Joint Design of Radio and Transport for Green Residential Access Networks

Matteo Fiorani, Sibel Tombaz, Fabricio S. Farias, Lena Wosinska, and Paolo Monti

***Abstract*—Mobile networks are the largest contributor to the carbon footprint of the telecom sector and their contribution is expected to rapidly increase in the future due to the foreseen traffic growth. Therefore, there is an increasing urgency in the definition of green mobile network deployment strategies. This paper proposes a four-step design and power assessment methodology for mobile networks, taking into consideration both radio and transport segments. A number of mobile network deployment architectures for urban residential areas based on different radio (i.e., macro base station, distributed indoor radio, femto cell) and transport (i.e., microwave, copper, optical fiber) technologies are proposed and evaluated to identify the most energy efficient solution. The results show that with low traffic the conventional macro base station deployment with microwave based backhaul is the best option. However, with higher traffic values heterogeneous networks with macro base stations and indoor small cells are more energy efficient. The best small cell solution highly depends on the transport network architecture. In particular, our results show that a femto cell based deployment with optical fiber backhaul is the most energy efficient, even if a distributed indoor radio architecture (DRA) deployment with fiber fronthaul is also a competitive approach.**

***Index Terms*—Mobile networks, Radio access networks, Transport networks, small cells, energy consumption.**

I. Introduction

MOBILE networks are the largest contributor to the energy consumption of communication networks. Today, they account for 0.3% of the energy consumed globally and their impact is expected to rapidly increase due to the exponential growth of mobile traffic foreseen in the short term future [1], [2], [3]. As a consequence, energy efficiency is a major concern for many mobile network operators worldwide.

A mobile network comprises of two segments: radio access network, which provides broadband wireless access to the end-users, and the transport network, which is responsible for interconnecting the radio network to the metro/core network infrastructure. There are many ongoing studies aimed at reducing the energy consumption of mobile networks, tackling the problem at the link, network and service level [4], [5].

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Among the various energy saving techniques proposed in the literature, base station (BS) sleeping and BS cooperation [6] have great potential for reducing the average network energy consumption by adapting the power levels to the spatial-temporal traffic fluctuations. Another interesting approach is the energy efficient scheduling and power allocation across a cluster of coordinated base stations [7]. Finally, a promising approach aiming at further reduction of energy consumption is the deployment of heterogeneous radio networks (HetNets) [8]. The intuition behind this last approach is the following. Radio access networks use mainly high-power base stations (BSs) with complex antenna systems, referred to as macro BSs. Macro BSs are deployed outdoor and are shown to be energy inefficient when serving indoor users [8]. This is because of the high attenuation experienced by the radio signal when it penetrates buildings, which in turn leads to high power losses (i.e., waste of energy). Heterogeneous radio networks (HetNets) on the other hand allow for the dense deployment of low-cost and low-power small BSs [8] in addition to macro BSs. In HetNets, part (or all) of the indoor users are served by the small BSs deployed indoor, while the macro BSs take care mainly of the outdoor users.

However, HetNets deployments may have an adverse effect on the complexity and the energy consumption of the transport network. This is due to the fact that HetNets drastically increase the number of BSs that need to be connected to the transport infrastructure. Several studies have already proven that in HetNets deployments the transport network consumes a large amount of power leading in some cases to higher energy consumption for the overall mobile network compared to the case in which radio deployments are based on macro BSs [9], [10]. As a consequence, to achieve an energy efficient mobile network deployment a careful design of the radio and the transport networks is necessary. In particular, for any specific radio network deployment, it is extremely important to being able to choose the best transport solution that guarantees a good overall energy performance.

For this reason this paper proposes a four-step methodology that is able to: *(i)* dimension the radio and the transport segments of a mobile network, and *(ii)* assess the power performance of the provided solution. The proposed methodology is general and can be used with any traffic scenario, (e.g., dense urban, urban, and rural), with any combination of BS types (i.e., homogeneous and/or heterogeneous deployment), and with any technological and architectural solution for the transport network (e.g., microwave, copper, fiber). The paper also presents a study where the proposed methodology is used to assess the power performance of a mobile network deployment based on

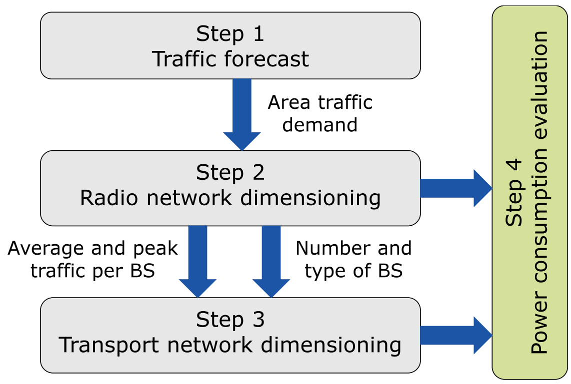


Fig. 1. Four-step design and assessment methodology for mobile networks.

the combination of different radio and transport deployment options. More specifically the solutions considered for the radio deployment includes macro BS, distributed antenna systems, and femto cell, while the options for the transport network technology include copper, microwave, and optics. The use case under exam is an urban area with traffic level that vary from today's requirement (i.e., 2015) up to the ones envisioned for the year 2022. The results for the assessment study show that, with the increase in the traffic levels expected in the next few years, HetNet deployments based on small indoor BSs with a fiber-based transport will become a very appealing option to provide coverage and capacity in very populated areas.

II. Methodology for Energy-Efficient Mobile Network Design

Figure 1 presents a methodology that can be used to design and evaluate the power consumption of a mobile network, including both the radio and the transport segment. The methodology comprises of four steps: (*i*) traffic forecast, (*ii*) radio network dimensioning, (*iii*) transport network dimensioning, and (*iv*) power consumption evaluation.

The first step deals with the *Traffic Forecast*. This phase provides an estimate of the average traffic demand that can be expected in the area under exam. The inputs for the traffic forecast phase are: the population density, the percentage of active users at busy hours, the user behaviour (i.e., heavy vs. ordinary users), the penetration rate of different mobile terminal types (e.g., pc, tablet, and smart-phone), and the average traffic requirement of each terminal type.

The second step is the *Radio Network Dimensioning* phase, which receives as input the results generated by the traffic forecast step in addition to a number of parameters related to the radio network equipment that can be used for the radio deployment. Among them there are, for instance, the capacity, coverage, and power consumption values of the BSs considered for deployment. The output of this phase is the number of BSs (for each type, if more than one) to be deployed together with their value of the average and peak traffic demand.

