Is Backhaul Becoming a Bottleneck for Green Wireless Access Networks?

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***Abstract*—Mobile operators are facing an exponential traffic growth due to the proliferation of portable devices that require a high-capacity connectivity. This, in turn, leads to a tremendous increase of the energy consumption of wireless access networks. A promising solution to this problem is the concept of heterogeneous networks, which is based on the dense deployment of low-cost and low-power base stations, in addition to the traditional macro cells. However, in such a scenario the energy consumed by the backhaul, which aggregates the traffic from each base station towards the metro/core segment, becomes significant and may limit the advantages of heterogeneous network deployments. This paper aims at assessing the impact of backhaul on the energy consumption of wireless access networks, taking into consideration different data traffic requirements (i.e., from todays to 2020 traffic levels). Three backhaul architectures combining different technologies (i.e., copper, fiber, and microwave) are considered. Results show that backhaul can amount to up to 50% of the power consumption of a wireless access network. On the other hand, hybrid backhaul architectures that combines fiber and microwave performs relatively well in scenarios where the wireless network is characterized by a high small-base-stations penetration rate.**

***Index Terms*—Energy Efficiency, Backhaul, Fiber, Microwave, VDSL2, Power Consumption, Traffic Model, Smallcells, Heterogeneous Networks.**

I. INTRODUCTION

Wireless access networks have undergone tremendous improvements to be able to provide high-capacity connectivity to an increasing number of mobile users. As a result, and also due to the widespread request for an (almost) ubiquitous access to data-traffic-demanding services (e.g., video), forecasts indicate that current traffic volumes will increase by 1000 times by 2020 [1]. In such a scenario operators are likely to face decreasing revenues in terms of per-unit-of-data consumed, thus highlighting the importance of having cost effective solutions in place while deploying and operating their wireless access networks. In this regard, energy efficiency is of great interest due to the fact that power consumption represents a non negligible portion of an operational expenditure (OPEX), a portion that is expected to increase even further if nothing would be done to address this issue [2].

One important step towards implementing energy efficient solutions in the wireless access network is the ability to precisely characterize the power consumption of each segment, i.e., wireless and backhaul. Even though accurate models for different base station (BS) types have been proposed (e.g., within the FP7 EARTH project [3]), relatively scarce attention has been paid to understand the role played by the backhaul in the overall network power consumption assessment. On the other hand, recent studies [4], [5] highlighted that the backhaul has a non negligible impact on the overall power budget of mobile heterogeneous networks. This is mainly due to the fact that in some cases power consumption of backhauling operations at one small BS might be comparable to the amount of power necessary to operate the BS itself [4]. Therefore, with a potential evolution towards denser heterogeneous wireless network deployments (i.e., where a massive number of small base stations are expected to be used) the power consumption of backhaul might potentially become a serious bottleneck.

The aim of this paper is to investigate the aforementioned specific aspects. With this objective in mind, we consider three different backhaul architectures and their respective power consumption models. Two architectures are based on a hybrid solution (i.e., one combining fiber and copper (VDSL-2 based) technologies, the other combining fiber and microwave) while the third backhaul architecture considered in the paper uses microwave only. In terms of wireless deployment strategy the paper presents three heterogenous deployment use cases. One is based on recent (i.e., year 2010) data traffic levels, while the other originates from the data traffic estimations for the year 2015 and 2020, respectively. These deployment scenarios are a combination of macro base stations and indoor small cells (i.e., femto base stations), an option which have attracted great interest in order to address coverage and capacity needs in residential and enterprise environments [6], [7]. The methodology followed in the study works as follows: for each specific wireless network deployment use case, the three backhaul network architectures under exam are dimensioned and their total power consumption is computed using the proposed power consumption models. The intention is to demonstrate how different assumptions on femto base station densities (used for indoor offloading), backhaul architectures, and area capacity requirements affect the total power consumption of the entire wireless access segment, while answering the questions on whether or not backhaul will be a bottleneck for future green and ultra-high capacity wireless access network deployments.

The remainder of this paper is organized as follows: Section II presents the network model and the assessment methodology. Long-term, large-scale traffic models and wireless network dimensioning are introduced in Section III. Detailed power consumption models for the selected backhaul archi-

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tectures is presented in Section IV, and numerical results are provided in Section V. The last section concludes the paper.

II. NETWORK MODEL AND METHODOLOGY

This section presents first the assumptions used and the general scenario under consideration. Then it explains the methodology used to estimate the total network power consumption.

