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Green Backhauling for Rural Areas

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***Abstract*—Providing wireless broadband access to rural and remote areas is becoming a big challenge for wireless operators, mostly because of the need for a cost-effective and low energy-consuming mobile backhaul. However, to the best of our knowledge, energy consumption of different options for backhauling of future rural wireless broadband networks has not been studied yet. Therefore, in this paper we assess the energy consumption of future rural wireless broadband network deployments and backhaul technologies. In the wireless segment, two deployment strategies are considered, one with macro base station only, and one with small base stations. In the backhaul segment, two wireless, i.e., microwave and satellite, and one optical fiber based (i.e., long reach passive optical networks) solutions are considered. These options are compared in terms of their ability to satisfy coverage, capacity and QoS requirements of a number of rural users in the time span that goes from 2010 until 2021. From the presented results it is possible to conclude that wireless backhaul solutions can significantly increase the energy consumption of the access network. In contrast, the long reach PON based backhaul has much higher energy efficiency and in the long term might be a better choice for wireless operators.**

I. INTRODUCTION

Today’s growing demand for new services and ubiquitous connectivity is triggering an exponential increase in the capacity demand in mobile broadband networks. For example, in 2010 there was a near-doubling of mobile broadband subscriptions worldwide [1], with the average downstream speed per subscriber growing by more than two times [2]. In urban and suburban areas, characterized by high population density, mobile operators have been willing to invest in new technologies and to deploy advanced wireless broadband solutions. This is, on the other hand, not the case for areas that are more economically challenging and that have so far been under-served, e.g., areas located in less accessible corners of developed countries, or rural areas of developing countries. One of the main obstacles in providing broadband wireless access in rural/remote areas is the deployment of cost-effective and low energy-consuming mobile backhaul (MBH) solutions. The MBH is the network segment that aggregates the traffic from the radio base stations (BS) toward the metro/core network. While in urban and suburban areas fiber-based backhaul options are attracting a lot of attention (i.e., for their capacity and energy consumption performance), in rural areas mobile operators have been so far reluctant to deploy optical MBH networks, due to their high deployment costs. For this reason, todays rural MBH networks mainly rely on wireless solutions, e.g., microwave or satellite, which are easier and faster to deploy [3][4]. However, they suffer from limited capacity performance.

The role of MBH in rural areas will become even more crucial as soon as mobile operators will move from traditional macro-based deployments to the ones based on small base stations (BS). Macro based deployments rely on few high-power BS with complex antenna systems, i.e., macro BS. On the other hand, small BS deployments are based on the dense utilization of low-cost and low-power BS. Mobile operators realized that providing high capacity levels by relying only on macro BS may result in high cost and low network efficiency [5]. This is not an attractive feature, especially in rural areas characterized by a low population density, where the ability to keep costs low and to deliver broadband access only where is needed, makes small BS a more natural choice. However, small BS deployments result in more complex and costly MBH networks, mainly because of the high number of BS sites. Consequently, with the deployment of small BSs, the MBH segment may end up consuming more energy and may become responsible for a significant portion of the total energy consumption of the mobile access network [6][7][8].

On the other hand, reducing the energy consumption in wireless access networks is of the utmost importance since it can become a significant part of operational expenditures (OPEX) [5]. The first step toward the deployment of an energy efficient wireless access network is the ability to precisely characterize the energy consumption of each segment, i.e., wireless plus MBH, and to evaluate the impact of different backhaul technologies and architectures.

With this aim in mind, this paper assesses the energy consumption of a wireless access network in a rural area considering different wireless deployments and MBH technologies. For the wireless segment, two homogeneous deployment strategies are considered: (i) macro BS, and (ii) small BS deployment. For the MBH segment, two wireless solutions, i.e., microwave and satellite, and an optical solution based on long reach passive optical networks (LR-PON) are considered [9][10]. All these options are compared in terms of their ability to satisfy the coverage, capacity and QoS requirements of a number of rural users in the time span that goes from 2010 until 2021. This work constitutes the first attempt to evaluate the energy consumption of wireless access networks in rural areas taking into consideration also the contribution of the MBH. From the presented results it is possible to conclude that from a mere power consumption perspective small BS deployments will soon become an attractive wireless deployment option able to significantly lower the energy consumption levels, especially in the presence of fiber-based MBH architectures, i.e., the one able to guarantee the lowest impact in terms of extra energy consumption.