The third step focuses on the *Transport Network Dimensioning* phase. This step leverages on the results from the radio network dimensioning phase. The results of this third phase are dependent on the traffic forecast and the specific transport technology and architecture considered for the deployment. Some important input parameters are the transmission and switching capacity values for the network equipment. All these inputs are utilized to calculate the total number of devices needed in the transport network.

Finally, the last step is the *Power Consumption Evaluation*. In this phase the total power consumption of the radio and transport network is calculated in order to estimate the total power consumption of the overall mobile network deployment. This is achieved by employing analytic power models and input values for the power consumption of the radio and the transport network elements.

The sections that follow provide a detailed explanation of the assumptions and parameters considered in each step of the methodology just described.

III. Traffic Forecast

In the study presented in this paper we analyze a residential area of A [km^2] in an urban environment characterized by a user (i.e., mobile subscriber) density denoted by ρ [$users$/km^2]. We consider the long-term large-scale traffic model presented in [11], [12] in order to estimate the traffic demand in the area. The mobile network deployment is performed according to the average area traffic demand at busy hours $\mathcal{T}_b$ [Mbps/km^2], which can be obtained through the following formula:

$$\mathcal{T}_b = \rho \cdot \alpha \cdot \sum_k r_k \cdot s_k, \tag{1}$$

where α represents the percentage of active users at busy hours, r_k is the average data rate generated by the subscribers using a terminal of type k, and s_k is the average fraction of subscribers using a terminal of type k. Following the guidelines provided in [11], three different terminal types are considered: PCs, tablets, and smart-phones. Users are divided into two groups (i.e., heavy and ordinary) where the average capacity requirement of an ordinary user are lower than the one of a heavy user [11]. Under the assumption that h is the percentage of subscribers classified as heavy users, the average traffic demand for terminal k (i.e., r_k [Mbps]) can be defined as:

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

In the equation r_k^{heavy} $[MB/hour]$ and $r_k^{ordinary}$ $[MB/hour]$ represent the average traffic generated by a heavy and an ordinary user during an hour, respectively. Using (1) in combination with the forecasted values of h, s_k, r_k^{heavy}, and $r_k^{ordinary}$, for a given year, it is possible to calculate the average area traffic demand at busy hours for the corresponding year.

IV. Radio Network Dimensioning

In order to dimension the radio network the following assumptions are made. We consider two types of BSs, i.e., macro and small indoor BSs. The urban area under exam is characterized by N_b residential buildings, which are different from business buildings and shopping malls because of their smaller size. For simplicity and without loss of generality, we assume buildings with the same number of floors (N_f) and apartments (N_a). A fixed ratio of users ($\Im$) in the area is assumed to be indoor. They can be served either by macro or by small indoor BSs. The remaining users (1-$\Im$) are outdoor and are served by macro BSs only. We assume that buildings and users are uniformly distributed over the area. As a consequence, the indoor users are uniformly distributed over the buildings and the apartments.

In the radio network dimensioning step we consider three possible radio network deployments. The first one, (i.e., Macro-Only), is based on the use of convectional macro BSs to serve all users (i.e., indoor and outdoor). The second deployment uses small BSs to serve the indoor users. This deployment is based on the distributed indoor radio architecture (DRA). The third deployment relies on uncoordinated indoor femto cells and is referred to as Femto-Based deployment. More details about DRA and the Femto-Based deployment are provided next.

A. Distributed Indoor Radio Architecture (DRA) Deployment

The DRA is a concept used in indoor deployments, which provides high capacity to indoor mobile users in business areas and shopping malls [13]. However, through a proper network design, a DRA could also be applied to residential areas, such as the one under consideration. A DRA is composed of three main elements: (*i*) the indoor antenna, (*ii*) the remote radio unit (RRU), (*iii*) and the digital unit (DU). The antenna is an ultra-compact indoor radio antenna, which is equipped with a small power amplifier and receives the radio signal from the RRU. In the current study we assume that the antenna provides high capacity over a large indoor area (from 500 to 800 m^2). The RRU performs analog signal processing and provides the radio signal to a maximum of A_{RRU} antennas. Considering the limited size of residential buildings, RRUs could be placed either inside the building or in a curb cabinet. The DU performs the digital baseband processing, which includes interference management and cells coordination. A large number of DUs can be pooled in a micro-datacenter (DU Hotel), usually located in a central office. In the DU Hotel the DUs are organized in racks for sharing power supply, cooling and interconnection network. A DU Hotel serves a large number of RRUs by exploiting the pooled baseband resources, so that a single DU Hotel may cover an entire residential area (this approach is also referred to as centralized radio access network (C-RAN)).

A DRA is deployed by a mobile operator using engineered deployment strategies. For this reason we can assume that if a building is equipped with DRA antennas all the users inside that building will be served by the DRA system. In our analysis we consider a residential area where each floor has a limited size (< 800 m^2), so that a single antenna can be used to cover an entire floor. The total number of antennas in the urban area depends on the DRA penetration rate (η). Here, η represents the fraction of buildings equipped with DRA antennas, which, under the assumption that indoor users are uniformly distributed over the buildings, corresponds to the fraction of indoor users served by DRA antennas. The number of DRA antennas in the area is given by: $N_{DRA} = N_b \cdot N_f \cdot \eta$. The parameter η can vary in the range [0;1]. The remaining users (i.e., which are not covered by the DRA) are covered by the macro BSs, whose number can be calculated according to the following formula:

$$N_{Macro}^{DRA} = \frac{\rho \cdot A \cdot \alpha \cdot (1 - \eta \cdot \Im)}{N_{users/BS}}, \tag{3}$$

note that the case $\eta = 0$ corresponds to the Macro-Only deployment (i.e., all the users are served by macro BSs). On the other hand, when $\eta = 1$ all the indoor users ($\rho \cdot A \cdot \alpha \cdot \Im$) are served by the DRA antennas, while only the outdoor users are served by macro BSs. Here $N_{users/BS}$ denotes the number of active users that can be served by a macro BS and is given by [9]:

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

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. Based on the assumption that co-channel small BS deployment has only a minor impact on the macro BS downlink performance [14], [15], the average macro BS capacity can be calculated via the following fluid model [16]:

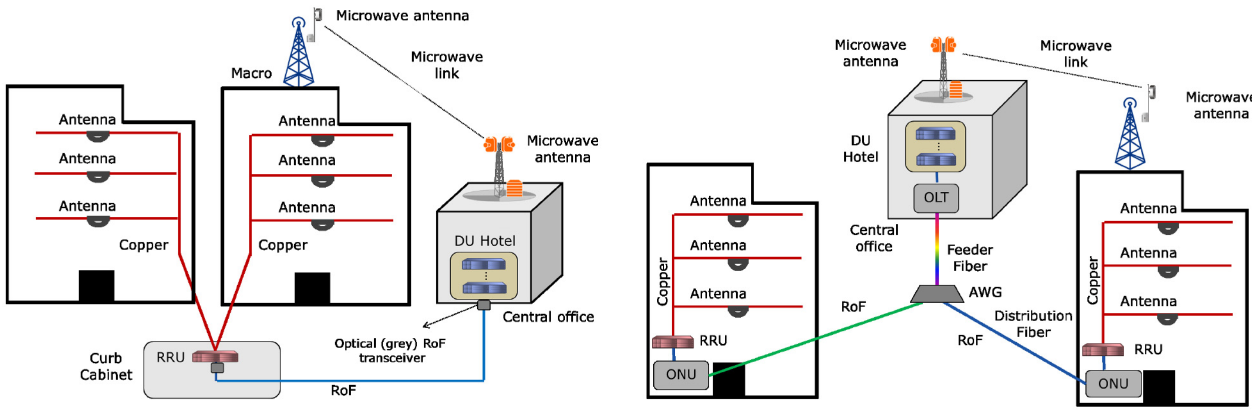
$$C_{macro} = N_s W log_2 \left(1 + \mathbb{E}_d \left[\frac{3\sqrt{3}(\gamma - 2)}{4\pi} \frac{R^2(2R - d)^{2-\gamma}}{d^\gamma}\right]\right), \tag{5}$$

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 equation (5) to compute the average macro cell capacity over different values of R, results confirm that, in the case of an interference limited system, 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 [17]. Thus, for the scenario considered in this paper the macro BS capacity is constant regardless of the number of small and macro BS in the area.

B. Femto-Based Deployment

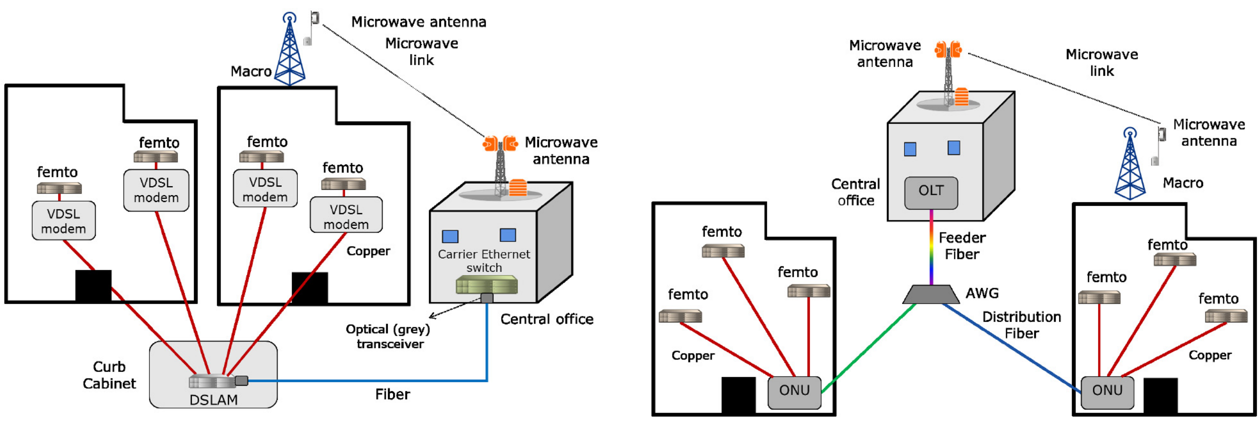
A femto cell is a stand-alone base station providing high capacity over a limited indoor area, ranging from 50 to 100 m^2 [18]. It is usually equipped with an omnidirectional antenna and has both radio and baseband functions. We assume that a single femto cell is sufficient to provide high mobile capacity inside a single apartment.

Residential femto cells are randomly deployed by the users in their apartments (similarly to Wi-Fi systems), so that the Femto-Based deployment does not follow any engineered strategy. In our reference residential area, the number of deployed femto cells (N_{femto}) is calculated as a function of the femto penetration rate (θ). Here, θ corresponds to the ratio of the users that are served by the femto cells (consistent with the definition provided in [9]). As a consequence, the number of femto cells in the residential area is given by: $N_{femto} = (N_b \cdot N_a \cdot \theta)/\Im$. The parameter θ can vary in the range $[0\,;\,\Im]$. Since the macro BSs



(a) DRA curb fronthaul architecture (DRA-CF). (b) DRA building fronthaul architecture (DRA-BF).

Fig. 2. DRA fronthaul architectures.



(a) Femto-Based curb backhaul architecture (Femto-CB). (b) Femto-Based building backhaul architecture (Femto-BB).

Fig. 3. Femto-Based backhaul architectures.

need to serve the remaining active users (i.e., which are not covered by femto cells), the required number of macro BSs in the area is given by the following formula:

$$N_{Macro}^{Femto} = \frac{\rho \cdot A \cdot \alpha \cdot (1-\theta)}{N_{users/BS}}. \tag{6}$$

Note that the case $\theta = 0$ corresponds to the DRA deployment with $\eta = 0$ and consequently to the Macro-Only deployment (i.e., all the users are served by macro BSs). On the other hand, when $\theta = \mathcal{I}$ all the indoor users ($\rho \cdot A \cdot \alpha \cdot \mathcal{I}$) are served by femto cells, while only the outdoor users are served by the macro BSs.

V. Transport Network Dimensioning

This section describes the dimensioning phase of the transport network for the DRA and the Femto-Based deployments. On the other hand, macro BSs are assumed to employ always a microwave (MW) transport network, as today the majority of the macro BSs worldwide are backhauled using microwave links. As a consequence, we assume that each macro BS is equipped with a MW antenna and is connected to the central office using a MW point-to-point link (Fig. 2 and Fig. 3). The central office is equipped with a MW hub supporting antennas (one per macro BS) to receive (transmit) the traffic from (to) the macro BSs.