A. Network Model and Assumptions

Let $\mathcal{A}$ $[km^2]$ be the dimension of the area under exam and ρ (users/km^2) be its population density. It is assumed to have N_b buildings each one with five floors, where each building is assumed to have ten apartments, i.e., the number of apartments $N_a = 10 \times N_b$. Users are assumed to be served by a macro plus femto base station deployment (Fig. 1) where the femto BSs, placed inside apartments and operating in licensed spectrum, address the indoor coverage and capacity needs in residential/enterprise environments, while macro BSs provide an umbrella coverage and serve the remaining users in the network [7]. The considered average data rate per user changes over the years (Section III.A), while the total power consumption of each network deployment instance (function of the specific backhaul architecture under exam) is computed following the methodology described in the next sub-section.

B. Methodology

The objective of the paper is to assess the fraction of the overall power consumed by the backhaul segment within a heterogenous wireless network deployment when current and future data traffic levels are considered. The methodology of this process can be summarized as follows.

The first step is the *Traffic Forecast* phase. This step generates an estimate of the average area traffic demand for a dense urban area at the busy hour for the specific year under exam (i.e., 2010, 2015, and 2020). This traffic estimate is based on long-term, large scale-traffic models and on forecasted data for network and service usage such as: (i) ρ, (ii) the percentage of users that are active at busy hour, (iii) their behavior (i.e., heavy vs. ordinary type), and (iv) the penetration rate of different terminal types (i.e., pc, tablet, and smart-phone). All the details regarding this phase are provided in Section III.A.

The second step consists in the *Wireless Network Dimensioning* phase. The result of this step is a function of the traffic forecast generated in the first phase and of a number of topology related parameters (e.g., $\mathcal{A}$, ρ, N_b, N_a, etc.,). Based on these input parameters this step returns the dimensioning for the wireless access segment, i.e., number of macro and femto BSs in addition with their peak traffic values. These numbers vary also depending on the femto base station penetration rate (η), i.e., the fraction of apartments assumed to be equipped with femto BS. The higher is this value the lower is the number of macro base stations that will need to be deployed. It is assumed that when $\eta > 0$, each building has at least one apartment with a femto BS. All the details regarding this phase are provided in Section III.B.

The third step is the *Backhaul Network Dimensioning* phase and provides the number of microwave antenna, fiber switches, DSL Access Multiplexers (DSLAMs), etc. The result is a function of the outcome from *Wireless Network Dimensioning* phase and also of the chosen backhaul architecture. All the details regarding this phase are provided in Section IV.

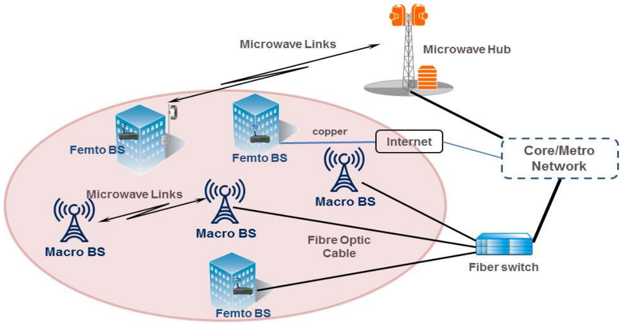


Fig. 1. Network Layout.

Finally in the last step (i.e., *Assessment of Total Power Consumption*) the total power consumption of the overall wireless access network considering both the wireless and the backhaul segment is computed. The calculations are based on the power consumption models presented in Section IV.

III. WIRELESS NETWORK DIMENSIONING

This section first introduces the long-term, large-scale traffic model used during the *Traffic Forecast* phase. Then it explains in detail how the work in the *Wireless Network Dimensioning* phase is carried out.

A. Long-Term Large-Scale Traffic Model

We consider the long term large scale traffic model presented in [8] in order to estimate the area traffic demand in an average European dense urban city for a given year. Since data volumes per subscriber do not depend on the specific deployment scenario, the daily generated traffic $R(t)$ over a given area can be defined as a function of ρ as follows:

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

Here r_k and s_k represent the average data rate and the fraction of the subscribers using terminal type k, respectively. $\alpha(t)$ represents a typical daily traffic variation in terms of percentage of number of active users for a given time t. Please note that, unlike in [8], we ignore the fact that total traffic is served by a few operators in a given area.

As in [8], three different terminal types are considered: PC, tablet and smartphone. On average a PC user is assumed to generate two and eight times more data traffic than a tablet and a smartphone user, respectively [8]. On the other hand, users are divided into two groups (i.e., heavy and ordinary users) where the capacity requirement of an ordinary user is 1/8 of the one of a heavy user [8]. Under the assumption that $h\%$ of the subscribers are classified as heavy users, the average daily data rate demand for terminal k can be defined as:

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

Here r_k^{heavy} [MB/hour] and $r_k^{ordinary}$ [MB/hour] represent the hourly average data rate of a heavy and an ordinary user, respectively.