II. METHODOLOGY

The methodology followed to assess the total energy consumption of a wireless access network (including the backhaul segment) in a rural area can be divided in four steps (Fig. 1).

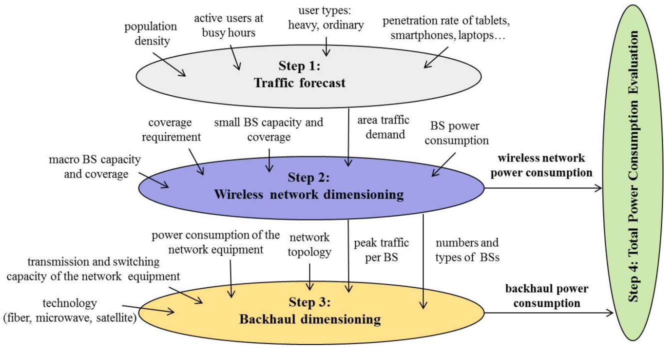


Fig. 1. Methodology used for evaluating the total energy consumption of a rural wireless access network.

The first step is about the *Traffic Forecast*. The output of this step is the characterization of the average area traffic demand for the region and for the time period under exam. The output of this phase is obtained using long-term traffic models gathered from the literature (see Sec III). Inputs for this step are: the area population density, the percentage of active users at busy hours, the specific user behavior (i.e., heavy vs. ordinary users), the penetration rate of different terminal types (i.e., laptop, tablet, and smart-phone), and the average data traffic demand of each terminal type.

The second step targets the *Wireless Network Dimensioning*. As an output, this phase returns the total power consumption of the wireless network segment, the number and type of BS deployed in the area, and the value of the peak traffic for each BS type in the considered time. These results are a function of: (i) the average area traffic demand (i.e., the output of Step 1), (ii) the broadband coverage requirement for the area, i.e., the fraction of the area where a wireless broadband service should be available, and (iii) the wireless deployment strategy, i.e., macro BS or small BS deployment. Other important input parameters for this step are the capacity, the coverage and the power consumption of each type of BS used for the deployment of the wireless access segment.

The third step represents the *Backhaul Dimensioning* phase. This step returns as a result the total power consumption of the MBH segment in the time period under exam. The result is dependent on the output of the wireless network dimensioning phase and on the specific choice for the MBH technology. The main input parameters for this phase are: the MBH network architecture and topology, the transmission/switching characteristics of the network equipment used, and their power consumption values.

Finally, the last step of the presented methodology is about the *Total Power Consumption Evaluation*. In this phase the total power consumption of the access network is calculated as the sum of the power consumed by the wireless segment and by the MBH. The technical details of each one of these steps are presented in the next two sections.

III. TRAFFIC FORECAST AND WIRELESS DEPLOYMENT

In this section, we first present the long-term traffic models used in the traffic forecast phase (i.e., *Step 1*), then we describe in detail the wireless network dimensioning operations (*Step 2*).

A. Traffic Forecast

We analyze a large area ($\mathcal{A}$) that can be representative of a remote region of a developed country (e.g., northern Sweden) or of a rural region in a developing economy (e.g., rural Africa). In the area the population is clustered in a number of villages ($N_{village}$) each one assumed to have the same size ($A_{village}$). We also assume that the number of villages covered with broadband access increases every year. The average data traffic demand in each of the covered villages for a specific year can be estimated using the following formula based on the long-term and large-scale traffic model presented in [11]:

$$\mathcal{T}(t) = \rho_{village}\, \alpha(t) \sum_k r_k\, s_k, \quad [\text{Mbps/km}^2]. \tag{1}$$

