Bringing 5G into Rural and Low-Income Areas: Is it Feasible?

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Abstract

Nowadays, at least two billion people are experiencing a complete lack of wireless cellular network coverage. These users live in rural areas and low-income regions, where network operators are not keen to invest, mainly due to high Capital Expenditure (CapEx) and Operational Expenditure (OpEx) costs, as well as the scarcity of electricity from the grid. We tackle this challenge by proposing a 5G network explicitly designed to serve rural and low-income areas. Our solution investigates the possibility of mounting Remote Radio Heads (RRHs) on top of Unmanned Aerial Vehicles (UAVs), as well as Large Cells (LCs) to increase the coverage range. In addition, 5G-nodes are powered by solar panels and batteries. Preliminary results, obtained over three representative case studies (located in Italy, Cook Islands, and Zimbabwe) show that providing connectivity in rural and low-income areas by means of the proposed 5G architecture is feasible. At the same time, we also show that the monthly subscription fee paid by the users can be kept sufficiently low, i.e., less than 1 [EUR/month] in low-income areas, and around 11 [EUR/month] in rural regions.

Index Terms

5G architectures; economic analysis; Internet for rural and low-income zones

I. INTRODUCTION

According to the recent study presented in [2], the Internet is the most powerful engine in the world for social and economic growth, and it needs to be open, secure, trustworthy, and accessible to everybody. In this scenario, the International Telecommunication Union (ITU) has reported that 69% of the world population is covered by third generation (3G) networks [3], which allow users to connect to the Internet. Moreover, the penetration rate of the Internet in North America is above 80% [4]. However, these numbers hide the dark side of telecommunication networks, which is the lack of connectivity and/or coverage experienced by a large number of people, especially in rural and low-income areas. Such zones include regions in which inhabitants density is lower compared with cities, but also areas densely populated where the Gross Domestic Product (GDP) is extremely low. As a result, at least two billion people experience a complete lack of wireless cellular coverage [5].

Nowadays, telecommunication networks are widely deployed in urban zones. In this context, telecom manufacturers and researchers focus on the development of the forthcoming 5G technologies, which will be available by 2020. 5G standards are currently investigated by several organizations around the world, including partnerships (such as the 5G Public Private Partnership in Europe, the IMT-2020 5G Promotion Group in China, the Fifth Generation Mobile Communications Promotion Forum in Japan, the 5G Forum in Korea, and 5G Americas) and international events. These efforts aim to build 5G networks which will dramatically improve the user experience, thanks to a sharp increase in the offered data rates, coupled also with extremely low latencies. In this scenario, services such as very high definition video, tactile Internet, virtual reality, and the Internet of Things will be made available.

5G has several advantages for the spreading of the Internet connectivity (see examples in the white papers of 5G-PPP [6]). Specifically, a high level of flexibility is introduced, i.e., the services and the network resources can be deployed where and when they are really needed. In addition, 5G integrates the exploitation of commodity Hardware (HW), with Software

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TABLE I
COMPARISON OF A CLASSICAL 5G URBAN SCENARIO WITH RURAL AND LOW-INCOME ONES

	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

(SW) solutions implementing networking functions, thus potentially decreasing the costs for installing and maintaining devices. Finally, both networks and services cooperate to deliver high bandwidth and extremely low delay to users, according to the 5G vision of “converged solution”.

Even though 5G introduces several positive aspects, its relevant technologies are “urban” in their nature. Specifically, the high performance requirements are made possible by an extremely rich and complex architecture (such as in [7]), composed of macro cells, small cells, fronthaul networks, backhaul networks, small computing nodes, and large Data Centres (DCs). The current models of telecommunication networks, which are business- and profit- oriented, suggest that 5G networks will be mainly deployed in extremely dense urban zones, where the revenues generated from subscribers are much higher than the Capital Expenditure (CapEx) and Operational Expenditure (OpEx) costs. On the contrary, rural and low-income zones are less desirable and attractive for operators, since the low density (and/or low-income) population does not justify the deployment of 5G networks.