Using (1) in combination with the forecasted values of h, the fraction of the subscribers using the three terminal types (i.e., s_{pc}, s_{tablet}, $s_{s.phone}$), and the average data rate requirements for a heavy user r_k^{heavy} [1], [8], [9], it is possible to calculate the peak area traffic demand at the busy hour as $\mathcal{T}$ [Mbps/km^2] $= max_t(R(t))$. Table I present this value specifically for year 2010, 2015 and 2020 under the assumption that 16% of the subscribers are active during the busy/peak hour (i.e., $\alpha_{max} = 16\%$), whereas ρ=3000 users/km^2 [8]. It should be noted that ρ and $\alpha(t)$ are assumed to be constant (i.e., they do not change with time).

TABLE I
ESTIMATED AREA TRAFFIC DEMAND IN A DENSE URBAN AREA IN EUROPE FOR 2010-2020 [1], [8], [9]

Year	h	s_{pc}/r_{pc}^{heavy}	$s_{tablet}/r_{tablet}^{heavy}$	$s_{s.phone}/r_{s.phone}^{heavy}$	$\mathcal{T}$
2010	10	0.1 / 56.25	0.03 / 28.1	0.3 / 7	2.6
2015	20	0.2 / 900	0.05 / 450	0.5 /112.5	82.8
2020	30	0.3 / 2700	0.1 / 1350	0.6 / 337	474.3

B. Macro+Femto Deployment

For the wireless network dimensioning, it is assumed that residential femto BSs are randomly deployed by the end user in their apartments. The number of deployed femto BSs (N_{femto}) is calculated as a function of the femto BS penetration rate (η) and the total number of apartments in the area: $N_{femto} = N_a \times \eta$. Since the macro-cellular network needs to serve the remaining active users (i.e., which are not covered by femto BSs) at the busy hour, the required number of macro BSs in a given network area $\mathcal{A}$ can be computed as:

$$N_{macro} = \frac{\rho \times \mathcal{A} \times (1-\eta) \times \alpha_{max}}{N_{active/macro}}. \tag{3}$$

Here $N_{active/macro}$ denotes the number of active users that can be served by a macro BS and is given by

$$N_{active/macro} = \frac{C_{macro}}{\bar{r}}, \tag{4}$$

where C_{macro} and $\bar{r} = \sum_k r_k\, s_k$ represent the macro BS capacity, and the average data rate requirement per active user, respectively. The fact that macro BSs can in theory support more users after offloading some indoor users to femto BSs is not considered here. It is also important to note that the fraction of the users that are served by femto BSs is assumed to be equal to η despite the fact that more users can be within the coverage area of a femto BS, in the case open access femto BSs [7] are used.

Based on the assumption that co-channel femto BS deployment has only a minor impact on the macro BS downlink performance [6], [10], the average macro BS capacity can be calculated via the following fluid model [11]:

$$C_{macro} = N_s W log_2\left(1+\mathbb{E}_d\left[\frac{3\sqrt{3}(\gamma-2)}{4\pi}\frac{R^2(2R-d)^{2-\gamma}}{d^\gamma}\right]\right) \tag{5}$$

where γ, N_s, W, R and d denote the path loss exponent, the number of sectors, the system bandwidth, the cell radius and the distance of a user from the serving macro BS, respectively.

After using Eq. (5) to compute the average macro cell capacity over different values of R, results confirm that, in the case of an interference limited systems, the spectral efficiency of a base station is independent from the total number of base stations in the considered area. This results are in accordance with the earlier findings in [12]. Thus, for the scenario considered in this paper the macro BS capacity is constant regardless of number of femto and macro BS density in the area.

IV. POWER CONSUMPTION MODELS

The total power consumption of a heterogeneous mobile network can be defined as:

$$\mathcal{P} = \sum_{i=1}^{m} N_i P_i + P_{bh}^{archl}, \tag{6}$$

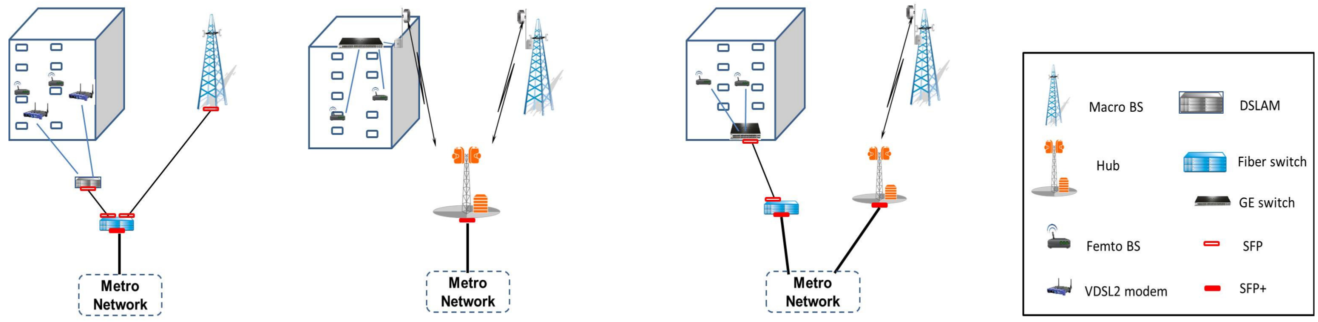
where m is the number of base station types used in the network, N_i and P_i are respectively the number and the power consumption of the base stations of a specific type, and P_{bh}^{archl} is the power consumption of the l-th backhaul architecture where $l \in \{1, 2, 3\}$. In this paper, two BS types are considered, i.e., macro BS and femto BS, with $m = 2$. The power consumption of a base stations (P_i) is computed according to [3] and using the following equation:

$$P_i = \begin{cases} N_s(a_M P_{tx} + b_M) & \text{for a macro BS} \\ a_F P_{tx} + b_F, & \text{for a femto BS,} \end{cases} \tag{7}$$

where P_{tx} denotes the power fed to the antenna. In Eq. (7) , a_M and a_F represent the portion of the power consumption for macro and femto BS respectively, that depends on: the transmit power, the feeder losses, and the power amplifier. Finally, b_M and b_F represent the power consumption of the active site cooling and the signal processing for macro and femto BS respectively, and constitute the major part of the total power consumption of a BS. The backhaul power consumption models for the selected architectures will be introduced in the following subsections.

A. Architecture 1: Fiber-to-the-node (FTTN) using VDSL2

The first backhaul solution is presented in Fig. 2(a) and is given by a hybrid architecture that employs both fiber and copper. Here, femto BSs are backhauled using Very-high-speed Digital Subscriber Line version 2 (VDSL2) modems, which provide high-speed connections over copper pair cables. Each femto BS is connected to a VDSL2 modem that is in turn connected to a DSLAM using a high speed connection over copper. The DSLAM is located in a remote node that is usually placed inside a street cabinet close to the user premises. We considered VDSL2 instead of the more widespread Asynchronous DSL (ADSL) because ADSL technologies support



(a) FTTN using VDSL2 (b) Microwave only (c) FTTB + Microwave

Fig. 2. Backhaul Architectures.

only capacities in the range between 8 and 24 Mbps, which is not sufficient to backhaul a femto BS. VDLS2 provides instead 100 Mbps for distances up to 300 m [13], but requires a careful network planning in order to make sure that the distance between the DSLAMs and the VDSL2 modems is less than 300 m. DSLAMs and macro BSs are connected to a number of fiber switches (FSs) using 1 Gbps point-to-point optical links. For transmitting and receiving the optical signal small form-factor pluggable transceivers (SFPs) are used. The FSs aggregate the traffic coming from the wireless network before sending it towards the metro network (MN) via 10 Gbps fiber links and SFP+ modules. The power consumption of the first architecture, i.e., P_{bh}^{arch1}, is obtained through the following formula:

$$\begin{aligned} P_{bh}^{arch1} &= N_{femto}P_{modem} + N_{DSLAM}(P_{DSLAM} + 2P_{SFP}) \\ &\quad + N_s^F P_s^F + 2N_{macro}P_{SFP} + N_{ul}P_{SFP+}, \end{aligned} \tag{8}$$

where P_{modem}, P_{DSLAM}, P_s^F, and P_{SFP} are power consumption values of a VDSL2 modem, a DSLAM, a fiber switch, and a SFP, respectively. On the other hand N_{DSLAM} and N_s^F are the number of DSLAMs and fiber switches in the area. N_{DSLAM} is a function of the number of ports per DSLAM (n_{ports}^D), i.e., $N_{DSLAM} = \lceil \frac{N_{femto}}{n_{ports}^D} \rceil$. Similarly, N_s^F is dependent on the number of ports of a FS (n_{ports}^F), i.e., $N_s^F = \lceil \frac{N_{DSLAM}+N_{macro}}{n_{ports}^F} \rceil$. Finally, N_{ul} is the total number of uplink interfaces used to connect toward the MN, while P_{SFP+} is the power consumption of a SFP+ used to transmit the backhauled traffic toward the MN. N_{ul} depends on the total aggregate traffic collected at the FSs, i.e., $Ag_{tot} = \mathcal{T} \times \mathcal{A}$, and on the maximum transmission rate of an uplink interface (U_{max}). N_{ul} can be computed as $N_{ul} = max(N_s^F, \lceil \frac{Ag_{tot}}{U_{max}} \rceil)$.