Here, $\rho_{village}$ [users/km^2] represents the user density in a village, while $\alpha(t)$ represents the percentage of active users at a given time of the day. Finally, r_k and s_k represent the average data rate generated by terminal type *k* and the fraction of the subscribers using terminal type *k*, respectively. r_k and s_k vary depending on the year under exam in accordance with the data reported in [11], [12], but are the same in all villages. Three terminal types are considered: laptops, tablets, and smartphones. In order to evaluate r_k, we assume that on average a laptop generates two and eight times more data traffic than a tablet and a smartphone, respectively. Furthermore, users are divided into two groups (i.e., *heavy* and *ordinary*) where the capacity requirement of an ordinary user are lower than the one of a heavy user. Under the assumption that h% of the subscribers are classified as heavy users, the average daily data traffic demand for terminal *k* can be defined as:

$$r_k = [h\, r_k^{heavy} + (100 - h) r_k^{ordinary}]/100 \quad [\text{Mbps}], \tag{2}$$

where r_k^{heavy} and $r_k^{ordinary}$ represent, respectively, the average data rate of an heavy and an ordinary user.

B. Wireless Network Dimensioning

Two possible cellular network deployment strategies are considered in this work: *(i)* macro BS deployment and *(ii)* small BS deployment. The total number of BSs that needs to be deployed in a specific year can be computed according to the following formula [11]:

$$N_{BS}^{i} = N_{village}^{B} \cdot \max\left(\frac{2A_{village}}{3\sqrt{3}R_{BS,i}^{2}}, \frac{\mathcal{T}_{max}A_{village}}{C_{BS,i}}\right), \tag{3}$$

where N_{BS}^{i} represents the total number of BS of type *i*, i.e., macro or small BS, that needs to be deployed to satisfy coverage and capacity requirements. $N_{village}^{B}$ is the number of villages with broadband coverage in a given year. Furthermore, $\mathcal{T}_{max}(= \max \mathcal{T}(t))$ is the maximum area traffic demand. The area covered by a BS is supposed to be hexagonal [11] and $R_{BS,i}$ represents the radius of the circle inscribed in the hexagon (for a BS of type *i*). Finally, $C_{BS,i}$ represents the maximum capacity of a BS of type *i*.

A wireless access segment is defined as *coverage limited* when the following condition is verified:

$$\frac{2A_{village}}{3\sqrt{3}R_{BS,i}^{2}} > \frac{\mathcal{T}_{max}A_{village}}{C_{BS,i}}, \tag{4}$$

in other words when the number of BS (N^i_{BS}) to be deployed is dictated by the coverage needs, i.e., left part of Eq.(4), rather than by rate requirements, i.e., right part of Eq.(4). On the other hand a wireless network segment is defined as *capacity limited* when the following condition is verified:

$$\frac{\mathcal{T}_{max} A_{village}}{C_{BS,i}} > \frac{2A_{village}}{3\sqrt{3}R^2_{BS,i}}. \tag{5}$$

In this case, the number of BS (N^i_{BS}) to be deployed is constrained by the capacity needs, i.e., left part of Eq.(5), rather than the area coverage requirements, i.e., right part of Eq.(5). After calculating N^i_{BS} using Eq.(3), it is possible to evaluate the total power consumption of the wireless access segment by applying formula:

$$P_{wireless} = N^i_{BS} \cdot P^i_{BS}, \tag{6}$$

where P^i_{BS} is the power consumption of a BS of type *i*.

IV. BACKHAUL DIMENSIONING

This section presents more details about the MBH dimensioning phase (*Step 3*). We assume that the distance between the BS and the access point to the metro/core network is 100 km. Furthermore, keeping in mind that the capacity of the BS may increase in the future, we assume that the data rate that the MBH must provide to each BS is 100 Mbps. We consider three different MBH technologies, namely microwave, satellite, and LR-PON. Each technology along with their power consumption models are presented next.

