Rethinking Cellular System Architecture for Breaking Current Energy Efficiency Limits

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Abstract— **Base stations have been identified to be the most power consuming part in current mobile networks. Since their power profile only depends to a small fraction on the actual traffic load, putting some base stations in sleep mode has been identified as a solution to scale the network's power consumption with the actual load. However, the traditional cellular approach limits the achievable energy efficiency because the requirements on system availability impose continuous full coverage of the service area. This paper presents a new system architecture that overcomes this limitation based on the new paradigm of "cell on-demand", which is currently studied in the Beyond Cellular Green Generation (BCG²) project of the GreenTouch consortium. We first outline the key characteristics of the new system architecture and the main technical challenges. Then, we present an analytical study for estimating the achievable energy-efficiency gains. We show that - depending on the daily load profile - we can improve current network energy efficiency by more than 50 times.**

Keywords; Mobile Network Architecture, Future Generation Mobile Networks, Network Management, Signaling

I. INTRODUCTION

The fact that base stations are energy hungry devices is very well known. This characteristic, in addition to the proliferation of their number due to the higher and higher traffic volume to be managed, makes network devices for the last-hop consuming over 80% of the power used in the entire access network.

Research on Green Networking, e.g., [1] , focuses on the network's energy consumption. Energy management strategies are being broadly investigated for many wireless technologies in the research community, e.g., [2]. Energy saving mechanisms are now available in many commercial products as well. The rationale behind these strategies is to exploit the available spare capacity in cellular networks when the traffic level is low in order to set some of the base stations to a sleep/low-power mode, e.g. [3]. Indeed, the typical energy consumption profile of base station hardware is characterized by a great difference between the power of the sleep/inactive mode and the minimum power in the active mode.

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The main effort of the research community is to reduce the power consumption of all different types of components in the base station by improving the adopted technologies (e.g. [5],[5],[6]). Some other approaches aim at improving the network deployment (e.g.,[7]) as well. However, since the possible gain on the energy efficiency is bounded by the baseline power consumption of active base stations, one has to recur to other approaches in order to radically change the power profile of the network.

The best possible consumption profile of an energy management strategy is a power consumption of the whole system linearly dependent on the traffic load, from very low with no traffic to maximum value with full load. If we were able to achieve this ideal behavior we could simply add any technology improvement and obtain a further incremental gain on the energy efficiency of the entire system.

In this perspective, energy system-level management strategies will be the only effective strategy in order to achieve a network energy profile that is proportional to traffic load. Unfortunately, there are severe constraints within the legacy cellular architecture used so far by all the wireless access technologies that hamper the way towards this ideal behavior and, more in general, prevent from reaching very large cuts of the energy consumption.

The cellular architecture of wireless access networks is based on the concept of full coverage of the service area, which guarantees that terminals located at any point in the area can request a channel and access the network at any time. The design of the cell layout is strongly influenced by several factors: transmission powers, propagation conditions, but also traffic distribution. Where the traffic density is low, commonly adopted cell patterns are usually driven by the full-coverage constraint and coverage ranges of base stations tend to be totally exploited in order to reduce the number of deployed devices. In this scenario, the overlap among neighboring cells is limited to what is necessary for the mobility management. In areas, instead, where traffic is high, base station deployment is much denser in order to reduce cell size and increase the available access capacity per unit area. As a consequence, the cellular layout achieves a redundant coverage, each location in the service area may be served by multiple base stations.

In this scenario, it is evident that "switch-off" energy management procedures in traditional cellular architectures

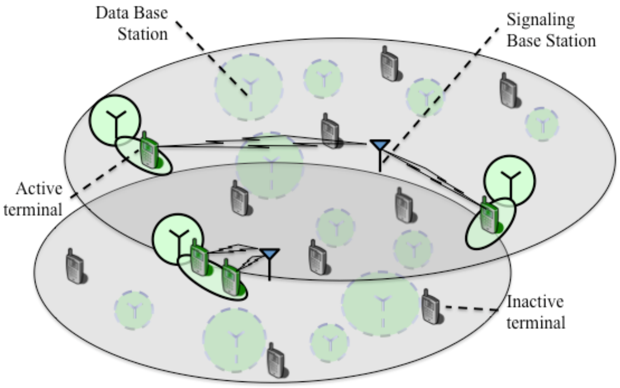

Fig. 1 The Cell on-Demand approach.

can only exploit the redundant coverage of the network that is used to provide enough capacity when peak traffic is high, but only during the time period when the traffic is low. However, since full coverage must be ensured at all time, a non-negligible number of network devices can never be switched off, even if there is no active user under their service areas.