B. Architecture 2: Microwave Only

The second backhaul architecture is shown in Fig. 2(b) and is based on microwave. The femto BSs inside a building are connected to a Gigabit Ethernet Switch (GES) using conventional *Fast Ethernet* connections operating at 100 Mbps. The GES aggregates the traffic from the femto BSs inside a building before sending it to a microwave antenna placed on the roof. Each building and each macro BS in the analyzed area is equipped with a microwave antenna operating in the frequency range between 5 and 8 GHz, which is the most suited for dense urban areas [14]. Microwave antennas are connected to hubs using a point-to-point star topology. The hubs are equipped with switches to aggregate the traffic from the microwave antennas and to transmit it toward the MN. The transmission toward the MN is realized using a 10 Gbps optical point-to-point links and SFP+ modules. The power consumption of the second architecture, i.e., P_{bh}^{arch2}, can be expressed as:

$$P_{bh}^{arch2} = \sum_{j=1}^{N_b+N_{macro}+N_{hub}} P_j^{MW} + N_{GES}P_{GES} + N_{ul}P_{SFP+}. \tag{9}$$

Here N_b, N_{macro} and N_{hub} are the number of buildings, macro BSs, and hubs, respectively. On the other hand, P_j^{MW} represents the power associated with MW backhaul operations at site j (building, macro BS, or hub). Finally, N_{GES} is the number of GESs, and P_{GES} is the power consumption of a GES.

It can be observed that N_{GES} is equal to the number of buildings if $\eta > 0$, due to the initial assumption that each building has at least one femto BS. It is also assumed that P_{GES} is a function only of the number of femto BSs in the building. Finally, the power consumption of a GES is assumed to scale linearly with the number of ports that are used for backhauling the femto BSs: $P_{GES} = \frac{N_{femto}}{N_b n_{ports}^{GES}} P_{GES}^{max}, \forall \eta > 0$, where n_{ports}^{GES} and P_{GES}^{max} are the total number of ports of the GES and its maximum power consumption, respectively. According to [5], P_j^{MW} can be defined as:

$$P_j^{MW} = \begin{cases} P_{low-c} & \text{if } N_j^{ant} = 1 \\ P_{high-c} + P_s^{MW} \left\lceil \frac{C_j}{C_{switch}^{MW}} \right\rceil & \text{otherwise} \end{cases} \tag{10}$$

where N_j^{ant} is the number of microwave antennas at site j, C_j is the aggregated traffic at the same site, while C_{switch}^{MW}

and P_s^{MW} are the maximum capacity of a switch inside a hub and its power consumption. Finally, P_{low-c} and P_{high-c} represent respectively the low and the high power consumption region of the microwave antennas [5]. Note that P_j^{MW} is a function of the number of antennas and not of the total backhauled capacity as it was the case in [5]. This is because sites with only one microwave antenna are assumed to work in low capacity traffic conditions (i.e., their aggregate capacity is $<$ 500 Mbps), whereas the sites with more than one antennas are assumed to operate in the high traffic capacity region (i.e., their aggregate capacity is $\geq$ 500 Mbps). According to this rationale, it is assumed that each building and each macro BS is equipped only with a single antenna. Instead, the hubs, which aggregate the traffic coming from several buildings or macro BSs, are equipped with more antennas and will thus require a switch. If $\eta > 0$ each building is assumed to be equipped with one GES, so that the number of GES is equal to the number of buildings (i.e., $N_{GES} = N_b$). This is because this work assumes that the GES has enough ports to potentially connect all apartments in a building. The hubs are assumed to equally share the traffic, making the total number of hubs in the area equal to $N_{hub} = \lceil \frac{N_b + N_{macro}}{n_{sup}^{MW}} \rceil$, where n_{sup}^{MW} is the max number of microwave links a hub can support. With the above mentioned assumptions, Eq. (9) can be simplified to:

$$\begin{aligned} P_{bh}^{arch2} &= (N_b + N_{macro})P_{low-c} + N_b P_{GES} \\ &+ N_{hub}P_{high-c} + N_{ul}P_{SFP+} + N_s^{MW} P_s^{MW}, \end{aligned} \tag{11}$$

where N_s^{MW} is the total number of switches inside the hubs, i.e., $N_s^{MW} = max(N_{hub}, \lceil \frac{Ag_{tot}}{C_{switch}^{MW}} \rceil)$. Finally, the total number of interfaces for the interconnection toward the MN is computed as $N_{ul} = max(N_{hub}, \lceil \frac{Ag_{tot}}{U_{max}} \rceil)$.