A. Microwave

Microwave is a cost-efficient technology for a flexible and rapid rural MBH deployment. The microwave technology has been developing rapidly over the recent years and today it is capable of providing low-cost, easily deployable, and high capacity backhaul. Usually microwave MBH operate in the 6-42 GHz band and rely on line-of-sight (LOS) propagation. The reference architecture of a microwave rural MBH is shown in Fig. 2(a). It is based on point-to-point (PtP) links and is organized in a tree-like topology.

Each BS is connected to a low-capacity microwave antenna, which operates at 100 Mbps. Up to N^1_{MW} BS sites can be connected using PtP microwave links to a network hub. As shown in Fig. 2(a), we assume that the network is equipped with two levels of hubs. This is because we calculated (according to the typical reach of a microwave PtP link) that two cascaded PtP microwave links are needed to cover a distance of 100 km and thus connect all the BS to the metro/core network. Each hub in the first-level is equipped with N^1_{MW} low-capacity antennas, a number of microwave switches to aggregate the traffic, and one high-capacity antenna for connecting to the second-level hub. The high-capacity antennas operate at ($N^1_{MW} \cdot 100$ Mbps). As many as N^2_{MW} first-level hubs are connected to a second-level hub using high-capacity microwave links. The hubs in the second level of aggregation are directly connected to the metro/core network. As a consequence, each second-level hub is equipped with N^2_{MW} high-capacity microwave antennas, a number of microwave switches for aggregating the traffic, and one or more enhanced small-form pluggable transceivers (SFP+). The total power consumption of the microwave MBH (for a given wireless deployment) is given by the following formula:

$$P^{MW}_{MBH} = N_{BS}P^l_{MW} + N^1_{Hub}P^1_{Hub} + N^2_{Hub}P^2_{Hub}. \tag{7}$$

P^l_{MW} represents the power consumption of a microwave antenna in a low-capacity mode. On the other hand, $N^1_{hub} = \lceil \frac{N_{BS}}{N^1_{MW}} \rceil$ is the number of first-level hubs in the first level of aggregation. Similarly, $N^2_{hub} = \lceil \frac{N^1_{hub}}{N^2_{MW}} \rceil$ is the number of hubs in the second level of aggregation. Finally, P^1_{Hub} and P^2_{Hub} represent, respectively, the power consumption of a first-level and of second-level hub, and can be computed using the following formulas:

$$P^1_{Hub} = N^1_{MW}P^l_{MW} + P^h_{MW} + P^S_{MW}\left\lceil \frac{C_j}{C^S_{MW}} \right\rceil, \tag{8}$$

$$P^2_{Hub} = N^2_{MW}P^h_{MW} + P^S_{MW}\left\lceil \frac{C_j}{C^S_{MW}} \right\rceil + P^p_{SFP}\left\lceil \frac{C_i}{C^p_{SFP}} \right\rceil, \tag{9}$$

where P^h_{MW} represents the power consumption of a microwave antenna in high-capacity mode. Moreover, P^S_{MW} and P^p_{SFP} are the power consumption of a microwave switch and a SFP+, respectively. Finally, C_j is the aggregated traffic capacity at the network site *j*, while C^S_{MW} and C^p_{SFP} are the switching capacity of a microwave switch and the capacity of a SFP+, respectively.