Typical energy savings with available energy management strategies within the current cellular technology context fall in the range of 20%-40%, depending on the considered traffic profiles and network layouts, e.g. [9],[2],[10],[11]. Paradoxically, these saving percentages may even reduce in the next generation cellular networks. Indeed, it is commonly accepted that these new architectures will consist of micro-cellular layouts which can reduce the nominal consumption. The coverage efficiency, namely, energy per covered area, of micro base stations is much higher than that of macro base stations. However, since micro cells provide high capacity with limited coverage overlap, they leave little room for energy management since almost all cells are essential for guaranteeing full coverage.

In this paper we present a new cellular network paradigm which is currently studied in the Beyond Cellular Green Generation (BCG^2) within the GreenTouch Consortium[1].

The new paradigm is presented in Section II. In Section III, we propose some models to predict the behavior of the proposed system and estimate the potential energy saving. Numerical results are presented and discussed in Section IV, while Section V concludes the paper with comments and research directions.

II. CELL ON-DEMAND APPROACH

Our proposed cellular network paradigm works on a different network architecture that supports efficient network adaptation and still satisfies the constraint of “always connected”. The rational behind the approach stems from the consideration that not much information needs to be exchanged in order to enable the “always connected” behavior. One has only to provide signaling information to allow the mobile to be paged and to reach the network when it is desired. Consequently, an architecture with better performance in term of energy consumption is an architecture where signaling and data networks are separated.

The separation brings two immediate advantages. First, base stations for data communication can be switched off as soon as no user is active under their coverage. Second, signaling base stations, which are only in charge of providing the “always connected” signaling service, can be simplified, they can be designed for low-data rates and long-range transmissions. That is clearly more efficient than the current mixing between data and signaling transmissions.

At the areas where no user is currently active, no signal from any data base station is provided in order to avoid the waste of radio resources. Fig. 1 shows the signaling nodes that allow coverage for the non-active spots in case some user becomes active. As soon as a user becomes active, he can communicate to the signaling base station his request and the system can provide data connectivity by turning on a data base station that can serve the user. Ideally, the user is “spotlighted” with the data service only where and when it is needed.

The system rationale is that on one hand, the radio for the access points is designed for high data rates and the network is flexible and smart. On the other hand, the signaling network is fixed in order to guarantee the coverage in the whole area and the radio devices are designed to be energy efficient for low data rates and long-range transmissions.

Clearly, data and signaling separation is not new in the networking literature, however in cellular networks it brings very important consequences which lead to a considerable amount of interesting technical issues. They arise from the interaction between signaling and data networks that calls for a renovated research effort in mobile networks.

The first issue arises when considering the information on the service requests from mobile users. Traditionally, the user terminal issues service requests to the same base station that will serve the request by allocating internal resources. In the proposed scenario, due to the signaling and data base station separation, a much richer context must be provided to the network. The user terminal location is needed at least to identify the data base station to be turned on, but it is not enough. The channel condition is necessary as well, as propagation impairments may cause poor radio channel conditions. However, the channel cannot be estimated a-priori, because the data base station can be inactive before the user arrival. This calls for clever estimation and prediction techniques.

Also the resource allocation is more difficult than in the traditional cellular network architecture. Even the identification of the best data base station to serve a request is not an easy task, it involves service and technology constraints, but, in particular, a trade-off between energy consumption and performance. If the base station is already active, the incremental cost for serving an additional user is usually much smaller than in case it needs to be reactivated, however, it may not be the base station able to provide the best performance to the user.