C. Architecture 3: Fiber-to-the-Building (FTTB) + Microwave

The third backhaul solution is shown in Fig. 2(c). It is a hybrid architecture that employs both fiber and microwave. Similarly to Architecture 2, the femto BSs inside a building are connected to a GES using *Fast Ethernet* connections. The GES connects to a FS using 1 Gbps optical point-to-point links. SFP transceivers are used at the GES and at the FS to transmit and receive the optical signal. The FSs are connected to the MN using 10 Gbps optical links and SFP+ transceivers. On the other hand, the macro BSs are backhauled using microwave. Again, we consider a point-to-point star topology where several microwave antennas are directly connected to a hub. The hubs are equipped with switches to aggregate the traffic from the macro BSs and are connected to the MN using 10 Gbps optical links and SFP+ modules. Considering the same assumptions used for Architecture 2, the power consumption of Architecture 3 can be defined as:

$$\begin{aligned} P_{bh}^{arch3} &= N_b(P_{GES} + 2P_{SFP}) + N_{macro}P_{low-c} + N_s^F P_s^F \\ &+ N_{hub}(P_{high-c} + P_{SFP+}) + N_s^{MW} P_s^{MW} + N_{ul}P_{SFP+}. \end{aligned} \tag{12}$$

It should be noted that in the architecture of Fig. 2(c) there are two types of aggregation points, i.e., *(i)* microwave hubs (supporting at most n_{sup}^{MW} microwave links each), and *(ii)* fiber switches (with n_{ports}^F each). Due to the fact that only macro BSs use microwave backhauling, the total number of hubs required in this architecture can be computed as $N_{hub} = \lceil \frac{N_{macro}}{n_{sup}^{MW}} \rceil$. On the other hand, $N_s^F = \lceil \frac{N_b}{n_{ports}^F} \rceil$. The total number of switches inside the hubs are calculated as a function of the aggregated outdoor traffic only $Ag_{tot}^{outdoor}$, i.e., $N_s^{MW} = max(N_{hub}, \lceil \frac{Ag_{tot}^{outdoor}}{C_{switch}^{MW}} \rceil)$. On the other hand, the number of uplink interfaces (N_{ul}) are calculated based on the total aggregated traffic collected at the fiber switches and hubs, i.e., $N_{ul} = max(N_{hub} + N_s^F, \lceil \frac{Ag_{tot}}{U_{max}} \rceil)$.

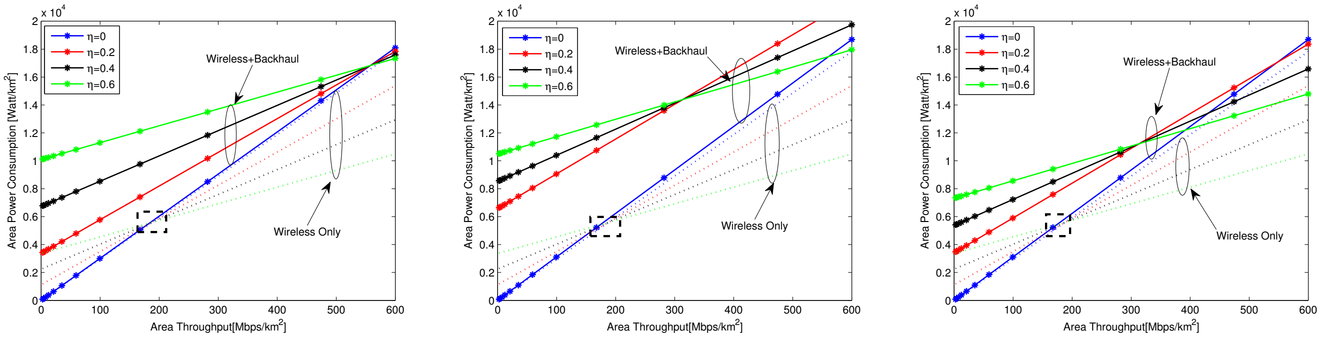
V. NUMERICAL RESULTS

In this section, we present the numerical results assessing the impact of the backhaul power consumption in future high data rate wireless access networks. We consider various realistic backhaul architectures that cope with the expected traffic demand up to 2020.

We consider a 10km×10km dense urban area of an average European city. The following assumptions are made: a population density of 3000 users/km^2; 100,000 apartments; 10,000 residential buildings; the average data rate demand increases exponentially. In order to calculate the average traffic demand at busy hours, we use the forecasted values in [1], [8] together with the long- term, large-scale traffic models presented in Section III. We assume that user demand is satisfied by a macro+femto deployment strategy where the femto BS penetration rate (η) varies between 0 and 0.6. This assures that the maximum percentage of users served by femto BSs is 60%, which corresponds to the expected fraction of traffic that will be generated indoors by 2015 [7]. In this scenario, the mobile data traffic is assumed to be aggregated towards the metro network via the three candidate backhaul architectures presented in Section IV. Detailed system and power consumption parameters are listed in Table II.