In this paper, we take a new look at 5G networks from the perspective of rural and low-income subscribers. In this context, several questions arise: Is it possible to define a holistic 5G architecture explicitly including rural zones and low-income ones? What are the costs and the revenues incurred by the network provider when a 5G network is deployed in such zones? The goal of this paper is to shed light on these issues, and to propose future research directions. In particular, after defining the main challenges to be solved, we detail our visions for 5G in rural and low-income zones. We investigate the possibility of mounting Remote Radio Heads (RRHs) on top of Unmanned Aerial Vehicles (UAVs). In addition, we consider also the case in which the connectivity is provided by Large Cells (LCs), which are able to increase the coverage range. We then evaluate the total profits of the network provider by adopting these solutions. To the best of our knowledge, none of the previous works has performed a similar analysis for 5G. Our preliminary results demonstrate that it is feasible to provide connectivity in rural and low-income regions, while keeping the monthly subscription fees of the users sufficiently low. However, we point out that this work is an initial step towards future research activities, which will involve several aspects, such as the investigation of the impact on the uplink, the integration of the UAVs mobility, and the evaluation of the amount of information exchanged by the RRHs with the rest of the network.

II. 5G TECHNOLOGY CHALLENGES

The deployment of 5G in rural and low-income areas is challenged by the peculiar features of the scenarios presented in Tab. I. In particular, the table reports a comparison between a classical 5G urban scenario [6] against 5G rural and low-income ones.[1] In contrast to 5G urban most advanced Internet services such as High-Definition (HD) streaming, tactile Internet, and the Internet of Things, many rural and low-income regions are still disconnected from the rest of the world and the lack of Internet coverage is the most critical problem to be tackled. Not surprisingly, in urban zones it is important to maximize bandwidth and minimize delay. On the other hand, in rural areas it is essential to guarantee a given minimum amount of bandwidth to users. Futhermore, in rural and low-income zones it is even more important to guarantee basic coverage and delay-tolerant communication rather than high bandwidth services. In addition, another aspect that cannot be neglected is that in rural and low-income zones the power grid may not be available and/or reliable, thus suggesting that renewable energy sources (such as solar and wind energies) are priority choices. Moreover, the monthly subscription fee should remain as low as possible,

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[1] Low-income areas include both low density regions in terms of populations as well as towns and cities.

TABLE II

MAIN PILLARS OF THE PROPOSED 5G ARCHITECTURE FOR RURAL AND LOW-INCOME AREAS

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 LCs mounted at ground to realize massive antenna array covering ultra-large sizes.

keeping also in mind that in low-income areas users should pay less money for an Internet connection compared with people in the urban regions. This also inevitably influences the associated business models in such zones, which cannot be based on the classical Return On Investment (ROI), but rather on the fact that the Internet is a primary need that should be provided, e.g., by the government or by the community rather than private operators.[2] Moreover, the network has to be flexible in all scenarios. For example, the network in rural and low-income zones has, e.g., to deal with the scarcity of electricity as well as to wisely manage the network resources in order to guarantee coverage. Finally, the differences in user mobility is another aspect to be considered. Specifically, rural and low-income zones are characterized by relatively lower mobility compared to urban ones.[3] This feature may also have an influence on the design of the network in such zones.

III. OUR VISION

Tab. II reports the main pillars of the proposed 5G architecture to serve rural and low-income areas. In particular, we foresee the exploitation of a converged solution managed by a centralized orchestrator, in which the network and computing resources are mostly running on top of commodity HW. In addition, the physical devices largely exploit solar panels, with batteries that are recharged during the day by the sun and provide the required power during night or bad weather conditions. Finally, we foresee the exploitation of radio elements mounted on top of UAVs and the installation of LCs deployed on cellular towers.

The elements of the architecture, which are shown in Fig. 1, are analyzed in more detail in the following subsections.

