in urban areas include the maximization of the bandwidth and the coverage, which are coupled with the minimization of delay. In rural areas it is instead very important to guarantee coverage and a given amount of bandwidth. Moreover, the coverage is also a stringent constraint in low-income zones. Focusing then on the energy sources, the power grid is in general available in urban areas, while off-grid energy sources, coming from renewable ones, should be exploited in rural and low-income areas. Focusing instead on the monthly subscription fee that the users pay, a similar fee could be paid by people living in urban and rural areas. However, people living in low-income zones should pay low fees. As a result, the business model behind the deployment of the network is based on ROI for the urban zones, while it needs to be subsidized by the government in both rural and low-income areas. In any case, the required network flexibility is always high. This is true in urban zones, where the stringent requirements in terms of bandwidth and delay are translated into large flexibility requests to the network. However, the network flexibility is also required in rural and low/income zones, where the network should cope with the fact that the energy coming from renewable energy sources is not always available. Finally, focusing on the user mobility, pedestrian, vehicular and high speed vehicular are normally characterizing urban areas; while rural and low income zones may be subject to lower mobility schemes compared to urban ones.

Given these challenges, we detail in Sec. 2 the main building blocks of an efficient 5G off-grid architecture. We then analyze the costs in Sec. 3 and face the costs minimization in Sec. 4. Sec. 5 details the efficient management of an UAV-based networks. Finally, Sec. 6 concludes the chapter.

2 An Efficient 5G Off-Grid Architecture

We describe in this section the main features which allow to define a 5G architecture for rural and low income areas, based on the requirements in terms of efficiency and off-grid operation analyzed in the previous section. Tab. 2 reports the main pillars that should be followed in order to deploy such architecture. First of all, the required level of flexibility imposes to deploy a converged solution, in which the operator has full control of the network and the computing resources. Moreover, there is not a strict separation between the devices at the edge, core and metro levels: each device becomes a commodity, which is transparently used independently from its level. A second aspect which allows a converged solution is the large exploitation of functionalities which are completely virtualized. In this way, both the network and the computing components are virtual functions which are controlled by an orchestrator managed by the operator. In addition, the management of the virtual components on a set of physical devices allows to improve the efficiency of the whole architecture. Focused then on the available energy, we expect a large exploitation of the energy from the sun, and hence the deployment of solar panels to power the physical devices. Clearly, this solution needs to be coupled with a set of backup batteries to provide the required level of energy when the sun is not available. Finally, focusing on the technology options, we expect the adoption of two distinct solutions, namely: i) Unmanned Aerial Vehicles (UAVs) carrying radio network elements, and in particular Base Stations (BSs) [2] and ii) Large Cells (LCs) mounted at ground site, realizing massive antenna arrays covering vast portions of territory [3].

To give more insight, Fig. 1 reports a scheme of the energy sources feeding a typical site hosting 5G equipment. In particular, three sources of energy are identified, namely: i) the power grid, which may not be available for all the locations and/or not reliable, ii) the solar panels providing energy from the sun, and iii) the backup batteries which are fed by the solar panels when extra-energy is generated, and supply energy when the generation is not enough. As shwon in Fig. 2, when the power grid is either unreliable or unavailable, as in the case of disdvantaged areas, emergency situations, or emerging countries, a backup traditional diesel generator might be needed. Power supply through diesel generator is already quite common in emerging countries in which the demand of communication services, as well as the demand of electricity in general, is growing at a faster pace than the evolution

Table 2 Main Pillars of the Efficient 5G Off-Grid Architecture [1]

Pillar	Description
Converged Solution	The networking and computing resources are jointly managed by an orchestrator.
	The physical devices of the access network are managed in conjunction with the metro and core ones.
Virtualization of Network Components	Virtualization of network and computing components by means of virtual functions that are controlled by a centralized orchestrator.
	Efficient management of the virtual resources on a set of physical devices.
Exploitation of Commodity Hardware	Exploitation of general purpose HW to host the virtual functions in order to reduce CAPEX and OPEX costs.
Solar-Powered Energy-Efficient Devices	Massive exploitation of solar panels to power the physical devices.
	Exploitation of backup batteries to provide electricity when the energy of the sun is not available.
Unmanned Aerial Vehicles and Ultra-Large Cells	Exploitation of the UAVs to carry radio network elements.
	Exploitation of LC mounted at ground to realize massive antenna array covering ultra-large sizes.