A. DRA Fronthaul Architectures

The DRA employs a fronthaul architecture to interconnect the antennas, RRUs and DU Hotel. The antennas are connected to the RRU using a copper cable (e.g., LAN cable CAT 5/6/7) and radio (RF) transmission over copper. The radio over copper transmission limits the distance between the antennas and the RRU to a few tens of meters, due to high frequency dependent losses. For this reason the RRUs are placed either indoor or in a curb cabinet, depending on the size of the building. In our analysis we consider a residential area with buildings of relatively small sizes, so that both options for placing the RRUs are viable. On the other hand, the RRUs are connected to the DU Hotel using fiber links and radio over fiber (RoF) transmission technologies (e.g., using the common public radio interface (CPRI) protocol [19]). RoF transmission protocols require a large amount of capacity and limit the distance between RRUs and DU Hotel to around 15 to 20 km due to strict latency requirements. Still, this distance enables the use of a single DU Hotel to cover a large residential area. We propose two different fronthaul architectures for DRA systems. The first architecture is focused on limiting the deployment costs and relies on mature transport technologies, while the second one is based on upcoming optical wavelength division multiplexing (WDM) technology and offers higher scalability.

The first architecture is shown in Fig. 2(a) and is referred to as DRA with curb fronthaul (DRA-CF). Here, using advanced radio transmission technologies over copper, the already existing copper infrastructure inside the building is exploited for connecting the antennas to the RRUs located in the curb cabinets. Each RRU in the curb cabinet is in turn connected to the DU Hotel in the central office using a RoF connection over a grey point-to-point (PtP) fiber link. The grey optical PtP links operate at 10 Gbps (to support the high capacity requirements introduced by RoF protocols). The actual traffic generated over the fiber links depends on the specific radio configuration and is independent on the actual traffic generated by the end-users. The transmission over the fiber is carried out using grey optical RoF transceivers (one at the RRU and one at the DU Hotel side).

The second architecture is shown in Fig. 2(b) and is referred to as DRA with building fronthaul (DRA-BF). Here, the RRUs are placed inside the residential buildings and each RRU is directly connected to an optical network unit (ONU). The ONUs are in turn connected to an optical line terminal (OLT) located at the central office through a dense wavelength division multiplexing (DWDM) - PON infrastructure [20]. In a DWDM-PON each ONU is assigned a dedicated wavelength for transmitting (receiving) the traffic to (from) the OLT. In this way, each ONU has a virtual dedicated PtP optical link toward the OLT over which communication is carried out using a RoF transmission protocol. We assume that each wavelength is operated at 10 Gbps (to support the high capacity requirements introduced by RoF protocols). Array waveguide gratings (AWG) [20], which are passive components and thus do not consume any power, are used at the remote node (RN) to multiplex (demultiplex) the wavelengths in the direction to (from) the OLT. In the feeder fiber (see Fig. 2(b)) interference among the different ONU transmissions is avoided because each ONU employs a different wavelength channel. The maximum number of wavelengths supported (in the feeder fiber) by a DWDM-PON is indicated with N_w^D and defines the maximum number of ONUs (and consequently RRUs) which can be supported by a single OLT. In the central office the OLT is directly connected to the DU Hotel.

B. Femto-Based Backhaul Architectures

Femto cells incorporate radio and baseband functions in a single radio component and thus are backhauled using traditional packet-based technologies. In our study, we dimension the backhaul network according to the peak capacity generated by the femto cells. A femto cell generates the peak capacity when a single user is connected in close proximity to the BS, so that it experiences ideal channel conditions and obtains the highest possible transmission rate, which we assume to correspond to 100 Mbps [18]. We propose two different backhaul architectures among which the first one relies on mature technologies, while the second one is based on the upcoming NG-PON2 technology [21].

The first backhaul architecture is shown in Fig. 3(a) and is referred to as Femto-Based with curb backhaul (Femto-CB). Here, femto cells are backhauled using copper cables and very-high speed digital subscriber line (VDSL) transmission protocol. Each femto cell is connected to a VDSL modem that is in turn connected to a DSL add/drop multiplexer (DSLAM) located at the curb cabinet. The VDSL protocol can guarantee 100 Mbps transmission capacity for distances up to 300 m (i.e., the distance between the femto cells and the DSLAM is limited to 300 m). The DSLAMs are connected to Carrier Ethernet metro/core switches located at the central office using grey optical PtP fiber links operating at 10 Gbps. The transmission over the optical fiber links is carried out using grey optical transceivers.

The second backhaul architecture is shown in Fig. 3(b) and is referred to as Femto-Based with building backhaul (Femto-BB). All the femto cells inside a residential building are connected to an ONU using copper cables operating at 100 Mbps (e.g., LAN cable CAT 5/6/7). Each ONU is in turn connected to the OLT in the central office through a hybrid time and wavelength division multiplexing (TWDM) - PON infrastructure [22]. The TWDM-PON supports a maximum of N_w^T wavelengths in the feeder fiber (usually $N_w^T << N_w^D$) operating at 10 Gbps. A group of ONUs is assigned the same wavelength for transmitting (receiving) the traffic to (from) the OLT. In order to avoid collisions in the feeder fiber, the ONUs employing the same wavelength use different time-slots for transmitting (receiving) traffic. The time-slots are assigned by the OLT via a specific dynamic bandwidth allocation (DBA) algorithm [23]. The TWDM-PON technology has been chosen to achieve a high sharing of the optical resources among the femto cells. In fact, the traffic requirements of packet-based backhaul are relatively small (compared to fronthaul) and consequently using a DWDM-PON infrastructure (such as the one proposed for the DRA) would lead to a severe under-utilization of the optical network resources (and waste of energy).

VI. Power Consumption Evaluation

This Section presents the analytical models used to evaluate the power consumption of the proposed transport architectures.