B. Satellite

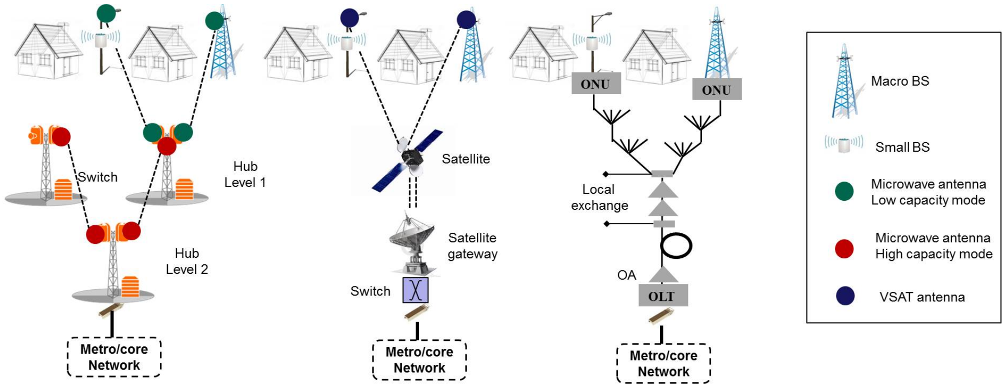
For very remote locations, satellite is a promising backhaul solution from the cost and performance perspective. The capability to operate independently of terrestrial networks ensures ease of installation with services up and running in a very short time, while overcoming the challenges of distance and terrain. Moreover, advances in satellite technology over the last decade have partially solved the issue of data speed and latency, while the use of Time Division Multiple Access (TDMA) enables connecting a large number of BS in a cost efficient manner.

The reference architecture of a satellite MBH is shown in Fig. 2(b). Each BS site is equipped with a very small aperture terminal (VSAT) antenna. We suppose that (N_{VSAT}) VSAT antennas share a single satellite link, of capacity C_{SAT}, in a TDMA fashion (so that each BS is provided exactly 100 Mbps). The satellite operates in a geostationary orbit. For simplicity, we assume that the satellite is powered by solar energy and thus it is not considered in the power consumption model. A ground station, known as satellite gateway, is used to relay data traffic to and from the satellite. The total power consumption of the satellite MBH (for a given wireless deployment) can be computed with the following formula:

$$P^{SAT}_{MBH} = N_{BS}P^l_{VSAT} + P^{GW}_{SAT}, \tag{10}$$

where P^l_{VSAT} is the power consumption of a VSAT antenna. P^{GW}_{SAT} on the other hand is the power consumption of the satellite gateway computed as follows:

$$P^{GW}_{SAT} = \frac{N_{BS}}{N_{VSAT}}P^h_{VSAT} + P^S_{SAT}\left\lceil \frac{C_j}{C^S_{SAT}} \right\rceil + P^p_{SFP}\left\lceil \frac{C_j}{C^p_{SFP}} \right\rceil, \tag{11}$$



(a) Microwave (b) Satellite (c) LR-PON

Fig. 2. Possible MBH architectures for rural areas.

where P^h_{VSAT} is the power consumption of a high-capacity satellite antenna. P^S_{SAT} and C^S_{SAT} represent, on the other hand, the power consumption and the capacity of a switch in the satellite gateway, respectively.

C. Long-Reach PON

LR-PON technologies are a costs effective alternative to traditional optical PtP and PON solutions and represent a strong candidate for future rural MBH. LR-PON is utilizing optical amplification and supports larger total split, longer reach, and higher bit rates, than todays PON standards. The higher split brings the opportunity to have multiple split stages to further increase infrastructure sharing and to minimize the cost per customer. A longer reach means that a BS can be served from a remote central office, hence reducing the number of rural exchanges needed. Several LR-PON solutions with reach of 100 km (or longer) have been proposed in literature [10][13].

The reference architecture for a LR-PON is shown in Fig. 2(c). It is based on a TDM PON that provides 10 Gbps symmetric capacity and has a total reach of 100 km. Each BS is connected to an optical network unit (ONU) composed of the customer premises equipment and of a SFP+. The distribution section, that connects the ONU to the local exchange (LE) site, has a length of 10 km. The feeder section consist of 90 km fiber between the LE site and the optical line terminal (OLT), which is directly connected to the metro/core network. The power consumption of a LR-PON based MBH (for a given wireless deployment) can be computed according to the following formula:

$$P^{LR-PON}_{MBH} = N_{BS}P_{ONU} + N_{PON}N_{OA}P_{OA} + N_{OLT}P_{OLT}, \quad (12)$$

where, P_{ONU}, P_{OA} and P_{OLT} represent the power consumption of an ONU, an OA, and an OLT, respectively. N_{OA} is the number of optical amplifiers (OA) per PON. In order to guarantee a capacity of 100 Mbps per BS, we assume that a LR-PON supports $N_{ONU} = 100$ BS. As a consequence, the number of PONs is given by $N_{PON} = \lceil \frac{N_{BS}}{N_{ONU}} \rceil$. We modelled the OLT using the approach proposed in [14]. The OLT is composed of a shelf, OLT line cards and SFP+ arrays. Each OLT line card occupies two slots in the shelf and supports N_{LR} LR-PON, while the shelf is equipped with N_{card} OLT cards. The total number of OLT is $N_{OLT} = \lceil \frac{N_{PON}}{N_{card}N_{LR}} \rceil$ while its power consumption is obtained through the following formula:

$$P_{OLT} = P_{shelf} + N_{card}P_{card} + \left(N_{PON} + \left\lceil \frac{C_i}{C^p_{SFP}} \right\rceil \right) P^p_{SFP}, \quad (13)$$

where P_{shelf} and P_{card} are the power consumption of the shelf and a OLT line card, respectively.

V. NUMERICAL RESULTS

In this section we evaluate the power consumption of the entire access network (*Step 4*) and discuss some selected results. The detailed system and power consumption parameters that we used in our assessment are listed in Table I.

We assume that in the year 2010 only a small percentage of the villages (i.e., 10%) are covered with broadband cellular access. We then assume that this percentage increases linearly every year, so that by 2019 all the villages will be served by a high-capacity wireless network. Therefore between 2019 and 2021, the only objective of an operator is to satisfy the capacity demand in all the covered rural villages. We also assume that the area between villages is a wild area covered with 2G cellular access for which an operator is not required to provide broadband services. Note that this region is not considered at all in the paper. The villages have the same user density ($\rho_{village}$) which does not change over the years. Furthermore, in our analysis we make the conservative assumption of considering only busy hours (i.e., $\alpha(t) = \alpha_{max} = 16\%$ [11]) and we estimate the maximum area traffic demand ($\mathcal{T}_{max} = \max \mathcal{T}(t)$) in each year. As an example, in Table I, we report the maximum area traffic demand for 2010, 2015 and 2020 calculated according to Eq. (1), Eq. (2) and the values for r_k and s_k in [8][11][12]. To calculate r_k we assumed that an ordinary user generates 1/8 the traffic of a heavy one [11]. As for the wireless deployment, we assume that macro BSs have 3-sectors with antennas above roof-top for longer reach. On the other hand, small BSs have single carrier and omni-directional antennas. The power consumption of macro and small BS is computed according

TABLE I
SYSTEM PARAMETERS AND POWER CONSUMPTION [1][8][11][12][14].

Traffic forecast	**Value**
Area ($\mathcal{A}$)	30,000 km^2
Number of villages ($N_{village}$)	60
Area of a village ($A_{village}$)	50 km^2
Population density ($\rho_{village}$)	100 user/km^2
Max. area traffic demand ($\mathcal{T}_{max}$) in 2010	2.6 Mbps/km^2
Max. area traffic demand ($\mathcal{T}_{max}$) in 2015	82.8 Mbps/km^2
Max. area traffic demand ($\mathcal{T}_{max}$) in 2020	474.3 Mbps/km^2
Wireless deployment	**Value**
Range macro/small BS (R^i_{BS})	3 / 0.5 km
Number of sector macro/small BS	3 / 1
Capacity macro/small BS (C^i_{BS})	45 Mbps / 15 Mbps
Power consumption macro/small BS (P^i_{BS})	954 W / 72.3 W
Bandwidth	10 MHz
Mobile backhaul dimensioning	**Value**
MW antennas (P^l_{MW}/P^h_{MW})	30 W / 50 W
MW switch (P^S_{MW}/C^S_{MW})	50 W / 8 Gbps
MW hub (N^1_{MW}/N^2_{MW})	16 / 16
SFP+ (P^p_{SFP}/C^p_{SFP})	2 W / 10 Gbps
SAT antennas (P^l_{SAT}/P^h_{SAT})	50 W / 75 W
SAT switch (P^S_{SAT}/C^S_{SAT})	50 W / 8 Gbps
SAT TDMA links (N_{VSAT}/C_{SAT})	10 / 1 Gbps
LR-PON ($N_{OA}/N_{LR}/N_{card}$)	3 / 8 / 9
LR-PON ($P_{ONU}/P_{OA}/P_{OLT}$)	5 W / 8 W / 1197 W