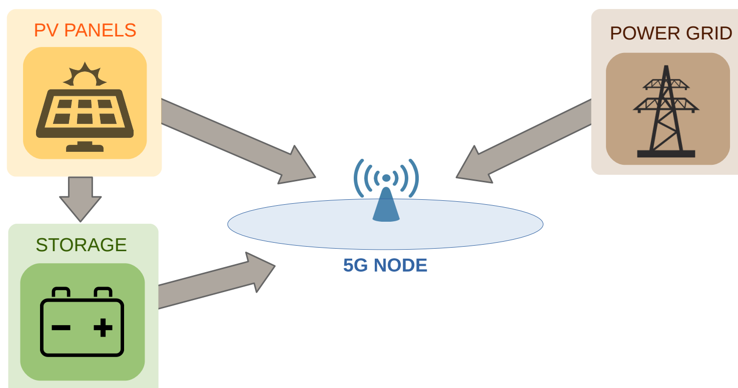


Fig. 1 Power supply for a 5G site with solar panels.

of the power grid. Frequent power outage events are possible in these environments, especially in periods of peak of electricity demand.

Focusing instead on the 5G sites, Fig. 3 reports the LC-based and UAV-based deployment options. In the LC-based solution (Fig. 3.(a)) the 5G site hosts the whole radio functionalities, which are installed in Commodity Hardware (CHW) and Dedicated Hardware (DHW). While we expect that most of functionalities are run by CHW, specific ones, like the processing of low-level functions, will be run in the DHW part of the site. On the other hand, in the UAV-based solution (Fig. 3.(a)) there is a physical splitting between the CHW (which is left at ground) and the DHW (which is carried by the UAV). In this way, it is possible to limit the weight of the load carried by the UAV, with a positive impact of the UAV flight time. However, the physical splitting requires to consider the physical channel constraints between the

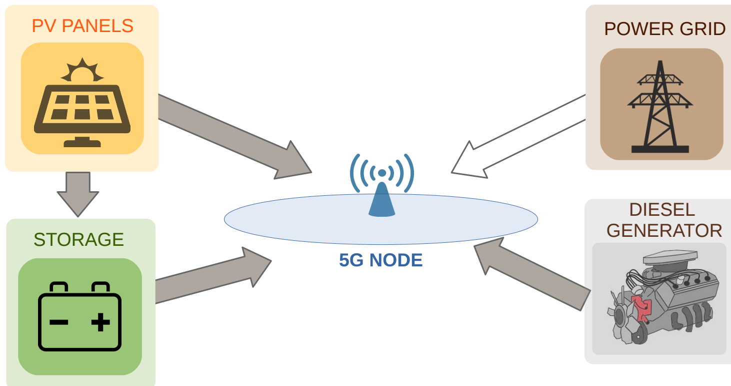


Fig. 2 Power supply for a 5G site with solar panels and diesel generator, in case the power grid is not available.

CHW and the DHW, which include e.g., a maximum distance that has to be enforced between the UAV and the site, and Line Of Sight (LOS) conditions.