A. Macro+DRA-CF Power Model

The total power consumption of the Macro+DRA-CF architecture ($P_{CF}^{DRA,tot}$) is obtained by summing the power consumption of the outdoor macro BS network (P_{Macro}^{DRA}) and the indoor DRA-CF network (P_{CF}^{DRA}), as per the following formula:

$$P_{CF}^{DRA,tot} = P_{Macro}^{DRA} + P_{CF}^{DRA}. \tag{7}$$

The power consumption of the outdoor macro BS network is given by the following formula:

$$P_{Macro}^{DRA} = N_{Macro}^{DRA} \cdot (P_{Macro} + 2 \cdot P_{MW}), \tag{8}$$

where P_{Macro} and P_{MW} represent the power consumption of a macro BS and a microwave antenna, respectively. Moreover,

N_{Macro}^{DRA} is calculated using (3), while P_{Macro} is derived using the models presented in [9], [11]. The power consumption of the indoor DRA-CF network is calculated according to the following equation:

$$P_{CF}^{DRA} = N_{DRA} \cdot P_{Amp} + \left\lceil \frac{N_{DRA}}{A_{RRU}} \right\rceil \cdot \left(P_{RRU} + 2 \cdot P_{Tr} + P_{DU}^{port} + \left\lceil \frac{P_{DU}^{rack}}{N_{DU}^{port}} \right\rceil \right), \quad (9)$$

where P_{Amp}, P_{RRU}, and P_{Tr} are the power consumption of an indoor antenna amplifier, a RRU, and a grey optical transceiver, respectively. The power consumption of the DU Hotel is divided in power consumption per DU port (P_{DU}^{port}) and power consumption per DU rack (P_{DU}^{rack}). On the one hand, P_{DU}^{port} represents the power consumption for the baseband processing functions associated to a single RRU. On the other hand, P_{DU}^{rack} includes the power consumption for the cooling, power supply and internal interconnect of a rack of DUs. Finally, N_{DU}^{port} represents the number of DU ports per DU rack.

B. Macro+DRA-BF Power Model

Similarly to the previous case, the total power consumption of the Macro+DRA-BF architecture ($P_{BF}^{DRA,tot}$) is obtained by summing the power consumption of the outdoor macro BS network (P_{Macro}^{DRA}) and the indoor DRA-BF network (P_{BF}^{DRA}), as per the following formula:

$$P_{BF}^{DRA,tot} = P_{Macro}^{DRA} + P_{BF}^{DRA}. \quad (10)$$

The power consumption of the outdoor macro BS network is the same as in (8), while the power consumption of the indoor DRA-BF network is given by the following equation:

$$P_{BF}^{DRA} = N_{DRA} \cdot P_{Amp} + N_b \cdot \eta \cdot \left[N_{RRU}^{b} \cdot \left(P_{RRU} + P_{DU}^{port} + \left\lceil \frac{P_{DU}^{rack}}{N_{DU}^{port}} \right\rceil \right) + N_{ONU}^{b} \cdot \left(P_{ONU} + \left\lceil \frac{P_{OLT}}{N_w^D} \right\rceil \right) \right], \quad (11)$$

where P_{ONU} and P_{OLT} are the power consumption of the ONU and OLT, respectively. In addition, N_{RRU}^{b} and N_{ONU}^{b} represent the number of RRUs per building and the number of ONUs per building.

C. Macro+Femto-CB Power Model

The total power consumption of the Macro+Femto-CB architecture ($P_{CB}^{femto,tot}$) is obtained by summing the power consumption of the outdoor macro BS network (P_{Macro}^{femto}) and the indoor Femto-CB network (P_{CB}^{femto}), as per the following formula:

$$P_{CB}^{femto,tot} = P_{Macro}^{femto} + P_{CB}^{femto}. \quad (12)$$

The power consumption of the outdoor macro BS network is given by the following formula:

$$P_{Macro}^{femto} = N_{Macro}^{femto} \cdot (P_{Macro} + 2 \cdot P_{MW}), \quad (13)$$

where N_{Macro}^{femto} is calculated using (6). Furthermore, the power consumption of the indoor Femto-CB network is given by the following equation:

$$P_{CB}^{femto} = N_{femto} \cdot (P_{femto} + P_{VDSL}^{m}) + \left\lceil \frac{N_{femto}}{N_{DSLAM}^{p}} \right\rceil \cdot (P_{DSLAM} + 2 \cdot P_{Tr}) + \left\lceil \frac{N_{femto}}{N_{DSLAM}^{p} \cdot N_s^p} \right\rceil \cdot P_s, \quad (14)$$

where P_{femto}, P_{VDSL}^{m}, P_{DSLAM}, and P_s are the power consumption of a femto cell, of a VDSL modem, of a DSLAM, and of a Carrier Ethernet switch, respectively. In addition, N_{DSLAM}^{p} and N_s^p are the number of ports of a DSLAM and a Carrier Ethernet switch, respectively. Finally, the power consumption of a femto cell is calculated according to the power models presented in [9], [11].

D. Macro+Femto-BB Power Model

The total power consumption of the Macro+Femto-BB architecture ($P_{BB}^{femto,tot}$) is obtained by summing the power consumption of the outdoor macro BS network (P_{Macro}^{femto}) and the indoor Femto-Based with BB network (P_{CB}^{femto}), as per the following formula:

$$P_{BB}^{femto,tot} = P_{Macro}^{femto} + P_{BB}^{femto}. \quad (15)$$

The power consumption of the outdoor macro BS network is the same as the one in (13), while the power consumption of the indoor Femto-Based with BB network is given by the following equation:

$$P_{BB}^{femto} = N_{femto} \cdot P_{femto} + I \cdot N_b \cdot N_{ONU}^{b} \cdot \left(P_{ONU} + \left\lceil \frac{P_{OLT}}{N_{femto}^{mux} \cdot N_w^T} \right\rceil \right), \quad (16)$$

where I is a boolean variable which takes value 0 when $\theta = 0$ and takes value 1 when $\theta > 0$ (i.e., $\theta \in (0; \mathfrak{I}]$). The factor N_{femto}^{mux} represents the number of femto cells that can be multiplexed over a single wavelength of the TWDM-PON infrastructure (using TDM).

VII. Numerical Results

In this section we assess the power performance of the proposed mobile network deployments. We consider increasing traffic demand for our residential areas up to traffic values expected for year 2022 (i.e., at which point it may be reasonable to assume the roll-out of new radio technologies, which might require different mobile deployments and power models).