A. RRHs mounted on top of UAVs

As the first solution to provide coverage and capacity over the territory, we consider the exploitation of radio cells mounted on top of rotary-wing UAVs flying at low altitudes. The possibility to exploit UAVs to carry base stations is under investigation by the research community (see, e.g., [14]). In our scenario, rather than bringing the whole base station on board of the UAV (which would notably increase its weight), we envision the exploitation of basic radio functionalities, which will be deployed on a Remote Radio Head Unmanned Aerial Vehicle (RRH-UAV). This device integrates an RRH equipped with a set of antennas and an UAV to move the RRH over the territory. The RRH performs basic radio operations, such as digital processing, digital to analog conversion, analog to digital conversion, power amplification and filtering. These functions are coded on the underlying HW of the RRH, which includes radio frequency circuitry and analog-digital converters. In this scenario, the RRH-UAVs can provide flexible coverage, by only serving zones where the users are located (i.e., not the whole territory). In addition, the RRH-UAVs can be exploited when the capacity of the network is needed (e.g., during the day). Each RRH-UAV may establish a radio link with other RRH-UAVs flying in the same zone. Finally, the UAV is recharged by a Solar-Powered Node (SP-node), which is equipped with solar panels and batteries, whose size needs to be properly dimensioned to take into account also the RRH-UAV power requirements.

In addition, each RRH-UAV is coupled with a BaseBand Unit (BBU) which is run as a virtual element on the SP-node. The BBU is in charge of performing baseband signal processing operations. The splitting between the RRH and the BBU has a number of advantages, including: (i) the loading of an RRH and not of an entire base station on board of the UAV, (ii) the possibility to pool different BBUs serving the RRHs. The connection between the RRH and the BBU is realized by means of

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[2] Private operators will not invest the cost of an infrastructure in such zones, due to the low ROI. Therefore, the government or the community should either invest in the deployment of a minimum infrastructure or even become a network provider.

[3] In urban zones users may travel on high speed trains across the city. In rural zones users are more fixed, e.g., they are located close to their houses. In low-income zones users may be traveling on foot or by means of low-speed vehicles.