to the power model presented in [15]. As regards the LR-PON backhaul, a single amplifier at the local-exchange site after the splitter will not be enough to ensure a good system performance, as the input signal to the OA will be extremely small. Assuming that the OA has a gain of 25 dB, we need to deploy two OAs in the local exchange site and a third OA before the OLT (to enhance the power budget in case the receiver sensitivity is not sufficient). We then conclude that the number of needed OA per PON is $N_{OA} = 3$.

Fig. 3 shows the power consumption of the wireless access segment only. We observe that, in the specific use case under exam, the wireless deployment is always coverage limited if small BS are used. This means that each year the number of BSs required to cover the area is enough to satisfy the area traffic demand. As a consequence the power consumption of the wireless segment increases linearly until all villages are covered in 2019 and then it stays constant. This also means that a dense small BS deployment has enough capacity to satisfy the increased traffic demand in 2021 and thus no additional deployment is needed. On the other hand, the macro BS deployment is coverage limited only up to the year 2014, and afterwards it becomes capacity limited. As a result, the power consumption of the macro BS deployment increases linearly with the number of BS until 2014 and then it increases exponentially up to 2021. From the figure it also becomes evident that, in the specific use case under exam, from 2016 on a small BS deployment is more energy efficient than its macro BS counterpart.

Fig. 4(a) presents the total power consumption of the access network, including both the wireless segment and the microwave MBH. To better evaluate the impact of the microwave MBH we also plotted the power consumption of the wireless access segment only (dotted lines). It can be observed that, using a small BS deployment, the impact of the microwave MBH is significant and in 2020 the microwave backhaul is responsible for up to the 50% of the total power consumption of the access network. On the other hand, using a macro BS deployment, the impact of the microwave MBH is much smaller and in 2020 is limited to less than 7%. The figure highlights also a shift in the time in which a small BS deployment becomes more energy efficient than one based on macro BSs.

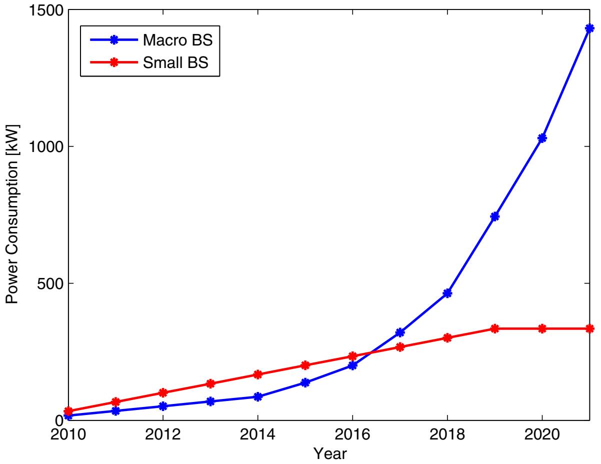


Fig. 3. Power consumption of the wireless network.