TABLE II
SIMULATION ASSUMPTIONS [4], [5]

Considered parameters for wireless deployment	Value
Population density per km^2	3000
Covered Area	10km×10km
Number of apartments	100000
Number of buildings	10000
Bandwidth	10 MHz
Number of sector Macro/Femto	3/1 m
Femto BS penetration rate	[0,0.6]
Path loss exponent	3.5
Power Consumption Parameters	Value
a_M/a_F	4.7/8
b_M/b_F	130/4.8 W
P_{modem}	5 W
$P_{ul}/P_{dl}/P_{SFP}$	2/1/1 W
P_s^F/P_s^{MW}	300/53 W
P_{DSLAM}/P_{GE}^{max}	85/50 W
P_{low-c}/P_{high-c}	37/92.5 W
$n_{ports}^D/n_{ports}^F/n_{ports}^{GE}/n_{sup}^{MW}$	16/24/12/16
C_{switch}^{MW}/U_{max}	36/10 Gb/s



(a) FTTN using VDSL2 (b) Microwave only (c) FTTB+Microwave

Fig. 3. Area power consumption as a function of target area throughput considering various backhaul options.

Fig. 3 shows (for each of the three considered backhaul architectures) the area power consumption of the overall wireless access network (wireless+backhaul) as a function of the area throughput (solid lines). In order to clearly see the backhaul impact, the figure also presents the area power consumption of the wireless part only (dotted lines). Note that a macro + femto deployment can be considered as an energy efficient solution only when the additional power consumption of the large number of femto BSs is compensated by a reduction in the macro BS density. In this respect, it can be observed that if we only consider the wireless segment power consumption, a macro + femto deployment ($\eta > 0$) is more advantageous than a macro-only (η=0) strategy only when the area throughput becomes sufficiently high, i.e., when the network is more capacity limited. Furthermore, we observe that this gain increases with denser femto BS deployment. However when also the backhaul power consumption is taken into account, the intersection point shifts to the right, i.e., much higher area capacity requirement is needed to justify a dense femto BS deployment. From Fig. 3 we observe that with a FTTN + VDSL2 and with a Microwave only backhaul solutions, the deployment of femto BSs is never beneficial for the traffic values forecasted between now and 2020, i.e., $\mathcal{T} = 474.3\text{Mbps/km}^2$. In the case of a FTTB + Microwave backhaul solution, a dense femto BS deployment, i.e., $\eta \geq 0.4$, becomes beneficial at very high area throughput values. This clearly indicates the significant impact of backhaul power consumption on energy efficient network deployment strategies for wireless access networks.

Fig. 4 depicts a comparison between the power consumption of each presented backhaul architectures as a function of the femto BS penetration rate. In this particular experiment $\mathcal{T} = 474.3\text{Mbps/km}^2$. It is shown that among the considered backhaul solutions, FTTB + Microwave, that relies on FTTB to backhaul the indoor traffic, is the most energy efficient. On the other hand, the power consumption of FTTN using VDLS2 increases linearly with femto BS density due to the distance constraints of VDSL2 technology that leads to the deployment of very large backhaul networks. Finally the backhaul solution based on microwave only seems to be the least energy efficient due to the high consumption values of the microwave antennas that needs to be deployed at each macro BS and at each building that has at least one femto BSs. The figure also shows the clear trade-off between the power saved by using low power base stations in the wireless segment and the excess power that has to be spent to backhaul their traffic.