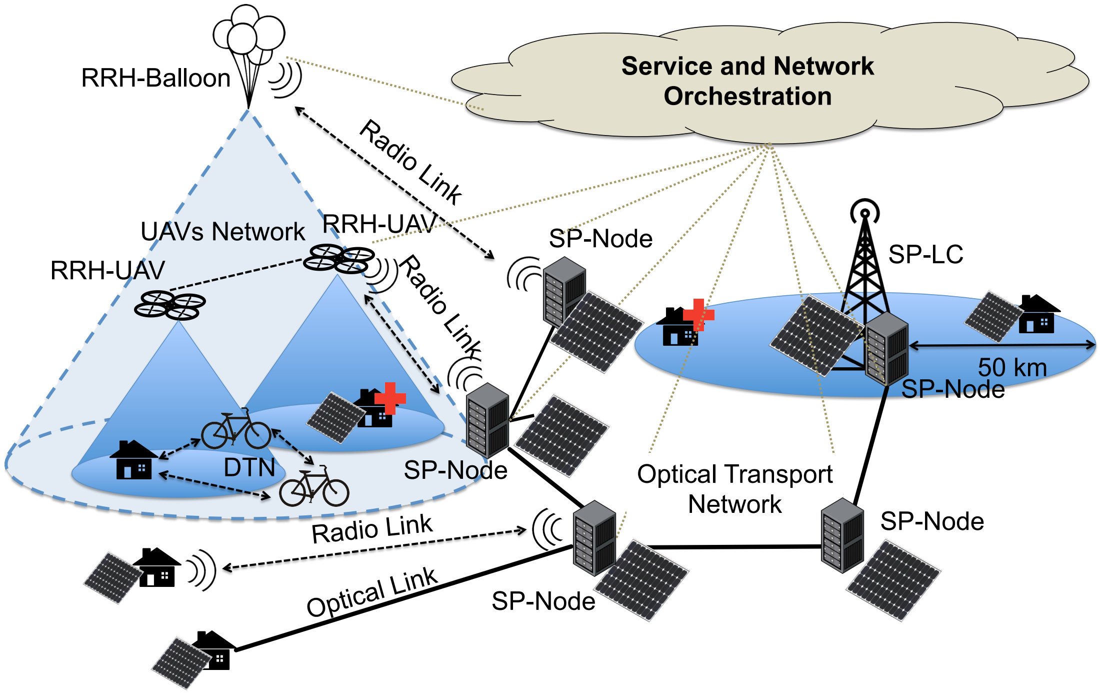

Fig. 1. Proposed 5G architecture for rural and low-income areas. (SP = Solar-Powered, LC = Large Cell, RRH = Remote Radio Head, UAV = Unmanned Aerial Vehicle, DTN = Delay Tolerant Network, SP-Node = Solar Powered Node). The dotted lines between the orchestration and the architecture elements are logical links.

a microwave radio link.[4] This connection is realized by means of one of the interfaces already available in the literature, e.g., Common Public Radio Interface (CPRI). However, we point out the need of investigating new interface solutions to reduce the amount of information exchanged between the RRH and the BBU, in order to limit the costs of maintaining an active microwave link. Finally, each community connected to a rotary-wing RRH-UAV may develop a Delay Tolerant Network (DTN) to further spread the information by means of low-velocity vehicles.

As an additional solution, the RRH may be mounted on other types of UAVs, such as balloons and tethered helikites, which fly at higher altitude compared with rotary-wing UAVs. Both of them are able to increase the flight time compared with rotary-wing UAVs. The typical service provided by these UAVs may be basic coverage and/or emergency calls. In addition, the link between the RRH and the BBU can be realized by means of a cost-efficient and highly-reliable optical cable when the tethered helikite solution is exploited.

B. *Large Cells*

As a second option to provide wireless access connectivity, we foresee the exploitation of LCs, with coverage radius in the order of dozens of kilometers. Two emerging technologies allow for this development. First, the use of very large arrays of antennas at a base station will in a near future lead to a better spatial use of the emitted energy: new beamforming techniques will allow for more energy-efficient modes of transmission which we here exploit to increase cell coverage. Second, 5G transmission schemes are developing towards an ultra-lean use of spectral resources which will also reduce energy consumption per served user. Depending on the actual power consumption (which is directly related to the coverage radius of the LC), the LCs may be solely powered by solar panels and batteries. Each LC is composed of an RRH placed in proximity to the antennas and a BBU hosted in an SP-node. The two elements are connected by means of an optical cable. However, one of the main issues of this solution is the amount of power required by the terminals in the uplink direction (especially when the distance between the LC and a user is in the order of several kilometers). Therefore, efficient techniques to limit the uplink power need to be deployed.

C. *Direct Optical Connections and Dedicated Radio Links*

We envision the exploitation of direct optical connections and dedicated radio links for very remote locations (not characterized by the user mobility). Clearly, as the costs for deploying such solutions may be really high, the government should

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[4] This solution has to be evaluated w.r.t. the Long Term Evolution (LTE) Up-Link Hybrid Automatic Repeat reQuest (UL-HARQ) latency constraint. In addition, reliability and cost issues should be carefully taken into account.

subsidize the initial investment for deploying this kind of connections.

D. Solar Powered Nodes

The primary goal of the SP-nodes is to provide a flexible, efficient, low-cost, and low-power solution to host virtualized functions, e.g., networking and computing resources. For example, an SP-node may host a BBU serving a RRH-UAV or a LC. In addition, SP-nodes act as interface with a low-cost and low-power optical backbone network, which is assumed to be available in selected locations. Moreover, each SP-node will host a set of solar panels and batteries, which will provide power also to the radio element to be connected with it, i.e., either a LC or a RRH-UAV.

E. Centralized Orchestrator

Our envisioned architecture will be controlled by a centralized orchestrator, which will act as the brain of the system. Specifically, this entity will manage the network and computing virtual resources across the different elements. This process will reflect the users requirements and the power available in each SP-node. In addition, the orchestrator will compute and coordinate the RRH-UAVs trajectories over the territory. In this context, different challenges need to be taken into account, including: the UAVs optimal deployment under flight-time and recharging-time constraints, the downlink/uplink power-constraints of RRH-UAVs, the air-to-ground channel modeling, and the interference management. Finally, the orchestrator will establish logical connections with the different elements to send control messages and to receive feedback information.