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[1] http://www.greentouch.org

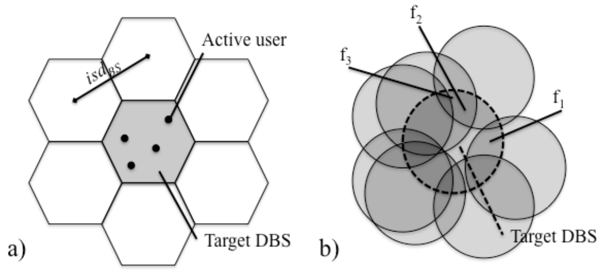

Fig. 2 Examples of the two analytical models. Poisson model, (a), and Integral Geometry model, (b).

Among the hardest technical challenges, there are for sure the design of an extremely energy efficient radio technology for the signaling access and the study of new network planning strategies which jointly consider both deployment and operational costs.

Together with the above-mentioned challenges, the proposed new architecture does not only bring strong energy efficiency advantages, but also it simplifies the management of heterogeneous wireless access technologies, as it reverses the classical approach to network selection. The user terminal is not longer in charge of independently selecting the base station to which associate to, but it is the network which "exposes" the best base station to the terminal by turning it on.

III. PERFORMANCE MODELS

In order to understand the potential energy saving provided by the radical architectural shift of the Cell on-Demand (CoD) approach, we have developed two statistical models. They focus on Data Base Stations (DBSs), since we believe Signaling Base Stations will have a limited impact on the total energy consumption of CoD network.

Both models assume Mobile Terminals (MTs) distributed over an area according to a 2-D Poisson process with density λ_{MT}. Data Base Stations deployment is assumed to be 2-D Poisson distributed as well, with density λ_{BS}, or, equivalently, with average inter-site distance isd_{BS}. The goal of these models is to compute the DBS activation probability β, which can be interpreted as the percentage of the number of active DBSs with respect to the total number of deployed ones or, alternatively, the percentage of the time a DBS is active.

The first model, named *Poisson model*, considers the service area of each DBS A_S (show in Fig. 2a), which can be approximately computed using the hexagonal-cell model as $A_s \cong \frac{\sqrt{3}}{2} isd_{BS}^2$, therefore the probability β can be computed as the probability that at least one MT is located in the service area of a given DBS:

$$\beta = 1 - e^{\lambda_{MT} A_S} \tag{1}$$

The second model, named *Integral Geometry model*, leverages the fact that the coverage area of each DBS, namely, the area where MT can decode transmissions from DBS, is larger than the service area, the area where DBS reference signal is received as the strongest. In this case, the overlap with adjacent cells can be used to save energy. Indeed, a DBS can be turned off when either no user is in its service area, or when users in its service area can be covered by a neighboring active DBS, thanks to the coverage area overlap. This overlap effect can be modeled using Integral Geometry techniques.

We consider a "target" DBS with circular coverage area A_C, radius R_C and perimeter P_C. This DBS can have N adjacent DBSs whose coverage areas intersect the target coverage area, as shown in Fig. 2b. The DBSs are randomly distributed, as explained at the beginning of the section, with coverage area, radius and perimeter equal to the ones of the target DBS.

The fraction $f_k \in [0,1]$ of the coverage area of the target DBS covered by exactly k adjacent DBSs can be computed using Integral Geometry [12] as:

$$f_k = \frac{\binom{N}{k} (2\pi A_C)^k \left(2\pi A_C + P_C^2\right)^{N-k}}{\left(2\pi(2A_C) + P_C^2\right)^N}. \tag{2}$$

Note that this value does not depend on the shape of the coverage area, provided it is convex, but only on its area and perimeter.