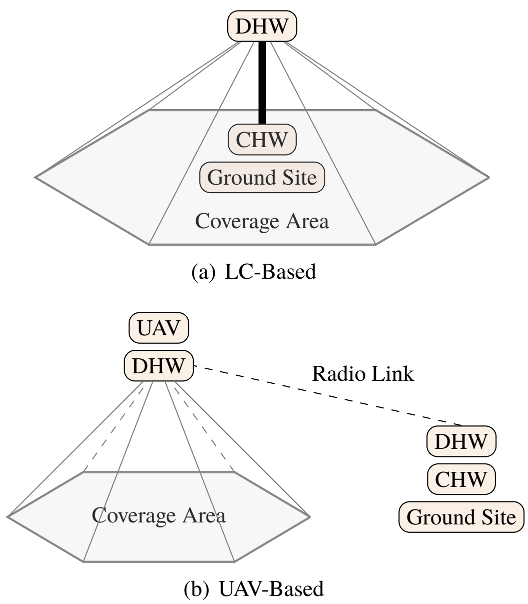


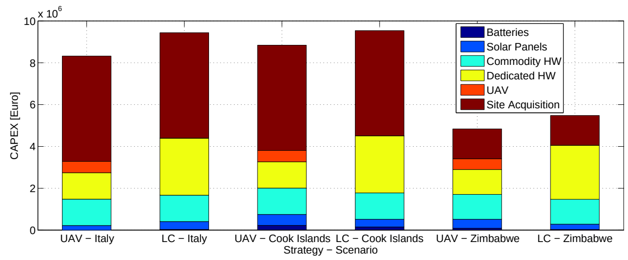
Fig. 3 5G deployment options under consideration [4].

3 Cost Analysis

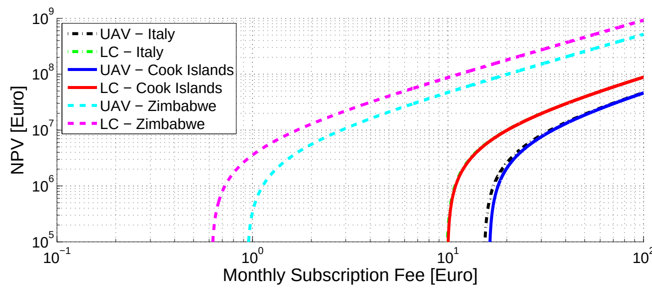
Up to this point, a natural question is: Is a 5G architecture tailored to off-grid scenarios efficient from a cost perspective? To answer this question, we consider the LC-based and UAV-based solutions reported in the previous section, and the set of parameters from [5], which include: the site cost, the battery cost, the solar panel cost, the CHW cost, the DHW cost and the UAV cost. We then apply the methodology of [5] to estimate the number of 5G sites and the required number of batteries and solar panels (which we assume are the same for all the sites), by considering three representative scenarios in the world, namely: i) the area of Frascati (Italy scenario), ii) the Rarotonga island (Cook Islands scenario), and iii) the city of Harare (Zimbabwe scenario). For each scenario, we consider the LC-based and the UAV-based solutions.

Fig. 4(a) reports the outcomes in terms CAPital EXpenditures (CAPEX) for the different scenarios and the different solutions. Interestingly, we can note that the site cost generally dominates over the other ones in the Italy and Cook Island scenarios. In addition, in the Zimbabwe scenario the site costs are lower compared to the Italy and Cook Islands ones. Moreover, the cost of solar panels and batteries is always much lower compared to the other costs. Eventually, the UAV-based solution includes also the cost for buying the UAV, which is again pretty low compared to the other ones. Overall, the total CAPEX costs are in the order of millions, being the Zimbabwe scenario the least expensive for the operator.

In the following, we investigate the impact of introducing OPerating EXpenditures (OPEX) costs and revenues from users in our analysis. Focusing on the OPEX costs, we introduce the maintenance operations. In addition, we assume that the revenues from users are computed from a given monthly subscription fee, which is applied to all the users. Moreover, for the Italian and the Zimbabwe scenarios, we assume that the energy can be derived also from the electricity grid. On the other hand, no connection from the electricity grid is assumed in the Cook Island scenario. Focusing instead on the revenues, we introduce the monthly subscription fee from users, by adopting the conservative assumption that all the users of a given operator pay the same fee. Fig. 4(b) reports the obtained results in terms of Net Present Value (NPV), an economic indicator including CAPEX, OPEX, revenues from users. In particular, when the NPV assumes positive values, the 5G deployment becomes profitable by the operator. The different curves of Fig. 4(b) are obtained by varying the user monthly subscription fee for the different deployment options and the different operators. Interestingly, we can note that, even by setting very low monthly subscription fees, in the order of 1 [EUR] for the Zimbabwe scenario and 10 [EUR] for the Cook Island and Italian ones, it is possible to generate a profit for the operator. Overall, the considered architecture is feasible, even in the Cook Island scenario, where the lack of the electricity grid forces the installation of a large number of batteries and solar panels.