F. Optical Transport Network

Our solution foresees the exploitation of an optical transport network, whose nodes should be deployed in (at least) few locations over the territory. Then, the UAVs and LCs provide connectivity to the users. Clearly, if the optical transport network is not available, the government should cover the related deployment and installation costs. However, a second solution may exploit satellite connections in order to connect the SP-nodes located in very remote regions. This option will be feasible if the cost per [MB] transported over the satellite network is kept sufficiently low.

IV. ECONOMIC ANALYSIS

We perform a preliminary economic analysis to estimate the costs and revenues generated by the proposed architecture in rural and low-income regions. Specifically, we assume to deploy a 5G network in two rural scenarios located in Italy and Cook Islands, and a low-income zone in Zimbabwe. Over these scenarios, we consider to deploy two types of 5G-nodes: (i) LC plus SP-node, and (ii) rotary-wing RRH-UAV plus SP-node. Each 5G-node is equipped with solar panels and batteries that provide electricity to the node over the 24h. For the Italy and Zimbabwe cases, we also assume the availability of the grid to provide an additional amount of electricity when needed (i.e., when the battery level is low and the solar energy is unavailable). On the other hand, for the Cook Islands case the system is completely sustainable, i.e., no electricity is requested from the grid.

Tab. III reports the main features of the considered 5G-nodes. Apart from the solar panels and the batteries, each node combines commodity HW, used to perform high level functionalities (i.e., typically the virtualized ones), and dedicated HW, which is instead able to perform low level tasks such as the RRH functionalities and the interconnection with the optical network. Clearly, in the UAV-based solution, a UAV is also required to carry the RRH. Finally, each node requires a yearly maintenance cost to perform basic functions such as inspection, cleaning of the solar panels, and SW updates.

Tab. IV summarizes the parameters set over the considered scenarios. More in depth, we assume a downlink traffic to each user equal to 100 [Mbps] in the Cook Islands and Italy. On the other hand, a 10 [Mbps] of downlink traffic is requested in Zimbabwe. Moreover, in both cases at most 50% of the inhabitants are active users requesting the service to the network. In addition, the table reports the parameters for the solar panels and the batteries for each 5G-node type, which have been obtained as follows. First, the hourly electricity requirements are computed by imposing a sinusoidal variation of power vs. time (with a daily pace of maximum and minimum values reported in Tab. III), and then repeated over the days up to the node lifetime. Second, the amount of hourly energy produced over one year by a 1 [kWp] solar panel (which relies on the last 30 years of weather data of the location and on the features of the solar panels reported in Tab. III) is extracted from publicly available data, and then repeated over the years up to the node lifetime. Third, the optimal minimum cost methodology of [15] is applied to find the combination of solar panels and batteries in order to: (i) satisfy the electricity requirements of the 5G-node, and (ii) minimize the total cost of deployed batteries and solar panels. Note that, for the Italy and Zimbabwe cases, we consider the total costs of electricity provided by the grid over the node lifetime as an additional term in the objective function. Finally, we would like to stress that the solar panels in our scenarios are dimensioned by taking into account historical weather data to increase the robustness of the system. However, future weather conditions are always uncertain. For example, in the presence of very exceptional and prolonged rainy conditions, an SP-node may require more energy than the one available from the solar panels and batteries. In this case, if the SP-node is connected to the electricity grid, the SP-node can remain powered on. On the contrary, if the power grid is not available, the SP-node has to be temporarily powered off, until the solar energy is available again.