Using Eq. (2), the probability P_k that at least a user lies in the fraction of target coverage area which is covered by k adjacent DBSs can be computed, similarly to the first model, as:

$$P_k = 1 - e^{-\lambda_{MT} f_k A_C}. \tag{3}$$

The final activation probability β can be computed by solving the following equation, where we applied the assumption of homogeneous scenario, which is equivalent to force the activation probability to be the same for every DBS:

$$\beta = P_0 + \tag{4}$$

$$+ (1-P_0) P_1 (1-\beta) + \tag{5}$$

$$+ (1-P_0)(1-P_1) P_2 (1-\beta)^2 + \tag{6}$$

$$+ \rightleftharpoons =$$

$$= P_0 + (1-P_0) P_1 (1-\beta) + (1-P_0) \sum_{i=2}^{N} \left(\prod_{n=1}^{i-1} (1-P_n) \right) P_i (1-\beta)^i \tag{7}$$

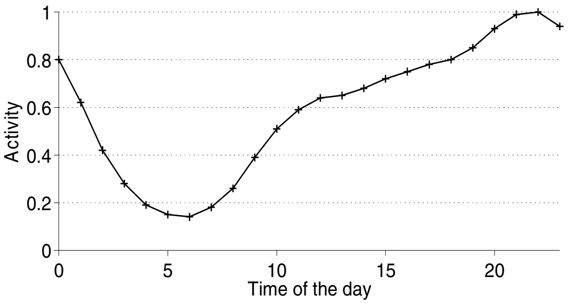

Fig. 3 Daily data traffic profile.

The formula (4)-(7) computes the DBS activation probability as the sum of the probabilities of the following disjoint events: there is at least one user in the fraction of the coverage area not covered by any adjacent DBS (Eq. (4)); there are no users in the area covered by no adjacent DBS, but there is at least one user in the area covered by one adjacent DBS and the adjacent DBS is switched off (Eq. (5)); there are no users both in the area covered by no adjacent DBS and in the area covered by 1 adjacent DBS, but there is at least one user in the area covered by 2 adjacent DBSs and both DBSs are switched off (Eq. (6)); etc.

IV. NUMERICAL RESULTS

The accuracy of the models and the achievable energy saving with CoD approach have been tested in the following scenario. We have considered the typical daily data traffic profile in Fig. 3 [13] while DBS types and relative parameters are shown in TABLE I.

TABLE I. DATA BASE STATION TYPES AND RELATIVE PARAMETERS

DBS type	**macro**	**micro**	**pico**
isd_{BS} [m]	500	150	50
λ_{BS} [DBS/km^2]	14	51	462
ON Power [W]	1000.0	144.6	14.7
Sleep Power [W]	0.1	0.1	0.1
Range R_C [m]	1500	1000	400

We have analyzed the potential energy saving within three network setups which are characterized by a traffic level and a network configuration which can be assumed to be similar to the 2010 parameters and the 2015 and 2020 predictions. Namely, we have considered a low-traffic area with density *6 Mbps/km^2* served by macro DBSs (2010 scenario), a mid-traffic area with density *30 Mbps/km^2* served 40% by macro DBSs and 60% by micro DBSs (2015 scenario), and high-traffic area with density *120 Mbps/km^2* served 10% by macro DBSs, 60% by micro DBSs and 30% by pico DBSs (2020 scenario). We fix the per-user traffic demand equal to *2 Mbps*.

In order to verify the accuracy of the model, we have compared the model predictions against results from a Monte Carlo simulator. The simulator generates several instances of the service area by deploying DBSs and MTs according to the given distributions. A covering heuristic assigns MTs to the smallest number of DBSs as possible, and then, unloaded DBSs are switched off. The activation probability is the average ratio among active and deployed DBSs. The instance generation and the heuristic algorithm are repeated for each time of the day in the profile of Fig. 3.