(a) CAPEX Breakdown



(b) NPV, 5% Discount Rate

Fig. 4 Capital Expenditure (CAPEX) breakdown and Net Present Value (NPV) by applying the UAV-based and LC-based strategies over the considered scenarios [5].

4 Cost Minimization

In the following, we then target the problem of cost minimization for the off-grid 5G architecture, by focusing on the UAV-based solution. The problem is then sketched as follows. Given: a set of UAVs, a set of areas to be covered, a set of candidate 5G sites and a set of candidate physical links connecting the sites. Minimize: total CAPEX cost, including: solar panels, batteries, 5G sites, physical links. Subject to: i) coverage of the areas, maximum number of batteries/solar panels per site, amount of energy available at the 5G site, amount of battery available on the UAV. The problem is then mathematically formulated and solved in [6], while here we report the main outcomes. In particular, we focus on a zone in Frascati (Rome), with the set of parameters reported in [6].

The optimal solution selects 3 sites to install out from a list of 9 candidates. Tab. 3 reports the breakdown of the number of batteries and solar panels installed in each site. Interestingly, we can see that each site has a specific set of solar panels/batteries. By further investigating this issue, we have found that each site manages a specific set of UAVs, which results then in a variegate amount of energy demanded to each site.

Fig. 5 reports then the breakdown of the total costs for the optimized UAV-based solution. Interestingly, the site acquisition costs dominates over the other ones, which

Table 3 Breakdown of the installed SPs and batteries for the UAV-based solution [6].

Metric	Site ID		
	9	10	15
Batteries	21	15	15
Solar Panels	10	8	7

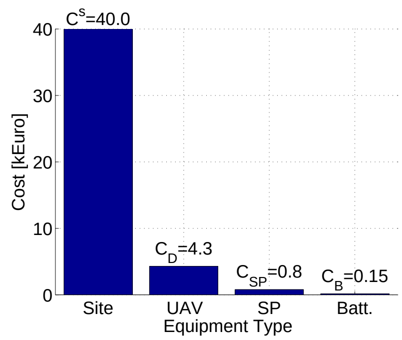


Fig. 5 Breakdown of the equipment costs for the UAV-based solution [6].

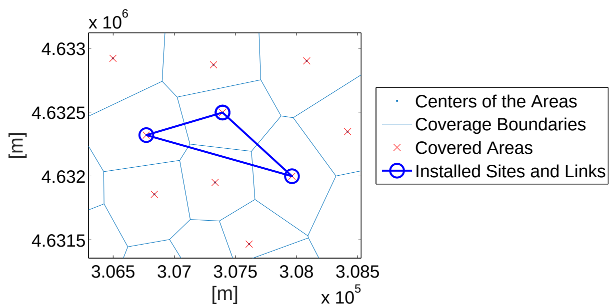


Fig. 6 Installed sites and fiber links for the UAV-based solution [6].

include the solar panels, the batteries, and the UAVs. This outcome confirms our previous finding of Fig. 4(a): the site acquisition costs are important aspects that should be considered during the deployment of 5G networks in off-grid scenarios.

Fig. 6 reports the installed sites and physical links in the considered scenario. Differently from currently deployed cellular networks, in our considered 5G architecture it is not mandatory to install a site in each area. In the UAV-based solution, in fact, the BS functionalities are carried by the UAV, thus allowing different zones to be covered solely by the UAV, and hence limiting the total costs.