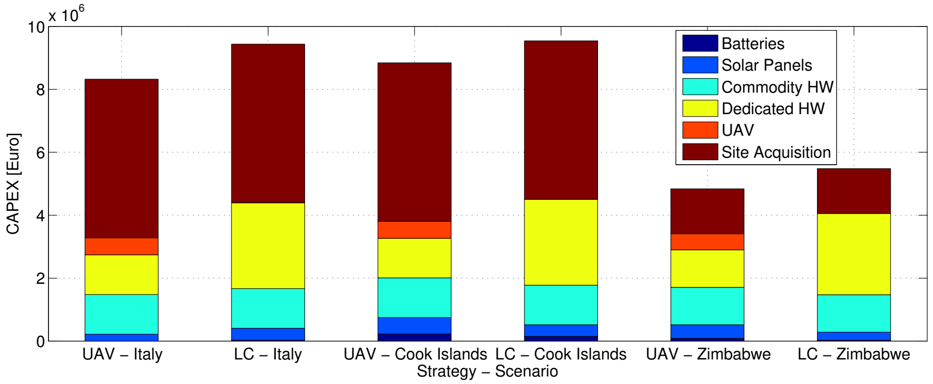
TABLE III
5G-NODE FEATURES [8], [9], [10], [11], [12], [13]

Feature	Symbol	Description	UAV-based Case	LC-based Case
Lifetime	L	Average time before disposal.	5 [years]	10 [years]
Cell radius	R	Maximum cell range.	0.5 [km]	10 [km]
Peak capacity	γ	Maximum available capacity available to users, obtained by multiplying the maximum number of users from the reverse link constraint of [9] for a maximum user downlink throughput of T^{MAX}=100 [Mbps].	4.2 [Gbps]	12.6 [Gbps]
Max. power	P^{MAX}	Maximum power consumed when the available capacity to users is maximum (the power scales with the amount of available capacity).	1.4 [kW]	3.5 [kW]
Min. power	P^{MIN}	Minimum power consumed when the node does not serve any user (20% of the maximum node power).	0.28 [kW]	0.88 [kW]
Battery Cost	C_B	Cost of a lead acid battery with 12 [V] and 200 [Ah] generating 2.4 [kWh].	0.15 [k€/battery]	
Solar Panel Cost	C_{SP}	Cost for a standard module type, size 1 [kWp], system losses 14%, tilt 20°, azimuth 180°, DC to AC size ratio 1.1, inverter efficiency 96%, ground coverage ratio 0.4.	0.8 [k€/kWp]	
Commodity HW Cost	C_{CHW}	Cost of the HW hosting high level computing and networking virtual functionalities.	10 [k€]	30 [k€]
Dedicated HW Cost	C_{DHW}	Cost of the HW deploying the RRH and the connection of the node with the optical network.	10 [k€]	65 [k€]
UAV Cost	C_{UAV}	Cost for a rotary-wing quadcopter, 4 engines, and maximum load weight equal to 5 [kg].	4.3 [k€]	-
Site Acquisition Cost	C_{SA}	The total site acquisition cost mainly depends on the cell type, the cost to connect the site to the electricity network (if available) and the cost to build an access road up to the cell location. This cost is related to the considered scenario.	See Tab.IV	
Node Maintenance Costs	C_M	Yearly cost for inspection, solar panel cleaning, and SW updates.	0.353 [k€/year]	0.530 [k€/year]

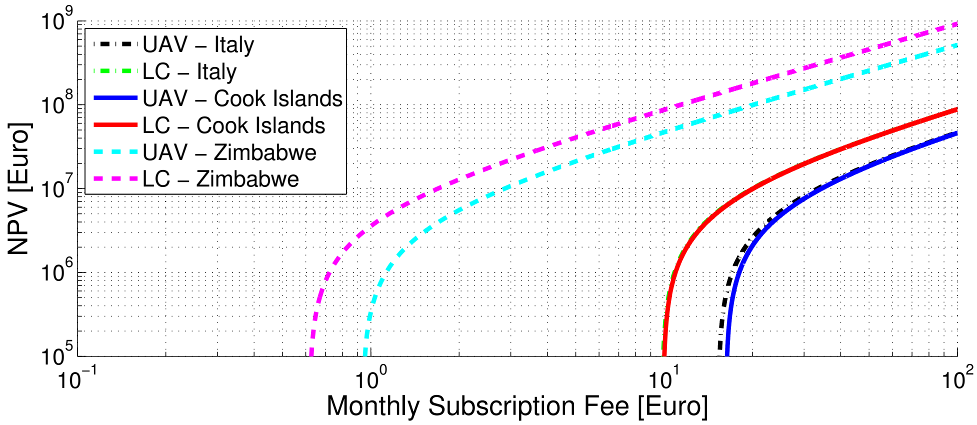
TABLE IV
PARAMETERS SET OVER THE DIFFERENT SCENARIOS.