Table I shows a qualitative assessment of the considered mobile networks, taking into consideration the following metrics: (*i*) deployment strategy, (*ii*) control & management complexity, (*iii*) deployment costs, (*iv*) scalability, and (*v*) potential for BS coordination. The Macro-Only and Macro+DRA mobile

TABLE I
QUALITATIVE ASSESSMENT OF THE PROPOSED MOBILE ARCHITECTURES

Deployment	Strategy	Ctrl. complexity	Deployment costs	Scalability	BS coordination
Macro-Only with MW	Engineered [+]	Low / efficient [+]	High (macro BS) [-]	Medium (MW) [-]	Tight [-]
Macro + DRA-CF	Engineered [+]	Low / efficient [+]	Medium [+]	Low (copper) [-]	Very tight [+]
Macro + DRA-BF	Engineered [+]	Low / efficient [+]	High (DWDM-PON) [-]	High (fiber) [+]	Very tight [+]
Macro + Femto-CB	User-driven [-]	High / inefficient [-]	Medium [+]	Low (copper) [-]	Tight [-]
Macro + Femto-BB	User-driven [-]	High / inefficient [-]	High (TWDM-PON) [-]	High (fiber) [+]	Tight [-]

deployments are operator engineered, making it easier to guarantee coverage as well as the quality of service to the end-users. Another advantage of an operator driven deployment is the fact that it simplifies network upgrades (e.g., software and hardware). In addition, the Macro-Only and the Macro+DRA deployments have simpler network control & management with respect to the Macro+Femto deployment. This is due to the fact that the network controller has full control of the mobile resources facilitating the resource allocation (e.g., cell coordination and interference management), enabling for a more efficient orchestration of radio and transport resources, and simplifying the network management. As for the deployment costs, the Macro-Only network tends to be expensive due the large number of costly macro BSs needed to satisfy the increasing traffic demand in residential areas. Also the Macro+DRA and Macro+Femto networks based on advanced optical WDM transport technologies (TWDM-PON and, in particular, DWDM-PON) are very expensive. This is because advanced WDM transmission components are relatively expensive and their massive deployment in residential areas may be very costly. On the other hand, Macro+DRA and Macro+Femto networks based on more mature transport technologies (i.e., copper and grey optics) are potentially less expensive to deploy. However, the solutions based on WDM technologies are more scalable, i.e., can be easily upgraded to support long-term traffic requirements (e.g., expected after 2022 and driven by upcoming 5G radio technology). As a consequence, Macro+DRA-CB and Macro+Femto-BB deployments are more scalable than Macro+DRA-CF and Macro+Femto-CB deployments due to the limits introduced by long range transmissions over copper cables. Another important aspect to take into consideration is the potential for providing efficient BS coordination. This influences for example the possibility of introducing advanced energy saving techniques (e.g., based on BS sleeping and BS cooperation). Three levels of BS coordination can be identified, i.e., moderate, tight and very tight [24]. Moderate coordination schemes include enhanced inter-cell interference coordination (eICIC), while tight coordination schemes include slow uplink/downlink coordinated multipoint (CoMP). These schemes introduce relatively loose requirements in terms of capacity and latency (i.e., in the range of few ms) on the transport network and can be supported by all the proposed architectures [25]. On the other hand, very tight coordination schemes, such as fast uplink/downlink CoMP, introduce strict requirements in terms of capacity and latency (i.e., in the order of few hundreds of μs) on the transport network. These schemes can be seamlessly implemented only in the Macro+DRA architectures, which use fronthaul and centralized baseband processing (i.e., DU Hoteling) and can guarantee high capacity and low latency in the transport [25]. In the following we show the comparison of the power consumption evaluation of the different mobile network architectures to identify which one is the most energy efficient. It is worth noticing that in our calculations we do not take into account energy saving techniques. The calculations are based on the reference values of the parameters shown in Table II, which are derived from [9], [10], [11], [26].

TABLE II
SYSTEM PARAMETERS AND POWER CONSUMPTION [9], [10], [11], [26]

Traffic Forecast	**Value**
Area ($\mathcal{A}$)	100 km^2
Population density (ρ)	3000 user/km^2
Percentage of users at busy hours (α)	16%
Area traffic demand ($\mathcal{T}_b$) in 2018	168 Mbps/km^2
Area traffic demand ($\mathcal{T}_b$) in 2020	480 Mbps/km^2
Area traffic demand ($\mathcal{T}_b$) in 2022	1243 Mbps/km^2
Radio Network Deployment	**Value**
Number of buildings (N_b)	10000
Number of floor per building (N_f)	5
Number of apartment per building (N_a)	15
Percentage of indoor users ($\mathcal{I}$)	60%
Number of indoor antennas per RRU (A_{RRU})	8
Number of RRUs per building (N^b_{RRU})	1
Number of DU ports per DU rack (N^{port}_{DU})	200
Transport Network Deployment	**Value**
Number of wavelengths DWDM-PON (N^D_w)	380
Number of wavelengths TWDM-PON (N^T_w)	4
Number of femto per wavelength (N^{mux}_{femto})	100
Number of ONUs per building (N^b_{ONU})	1
Number of ports of DSLAM (N^p_{DSLAM})	24
Number of ports of Carrier Eth switch (N^p_s)	12
Power Consumption Evaluation	**Value**
Pw. cons. macro BS (P_{Macro})	650 W
Pw. cons. microwave antenna (P_{MW})	30 W
Pw. cons. Ant. amplifier (P_{Amp})	5 W
Pw. cons. remote radio unit (P_{RRU})	100 W
Pw. cons. optical grey transceiver (P_{Tr})	2 W
Pw. cons. per DU port (P^{port}_{DU})	25 W
Pw. cons. per DU rack (P^{rack}_{DU})	150 W
Pw. cons. ONU / OLT (P_{ONU}/P_{OLT})	5 W / 1197 W
Pw. cons. femto cell (P_{femto})	10 W
Pw. cons. VDSL modem (P^m_{VDSL})	10 W
Pw. cons. DSLAM (P_{DLAM})	40 W
Pw. cons. Carrier Eth switch (P_s)	300 W

Fig. 4 shows the power consumption of a mobile access network based on the Macro+DRA system as a function of the area traffic demand ($\mathcal{T}_b$) for some selected values of the DRA penetration rate (i.e., $\eta = 0.5$ and $\eta = 1$). Note that

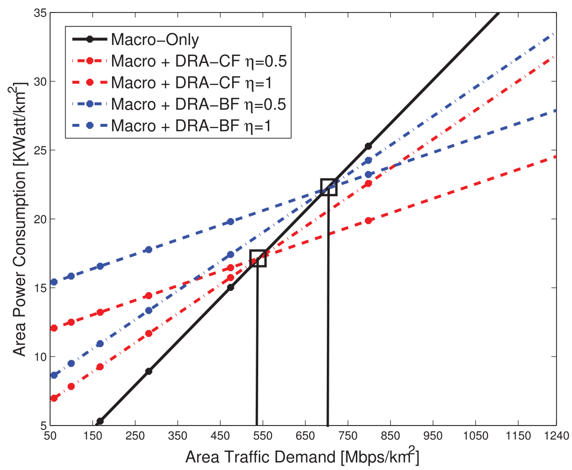


Fig. 4. Power consumption as a function of the area traffic demand using Macro-Only and Macro+DRA systems.