Finally, Fig. 7 reports the total battery level in each installed 5G site. We consider a time period equal to one month in our analysis. Interestingly, we can note that the battery level presents a clear day-night trend, with an increase during the day (as a consequence of the fact tha the solar panels are able to recharge the batteries), and a decrease during the day. Each site has a specific maximum battery level, due to the fact that the number of installed batteries is not the same across all the installed sites

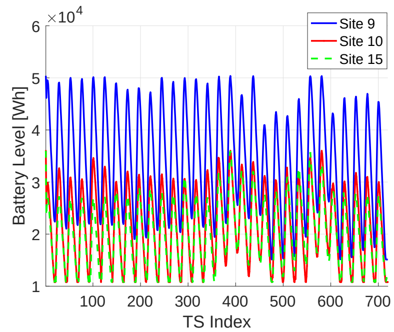


Fig. 7 Temporal variation of the battery levels [6].

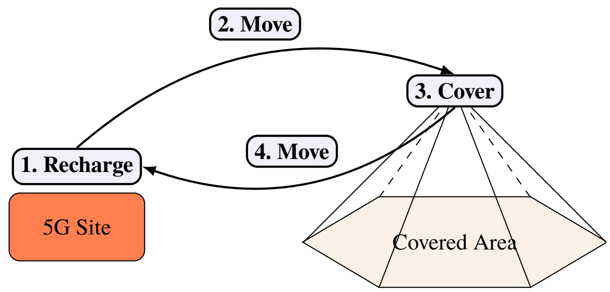


Fig. 8 An example of an UAV mission composed of recharging, moving and covering actions [7].

(as reported in Tab. 3). Finally, even considering the same site, we can note that the battery level does not have always the same trend: this is due to the fact that each UAV can move also across the sites, and hence varying the total demand of energy required to each site.

5 Efficient Management

The efficiency of the 5G network can be further improve by minimizing the amount of energy consumed during operation. In the considered UAV-based architecture, this is achieved by minimizing the amount of energy used by the UAVs when covering a set of areas. Fig. 8 reports an example of an UAV mission composed of different steps, namely: i) recharging in a ground site, ii) moving from the ground site to an area, iii) covering of an area, and iv) moving back to the ground site. In order to limit the amount of energy requested to the ground site during the recharging operation, it is of mandatory importance to reduce the energy consumed when moving the UAV. Therefore, an efficient management of the UAVs is pursued in this step. In order to target this goal, we introduce a framework based on multi-period graphs, a powerful modeling tool which allows to model the trajectory of UAV through space and time.

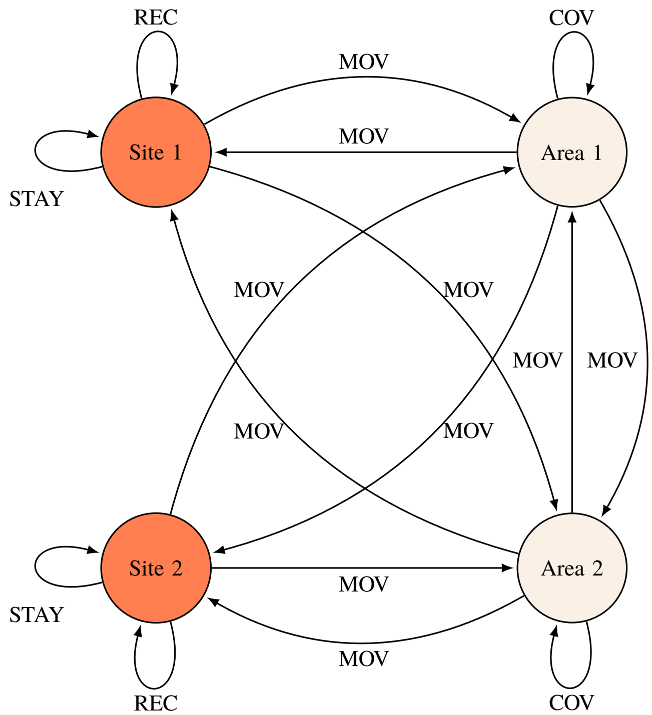


Fig. 9 Possible links between two sites and two areas. Each link consumes one TS [7].