Parameter		Symbol	Scenario		
			Italy	Cook Islands	Zimbabwe
Type		-	Rural	Rural	Low-Income
Area description		-	Municipalities of Piscina, Airasca and Scalenghe	Coastal area of Rarotonga	Downtown area of Harare
Area size		A	55.9 [km^2]	30 [km^2]	60 [km^2]
Average density		δ	189.30 [users/km^2]	352.4 [users/km^2]	1666.67 [users/km^2]
Average downlink throughput		T	100 [Mbps/user]		10 [Mbps/user]
Number of inhabitants		N_U	10582	10572	100000
Active users ratio		α	0.5		
Electricity grid cost		C_E	0.2 [€/kWh]	no connection	0.2 [€/kWh]
Solar panel power	UAV-based	P_{SP}	2.2 [kWp/site]	5.2 [kWp/site]	4.5 [kWp/site]
	LC-based		11.2 [kWp/site]	11 [kWp/site]	8 [kWp/site]
Number of batteries	UAV-based	N_B	0 [units/site]	12 [units/site]	3 [units/site]
	LC-based		5 [units/site]	24 [units/site]	5 [units/site]
Number of Deployed 5G-nodes	UAV-based	N_C	126	126	120
	LC-based		42	42	40
Site Acquisition Costs	UAV-based	C_{SA}	40 [k€/site]	40 [k€/site]	12 [k€/site]
	LC-based		120 [k€/site]	120 [k€/site]	36 [k€/site]

In the following, we compute the minimum number of 5G-nodes to serve the users, by adopting the methodology of [8]. We refer the reader to [8] for the detailed explanation, while here we report the main steps. We assume an hexagonal cell layout, and we compute the total amount of traffic requested by the users over each scenario. The number of 5G-nodes N_C is equal to the maximum between: (i) the number of cells required to cover the area of size A with hexagonal cells of radius R, and (ii) the total traffic generated by users $N_U \cdot \alpha \cdot T$ (where N_U is the total number of users in the scenario, α is the active users ratio, T is the average throughput per user), divided by peak capacity γ provided by one cell. The aforementioned



(a) CAPEX Breakdown



(b) NPV, 5% Discount Rate

Fig. 2. Capital Expenditure (CAPEX) breakdown and Net Present Value (NPV) by applying the UAV-based and LC-based strategies over the considered scenarios.

parameters, which are reported in Tab. III and in Tab. IV are different between the UAV-based and the LC-based cells. The obtained values of N_C are reported in Tab. IV.

The total CapEx needed to deploy the network for the UAV-based cell is equal to:[5]

$$\begin{aligned} CAPEX = N_C(C_B N_B + C_{SP} P_{SP} + C_{CHW} + \\ C_{DHW} + C_{UAV} + C_{SA}) \end{aligned} \quad (1)$$

where C_B is the cost of a battery, N_B is the number of batteries per site, C_{SP} is the cost for one [kWp] of solar panel, P_{SP} is the power of the solar panels per site, C_{CHW} is the commodity HW cost, C_{DHW} is the dedicated HW cost, C_{UAV} is the UAV cost and C_{SA} is the site acquisition cost. Focusing on the LC-based case, the total CapEx is computed from Eq. 1, without the C_{UAV} costs. The input parameters for the two cases are reported in Tab. III and in Tab. IV. The total CapEx costs over the three scenarios are reported in Fig. 2(a). Interestingly, in each scenario the UAV-based solutions require consistently less CapEx than the LC-based one (despite the higher number of deployed cells N_C of the former compared to the latter). Finally, in all the cases we can note that the largest contributions to the costs are due to site acquisition and commodity/dedicated HW costs, while the UAVs, the solar panels and the batteries have a lower impact on the CapEx. In the next part, we compute the yearly OpEx as:

$$OPEX_i = N_C \left[365 \cdot \left(\sum_h P_h C_E \right) + C_M \right] \quad (2)$$

where P_h is the power required to the electricity grid by the site at hour h,[6] C_E is the cost for one [kWh] of energy, and