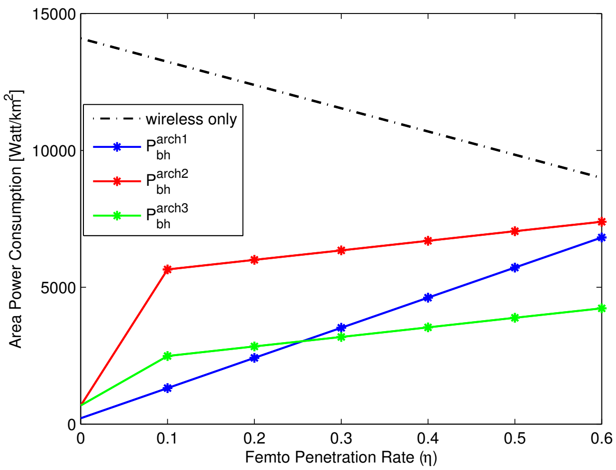
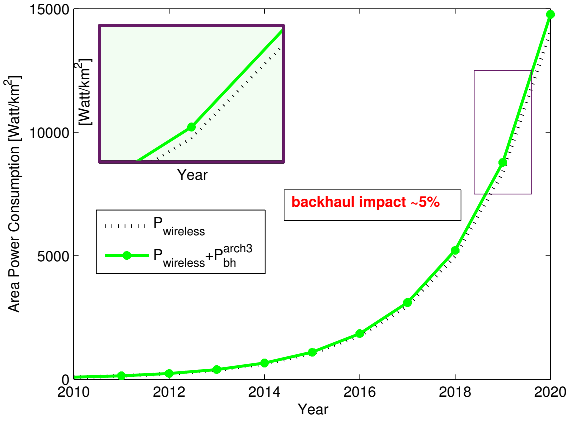
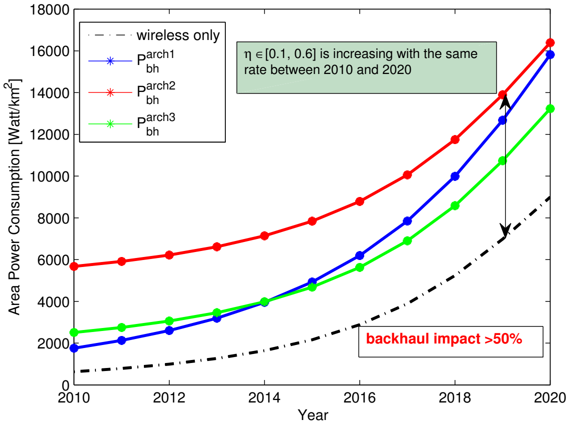


Fig. 4. Area power consumption vs. femto BS penetration rate for the traffic demand in 2020, i.e., $\mathcal{T} = 474.3\text{Mbps/km}^2$.

Finally, the impact of backhaul on the total power consumption between 2010 and 2020 is illustrated in Fig. 5, for homogeneous, i.e., macro-only ($\eta = 0$), and heterogeneous, i.e., macro+femto ($\eta > 0$), wireless network deployment scenarios. Note that in this specific experiment it is assumed that the area traffic demand ($\mathcal{T} \in [2.6, 474.3]$ Mbps/km^2) and the femto BS penetration rate ($\eta \in [0.1, 0.6]$) per-year-increase is constant, i.e., 68 % and 20%, respectively. This was done to mimic a possible operator strategy whose goal is to offload 60% of the mobile traffic using femto BSs by 2020. From Fig. 5 it can be observed that the area power consumption of the macro-only deployment increases exponentially due to high-densification of macro BS necessary to cope with the exponential traffic increase. However in this scenario, backhaul consume only 5% of the total power. On the other hand, even though offloading traffic to indoor femto BSs results in significant energy savings for the wireless part (Fig. 5(b)), this benefits come with a drastic increase in the backhaul power consumption, i.e., the backhaul can constitute up to 50% of



(a) Area power consumption change over the years for macro-only deployment scenario ($\eta = 0$).



(b) Area power consumption change over the years for macro+femto deployment scenario ($\eta \in (0.1, 0.6)$).

Fig. 5. Impact of backhaul on the total network power consumption over the years between 2010 and 2020. Note that mobile data traffic and femto BS penetration rate are assumed to increase respectively 68 and 20 percent annually during this period.

the total power consumption. These results clearly indicate that neglecting the backhaul power consumption while designing green wireless access network deployment strategies can result in incomplete and disputable conclusions.

VI. CONCLUSION

In this paper, we investigated the impact of backhaul on the total power consumption of wireless access networks, taking into account the expected traffic growth between 2010 and 2020. We demonstrated how different assumptions on indoor offloading with various femto base station densities, backhaul architectures, and capacity requirements affect the total power consumption. This was done to understand whether or not backhaul will be a bottleneck in future green and ultra-high capacity wireless access networks.

The results presented in the paper indicate that backhaul can potentially become an issue in the case of dense small cells deployment. In fact, it was shown that the backhaul power consumption can amount to up to 50% of the total power consumption of the wireless access network. As a consequence, when considering a potential evolution towards heterogeneous wireless network deployments, where a massive number of small base stations will be used, backhaul power consumption has to be included in the energy efficiency analysis in order to achieve a truly green wireless access network architecture. The presented results also highlight the importance of designing energy efficient backhaul architectures. In particular, it was shown that a hybrid backhaul solution combining a Fiber to the Building (FTTB) option (i.e., to backhaul femto base stations) and microwave links (i.e., to backhaul macro base stations) is a promising candidate in scenarios where the wireless network is characterized by a high femto base stations penetration rate.

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