To this aim, we associate a link to each possible action, namely: covering an area, moving, and recharging. Fig. 9 reports a scheme of the links between two sites and two areas. The idea of the multi-period graph is to associate a time slot to each arc, and to consider the pairs (place,time slot) as nodes of the graph, and the links as the UAV action performed between one node and another one. Fig. 10 reports a generic multi-period graph composed of one source node, different nodes, and one one sink node. Each link is an action performed by the UAV. When the place is not varied between one time slot and the following one, the following actions can be performed: i) recharging if the current place is a site, ii) staying fixed at ground (and not consuming energy) if the place is again a site, iii) covering if the current place is an area. On the other hand, when the place is varied, the only possible action is moving between the two places. We then associate a flow variable to each UAV and to each link. By properly setting the flow variables over the multi-period graph, we are able to control the energy consumption and the trajectory of the UAVs (we refer the reader to [7] for a detailed explanation on this aspect).

We define the following energy-efficient (EE) strategy over the multi-period graph. Given: a set of areas to be covered, a set of UAVs, a set of sites, a set of solar panels and batteries for each site. Minimize: total energy due to moving of the UAVs. Subject to: energy available at the 5G site, coverage of the areas, minimum and

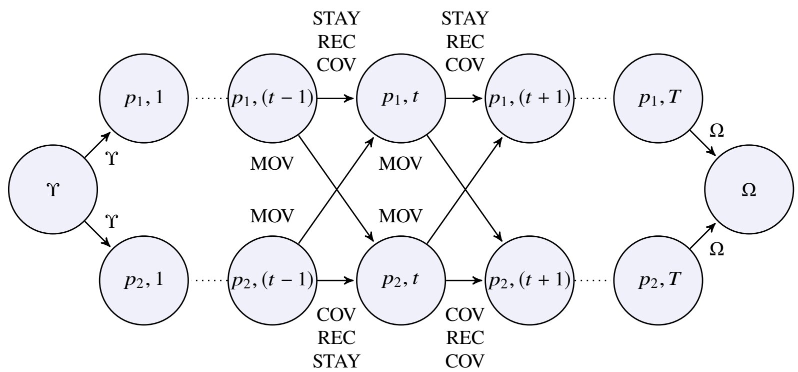


Fig. 10 General transitions between the states of the multi-period graph. The source node ϒ, a set of two places $\{p_1, p_2\}$, and the final sink node Ω are shown [7].

Table 4 EE and MC comparison [7].

Metric	MC	EE		
		TL=2 [h]	TL=24 [h]	TL=48 [h]
Energy due to moving operations [Wh]	86982.4	31150.6	29115.7	23858.8
Problem gap [%]	$< 10^{-6}$	54.6	50.2	38.1

maximum battery level of each UAV. We then consider a rural area in Frascati, and a representative set of parameters, reported in [7]. We then run the energy-efficient (EE) strategy based on the multi-period graph, and compare it against a maximum coverage solution (MC), which does not take into account the energy consumed by the UAV. Tab. 4 reports the comparison between the two strategies, by considering the EE solution obtained after 2, 24 and 48 [hours] of computation. We consider as terms of comparison the total energy consumed by the UAV for moving operations and the values of problem gap of the obtained solution w.r.t. the optimal one. Several considerations hold in this case. First, the energy due to moving is notably reduced by the EE strategy, which ensures full coverage like the MC one. Second, the energy due to moving tends to decrease as the computation time of the EE problem is increased. Third, the gap of the MC solution is very low, as this solution is pretty easy to be retrieved. Fourth, the gap of the EE strategy is higher than the one of MC, as the former is much more complex to be solved compared to the latter. Nevertheless, the EE strategy is able to find a solution already limiting the values of energy consumed by the UAV even after two hours of computation. Overall, the presented results demonstrate that it is possible to efficiently limit the amount of energy consumed in an UAV-based 5G network based on an off-grid architecture.