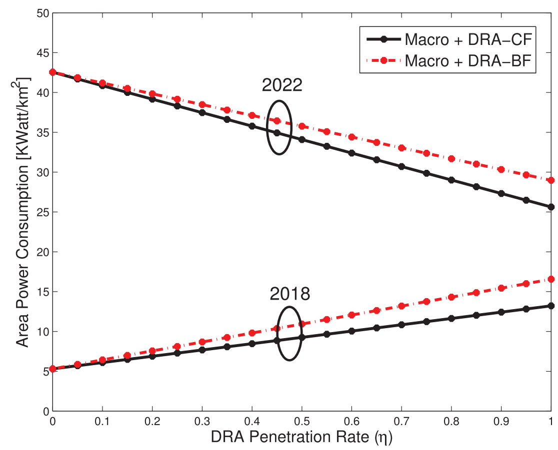


Fig. 5. Power consumption as a function of the DRA penetration rate using Macro+DRA systems.

$\eta = 0.5$ and $\eta = 1$ correspond to the cases where half and all the indoor mobile users are served by the DRA antennas, respectively. Both DRA-CF and DRA-BF are considered. The results are compared against a traditional Macro-Only deployment (which corresponds to a Macro+DRA architecture with $\eta = 0$). The figure shows that when the area traffic demand is low the Macro-Only deployment is more energy efficient than the Macro+DRA deployments, independently from the adopted fronthaul architecture. The reason behind this result is that for low traffic demands the macro network used for area coverage is also able to satisfy (almost entirely) the capacity requirements. As a consequence, the DRA indoor infrastructure (including transport) is heavily under-utilized leading to a waste of energy. Increasing the value of $\mathcal{T}_b$ leads to a better energy efficiency for Macro+DRA with respect to the Macro-Only deployment. This is due to the fact that in the Macro+DRA architecture the increasing traffic generated by the indoor users can be served more effectively using the indoor wireless infrastructure (instead of using power costly outdoor macro BSs). In our calculations, the Macro+DRA-CF becomes more energy efficient than the Maro-Only deployment for traffic demands higher than 540 Mbps/km^2, while the Macro+DRA-BF becomes more energy efficient than the Macro-Only deployment for traffic demands higher than 700 Mbps/km^2. This reflects the fact that the DRA-CF transport architecture is more energy efficient than the DRA-BF. The reason for this results is that the main contributors to the power consumption of the DRA deployments are the RRUs (accounting for more than one-third of the total power consumption). In the DRA-CF architecture the RRUs are placed inside the curb cabinets leading to a more efficient sharing of the radio resources (i.e., the RRUs can be shared among antennas in different buildings ensuring that their utilization is maximized). This is referred to as stacking gain. Fig. 5 shows the power consumption of a mobile access network based on the Macro+DRA system as a function of the DRA penetration rate (η) and for traffic forecast values for the years between 2018 and 2022 (according to the traffic forecast model presented in Section III). The case $\eta = 0$ represents the Macro-Only deployment. It can be observed that in the year 2018 the Macro-Only deployment is the most energy efficient and that the power consumption of the mobile access network increases with η. On the other hand, the situation in the year 2022 is different due to the increased user traffic requirements. In Fig. 5 it can be observed that the power consumption of a Macro-Only deployment is much higher than the power consumption of the Macro+DRA architectures and that the area power consumption decreases with η. The Macro+DRA-CF architecture is the most energy-efficient and in our calculations consumes up to 45% less power than the Macro-Only deployment. Note that utilizing a more aggressive traffic forecast model, such as those presented in [27], the Macro+DRA networks are expected to become more appealing in terms of energy efficiency at an earlier time. In Fig. 6 the power consumption of the mobile access network with Macro+Femto deployments is shown as a function of the area traffic demand ($\mathcal{T}_b$) for some selected values of the Femto penetration rate (i.e., $\theta = \mathcal{I}/2 = 0.3$ and $\theta = \mathcal{I} = 0.6$). Note that $\theta = 0.3$ and $\theta = 0.6$ correspond to the cases where half and all the indoor mobile users are served by the femto cells, respectively. Both the backhaul architectures, i.e., curb and building backhaul, are considered and the results are compared with the Macro-Only deployment. The figure shows similar trends as those already observed for the Macro+DRA deployments (Fig. 4). Namely, when the area traffic demand is low the Macro-Only deployment is more energy efficient than the Macro+Femto ones due to under-utilization of the Femto-Based radio and transport infrastructure. On the other hand, increasing the area traffic demand leads to increasing the energy efficiency of the Macro+Femto architectures over the Macro-Only deployment. The results show that the Macro+Femto-BB architecture becomes more energy efficient than the Macro-Only network for area traffic demands higher than 350 Mbps/km^2, i.e., much earlier than the Macro+Femto-CB architecture (which becomes more energy efficient than the Macro-Only for 590 Mbps/km^2). This reflects the fact that the Femto-BB transport architecture is more energy efficient than the Femto-CB one. The reason is the very high power consumption of the VDSL infrastructure (VDSL modems and DSLAMs) utilized in the Femto-CB backhaul network. In fact, in our calculations, the VDSL infrastructure consumes more

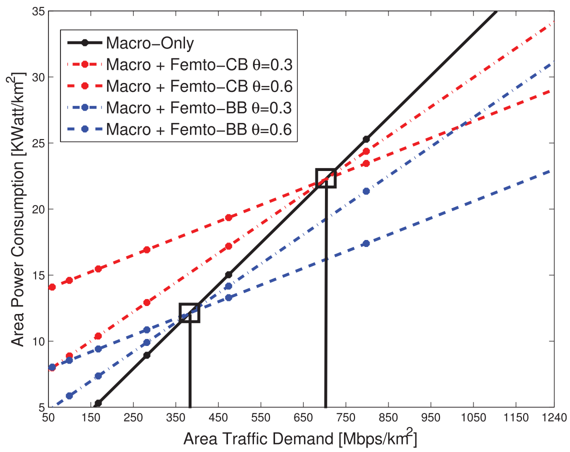


Fig. 6. Power consumption as a function of the area traffic demand using Femto-Based systems.