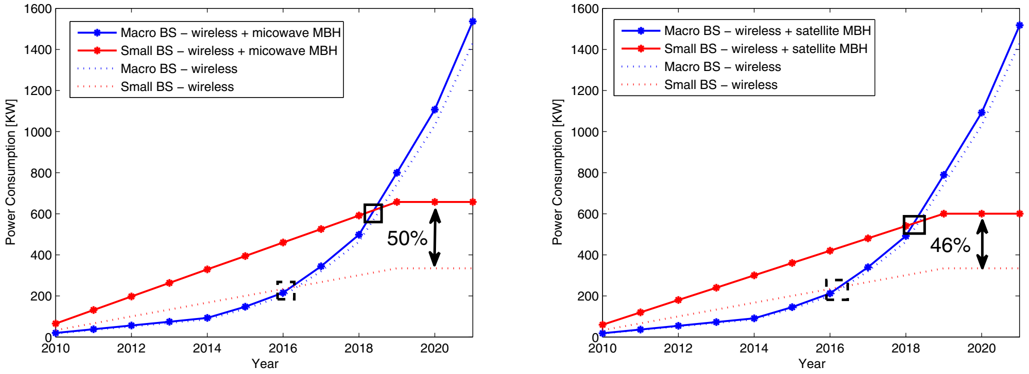
Fig. 4(b) shows the total power consumption of the access network, in the case of a satellite-based MBH. Also in this case we observe that, using a small BS deployment, the impact of the satellite MBH on the total power consumption of the access network is significant and corresponds to 46% of the total in the year 2020. On the other hand, using a macro BS deployment, the contribution of the satellite MBH on the total power consumption is limited to less than 6%. This fact reflects again in a shift of more than 2 years for the time in which a small BS deployment becomes more energy efficient than one based on macro BSs.

Fig. 4(c) presents the total power consumption of the access network, when a LR-PON-based MBH is deployed. It can be observed that the LR-PON MBH has almost a negligible impact on the power consumption of the access network. Consequently, a LR-PON MBH leaves untouched the time in which a small BS deployment is more energy efficient than the macro BS deployment. We can then conclude that LR-PON is by far the most energy efficient MBH technology among the considered ones. To further prove this fact in Fig. 4(d) we compare the power consumption of the three MBH solutions studied in the paper (considering the MBH segment only). It is clearly shown that the LR-PON consumes much less power than the wireless solutions.

VI. CONCLUSIONS

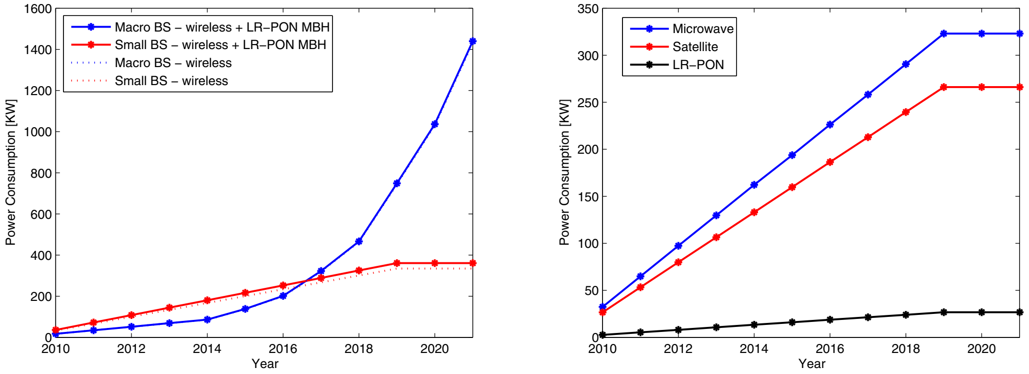
In this paper we assessed the energy consumption of future high capacity mobile networks for rural areas considering different wireless deployments and backhaul technologies. In the wireless segment, we considered both macro and small BS deployment able to satisfy the coverage and capacity requirements of the years that go from 2010 until 2021. For the backhaul segment, we considered two wireless solutions, i.e., microwave and satellite, and an optical fiber based option utilizing the LR-PON technology.

The results show that wireless MBH solutions have a large negative impact on the energy consumption of the access



(a) Microwave backhaul.

(b) Satellite backhaul.



(c) LR-PON-based backhaul.

(d) Comparison of backhaul technologies.

Fig. 4. Total power consumption (wireless segment + MBH) of a wireless access network in a rural area.

network (up to 50%) and reduce the energy advantage of using small BS deployments compared to their macro counterpart. On the other hand, a MBH based on the LR-PON technology has a very small impact on the energy consumption of the access network and may represent the best choice for wireless operators in the long term.

VII. ACKNOWLEDGMENT

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