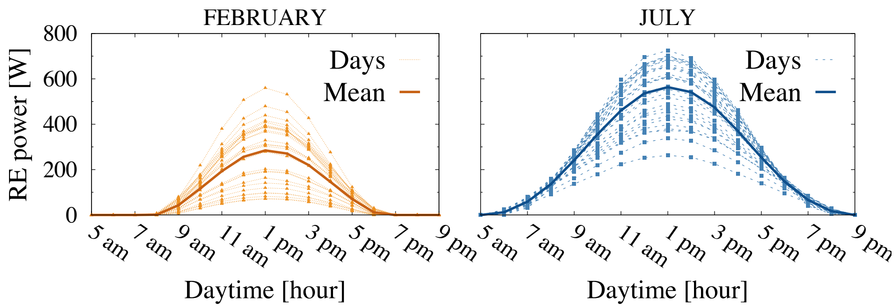


Fig. 11 Daily profiles of renewable energy production per 1 kWp in different sample months in Torino (results obtained with PVWatts) [9].

5.1 Renewable Energy Sources

An interesting option to power mobile networks are renewable energy sources (RES). Besides the potential benefit in terms of OPEX reduction, the introduction of RES is particularly relevant when we consider the need to bring cellular network services to portions of the world population that do not have access to a reliable power grid. The demand of cellular networks and services is growing fast in geographical areas in which the power grid is not reliable and long periods of power outages are frequent. The solution most frequently adopted by operators relies on the use of diesel power generators, which are however extremely costly, because of the price of fuel, the cost to transport it and the frequent costly maintenance interventions. In these scenarios, the use of RES has become an extremely attractive option [8]. The typical power supply in this case is similar to the one reported in Fig. 2, with small solar panels that power a BS or a few BSs, some battery units where extra energy can be stored to be used when needed, and possibly a backup generator, such as a diesel generator.

Even in geographical areas in which the power grid is available and reliable, the solar solution can be interesting: it can be economically effective in rural areas, where the cost of bringing a power cable to the BS may be higher than that of a solar panel and in urban environments, in which bringing a power connection to a BS may require digging across streets. In addition, the introduction of RES allows for a reduction of operational costs.

A RES-based power supply raises, however, some critical issues associated to the intermittent nature of RES. As an example, Fig. 11 shows the daily energy production profiles of a solar panel of 1 kWp (the kWp, kilowatt peak, is the maximum electric power that can be supplied by a photovoltaic panel in standard conditions) in Torino [9]. The plot on the left refers to the days of February, the one on the right to

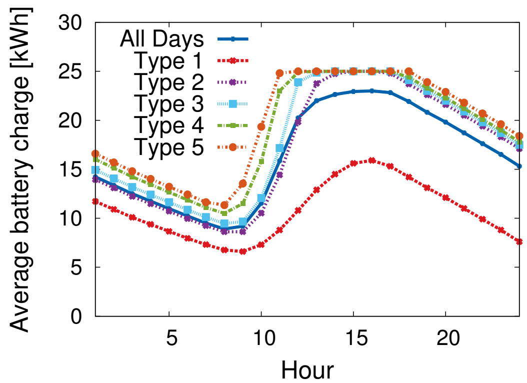


Fig. 12 Average hourly battery charge for a panel of 30 kW peak, battery capacity equal to 25 kWh, in Torino [11].

those of July; the values are obtained with the tool PVWatts and derived from real location based data and considering the Typical Meteorological Year [10]. Some aspects of these patterns are critical for the design and dimensioning of the power supply system. First, there are several hours (during night) in which there is no production at all. Since service continuity is needed, powering the BS during these periods require some power supply that is alternative to the RES, either the power grid or some battery that must have been previously charged. Second, there are quite significant differences in the various seasons. In a location like Torino, the summer production is roughly double the winter production. Hence, a power supply system that is dimensioned over the winter electricity demand of the BS is over-dimensioned during summer time. Finally, even in the same season, there are differences in the energy production levels among different days. This implies that a proper dimensioning needs to cope with the effects of variable production levels even in the short term.