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[5] The costs for deploying the optical transport network connecting the SP-nodes are assumed to be covered by the government.

[6] The hourly power required to the grid is the difference between the power required to power on the equipment site P_h^E at hour h minus the power available from the solar panels and the batteries. Note that P_h^E is the output of a sinusoidal function with daily periodicity between P^{MAX} and P^{MIN} values reported in Tab. III.

C_M is the maintenance cost. Clearly, for the Cook Islands scenario, the electricity cost is not included, as in this case no connection to the electricity grid is assumed.

In the following, we assume that each user pays a monthly subscription fee F to use the network. We then compute the revenue REV_i of the network provider in each year of the lifetime as:

$$REV_i = N_U \cdot 12 \cdot F \tag{3}$$

We then denote the net cash flows CF_i of operator of each year i as: (i) $-CAPEX$ for year $i = 0$, (ii) $REV_i - OPEX_i$ for year $0 < i \leq L$, where L [years] is the lifetime of the architecture. Given the knowledge of CF_i, we then investigate whether the revenues are able to compensate the CapEx and OpEx, by computing the Net Present Value (NPV). Specifically, the NPV is defined as the summation of the cash flows CF_i over the entire lifetime L, each normalized by $(1+\eta)^i$, where η is the discount rate, i.e., the return (in percentage) that could be earned with a classical financial investment (such as bank funds, loans, etc.). In our case, we set $\eta = 5\%$. When NPV>0, the investment would add value to the firm, and the project should be financed. In our case, we use the NPV to evaluate the profitability of the adopted solutions. Fig. 2(b) reports the NPV considering different monthly subscription fees applied to users. When the fee applied to users is very low, the costs for deploying the 5G network are much larger than the net revenues. Hence, the NPV tends to be reduced, being eventually close (or below) zero. This is evident from the vertical asymptotes reported in Fig. 2(b), which correspond to break even fees changing the sign of NPV (i.e., from negative to positive values). Interestingly, we can note that, as long as the fees are larger than or equal to 11 [EUR] for the Cook Islands and Italy scenarios, the NPV is more than one million euro, thus generating a profit for the network provider. In addition, the minimum fee generating a revenue in Zimbabwe with the UAV-based solution is even smaller, being able to generate profit even when the monthly subscription fee is close to 1 [EUR].[7] Moreover, the LC-based solution is even more efficient than the UAV-based one, being the minimum fee equal to 0.61 [EUR] per user in this scenario.

V. CONCLUSIONS AND FUTURE WORK

We have focused on the problem of providing 5G services in rural and low-income areas. After highlighting the main challenges, we have outlined the main pillars and a proposal for an innovative 5G network architecture. We have then considered the possibility to deploy UAV-based and LC-based 5G-nodes over two rural scenarios and a low-income one. Our results show that the 5G-nodes can efficiently exploit renewable energy sources to provide the service. In addition, the monthly subscription fee charged from users can be kept sufficiently low (especially in low-income areas), while providing an adequate service to users.

As future work, we plan a number of research activities. First of all, more detailed models to compute the minimum number of 5G-nodes to serve the users can be investigated. The mobility of UAVs is another aspect that may be considered, as well as the impact of the UAVs recharging time. In addition, the impact on the uplink performance is another interesting work. Moreover, different functional splits aiming at reducing the amount of data transferred between the RRH and the rest of the network will be also investigated. Finally, we plan to investigate the impact of the optical transport network topology on the deployment of the SP-nodes.

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