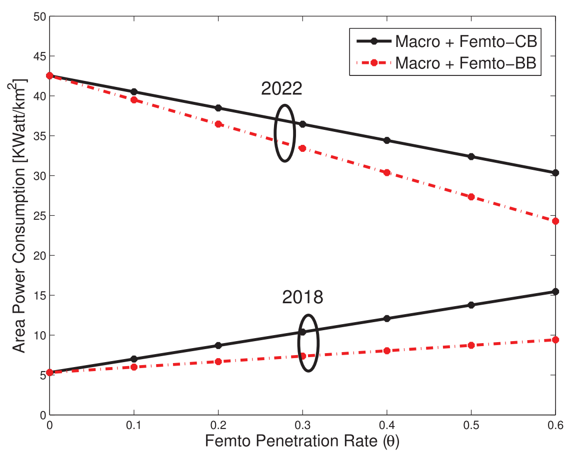


Fig. 7. Power consumption as a function of the Femto penetration rate using Femto-Based systems.

than half of the total power consumption of the Femto-CB architecture. On the other hand, the Femto-BB architecture utilizes the TWDM-PON technology which is extremely energy efficient and reduces drastically the overall power consumption.

Fig. 7 shows the power consumption of a mobile access network based on the Femto-Based architectures as a function of the Femto penetration rate (θ) and for traffic forecast values for the years between 2018 and 2022 (according to the traffic forecast model presented in Section III). Here, θ varies in the range $[0;\Im]$, with $\theta = 0$ representing the Macro-Only deployment. It can be observed that in the year 2018 the Macro-Only deployment is the most energy efficient, while in 2022 the power consumption decreases linearly with increasing θ. In particular, in the year 2022 the Macro+Femto-BB is expected to consume around half the power consumption of the Macro-Only deployment. It is again worth to keep in mind that using a more aggressive traffic forecast model (e.g., [27]) the Macro+Femto networks are expected to become more energy efficient at an earlier time. In Fig. 8 we show the power consumption of all the considered mobile architectures as a function of the area traffic demand. For the Macro+DRA and the Macro+Femto architectures we assume that the penetration rate increases linearly over

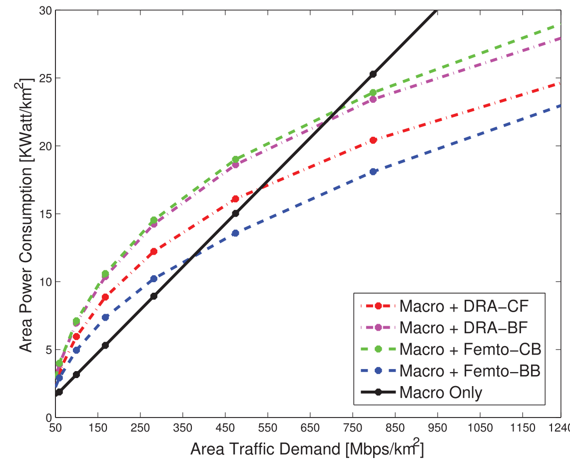


Fig. 8. Power consumption increase over the years for different mobile network architectures.

the time, starting from the year 2015 (when all the users are served by the macro BSs) up to the year 2022 (when all the indoor users are served by small cells). The figure shows that for traffic demands higher than 700 Mbps/km^2 all the HetNet deployments consume less power than the Macro-Only. It can be also observed that the transport architecture of the indoor small cells plays a key role in the power consumption of the HetNet deployments. The Macro+Femto-CB architecture is the less energy efficient due to the high power consumption of the VDSL infrastructure. On the other hand, the Macro+DRA architectures are more energy efficient, but are limited by the high number and power consumption value of the RRUs, not to mention the high capacity requirements of the RoF transmission technologies, which reflects in more equipment at the central office. Finally, the Macro+Femto-BB is the most energy efficient solution thanks to the multiplexing of large number of femto cells over the TWDM-PON infrastructure.

VIII. Conclusions

Green mobile deployments require a careful design of both the radio and the transport network. This paper first proposes a four-step design and power assessment methodology for mobile networks, then it introduces several mobile deployments alternatives for residential areas together with their power models. The proposed deployments are based on different radio technologies (i.e., macro BS, DRA, and femto cell) and on different transport options (i.e., copper, microwave, grey/WDM optics). The power consumption of the proposed mobile deployments is evaluated considering traffic levels expected up to the year 2022.

The results show that with low traffic levels a Macro-Only deployment shows good energy performance. On the other hand, for higher traffic levels, HetNet deployments based on small indoor BSs become highly beneficial and might consume less than half the power required by a Macro-Only network. It was also found that the transport architecture plays a fundamental role in the power consumption of HetNet deployments and might limit considerably the total energy saving. Our results show that a Macro+Femto-BB architecture is an energy efficient solution because it integrates effectively femto cells and TWDM-PON backhaul. On the other hand, a Macro+DRA-CF architecture is also a promising architecture that can represent a good option in fiber scarce residential areas. Finally, in our future work we plan to extend this study by applying the proposed methodology to assess the impact of the spatial and temporal traffic fluctuations on the energy consumption of the entire network (i.e., radio + transport). In this regard we plan also to investigate potential dynamic energy management schemes specifically tailored for the proposed architectures. In addition, we plan to study the possible beneficial effects on the network power consumption derived from having macro BSs with an increased capacity as a result of the introduction during the years of new and more power efficient technologies.

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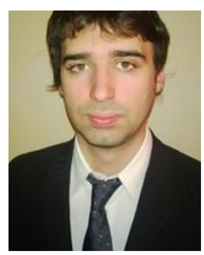

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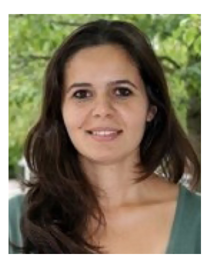

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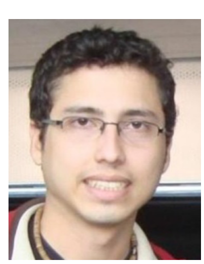

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