To understand the effect of production level variability among days of the same season, consider the case analyzed in [11]: a winter period in the city of Torino, a power supply system of 30 kWp, and a battery with 25 kWh capacity. We partition the winter days into five types based on their production level, so that type 1 collects the 20% of the days with the lowest production, and type 5 collects the 20% of the days with the highest production, and types 2-4 collect intermediate cases. Fig. 12 shows the average battery charge in different hours of the day for the five day types. The thick blue line is the average. During night, the battery is used to power the BS (assumed for deriving the results to be a LTE BS). The battery charge reduces, almost at constant rate, during night. During day time, the solar production allows to power the BS and to recharge the battery. In day of type 5, the energy production is large, the battery can hence be fully charged during the day. On the contrary, in days of type 1 the production is low and the battery is charged only partially. A few consecutive days of type 1 will hence induce some BS power outage, unless some backup supply is available. The results suggest that, when dimensioning the power system, a careful evaluation of the effects of energy production variability is needed.

In traditional 3G and 4G cellular systems, the power demand of the BSs is very little load proportional, i.e., it is almost constant regardless the load that is carried. This does not cope well with the characteristics of the RES power supply, that is highly variable. Indeed, it turns out that, for an entirely off-grid operation, RES power supply systems, solar panels and batteries, have to be quite over-dimensioned, so as to provide power even in low production seasons, and in case of consecutive days of little production. To this extent, the flexibility of 5G technology brings new opportunities. The possibility to allocate resources in a very dynamic way, and to dynamically distribute the virtualized network functions among the nodes of the network, translates into the possibility to make also the electricity demand more flexible and more suited to be powered with RES.

6 Conclusions and Future Work

In this chapter, we have faced the aspects of efficiency and off-grid operation of a 5G network tailored to serve rural and low-income areas. After proposing a set of pillars of a reference architecture, we have analyzed the total costs that are incurred when UAV-based solutions and LC-based ones are deployed. Overall, the considered solutions allow to achieve a profit for the operator, even when the monthly subscription fee is in the order of 10 [EUR] for the rural scenarios and 1 [EUR] for the low income ones. Moreover, we have shown that the site acquisition costs generally dominate over the other ones, which include e.g., the solar panels, the batteries, and the UAVs. In the second part of our work, we have targeted the minimization of the CAPEX costs, by showing that an UAV-based solution is able to limit the number of ground sites used to host 5G equipment, while allowing the coverage of the areas through the exploitation of the UAVs. Finally, we have targeted the energy-efficient operation of a 5G network, by adopting a framework based on multi-period graphs in order to model the trajectory of the UAVs, as well as the actions that they take over time. Results show that it is possible to wisely reduce the amount of energy spent for moving the UAVs, while allowing the coverage of the areas.

As next step, we plan to face several implementation aspects, such as: the presence of regulatory constraints which limit the UAV flight over the users, the practical limitations introduced by the radio channel between the UAV and the ground site, the definition of the technologies that are exploited for the realization of the LCs, the modelling of the energy of the UAV by considering also the height at which the UAV are required to fly.

Finally, we have considered the introduction of renewable energy sources to power the nodes of the network. The case is interesting in a number of scenarios: in emerging areas in which the power grid is not reliable, in emergency situations or disadvantaged areas in which bringing the power is hard and costly, in other cases as a mean to reduce operational costs. Renewable sources are intermittent and highly variable, both on the time scale of days as well as on a seasonal basis. While in a traditional network the power requirements are extremely rigid, in the 5G case the network is more flexible and it is, hence, possible to envision a network that can easily and effectively adapt to the highly variable patterns of energy production that are typical of renewable sources.

Acknowledgements This work has received funding from the project BRIGHT, under the Call Mission Sustainability 2016.

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