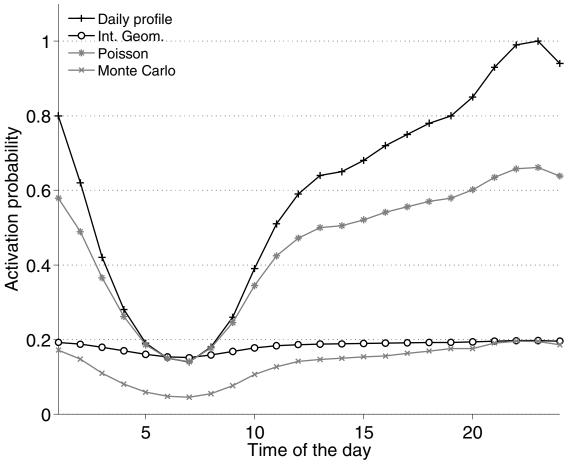

Fig. 4 Daily traffic profile plotted against DBS activation probabilities in 2010 scenario.

Fig. 4 shows the daily traffic profile plotted along with the activation probabilities computed with the models and the Monte Carlo simulator. Note how the overlap among cells allows switching off many DBSs, making the *Poisson model* overestimate the practical activation probability computed by the simulator.

The gap between the results of the *Integral Geometry model* and the ones of the simulator is mainly due to the active DBS selection process. While in the Integral Geometry model the activation probabilities among nearby DBSs are assumed to be independent (see Eq. (7)), in the Monte Carlo simulator they are not. Indeed, since the simulator includes an optimization phase to minimize the number of active DBSs, the activation probabilities of DBSs close to already active DBSs are smaller, in particular when the traffic is low. Nevertheless, the Integral Geometry model appears to give a correct, although conservative, estimation of the behavior of the CoD network. The results from both models over 2015 and 2020 scenarios are shown in Fig. 5.

To evaluate the energy saving of CoD networks with

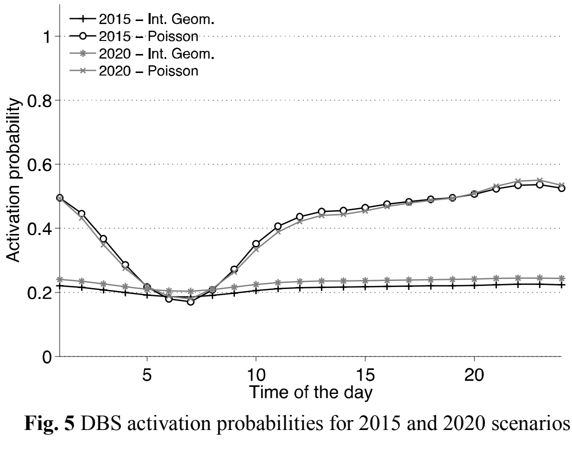

Fig. 5 DBS activation probabilities for 2015 and 2020 scenarios.

respect to legacy systems in different scenarios and with different traffic levels, we use *energy-per-bit [Joule/bit]* as energy efficiency performance figure. This value can be computed as the ratio between the energy required by DBSs in their activity for the entire day and the total amount of traffic volume served within the same day.

TABLE II. shows achievable energy efficiencies with both CoD and legacy approaches. CoD energy efficiencies have been computed using the Integral Geometry model, while legacy energy efficiencies consider all the deployed DBSs always active.

The CoD approach allows achieving much higher energy efficiencies, reducing the amount of energy needed to exchange information bits. Compared to the current situation, legacy 2010 scenario, CoD networks can potentially lead to a 2020 scenario where cellular networks can be operated more than 50 times more efficiently. The use of CoD networks in the 2020 scenario allows to achieve an energy efficiency more than four times higher than one with the legacy approach.

TABLE II. ENERGY EFFICIENCY VALUES FOR LEGACY AND BCG CELLLULAR NETWORKS

Efficiency [J/Mbit]	**2010**	**2015**	**2020**
Legacy	1295.6	353.44	97.49
CoD	221.14	75.23	22.72

V. CONCLUSION

This paper discusses a new cellular network paradigm based on the separation between data and signaling networks. It analyzes its potential energy saving over traditional approaches throughout analytical models.

We believe that this way of thinking wireless networks is one of the most promising approach to achieve a significant reduction on the energy consumption of networks as a whole and still be able to cope with high quality of service requirements.

Several important challenging issues have been presented as well. Context management, resource allocation, signaling radio interface design, and network planning strategies are some of the interesting research directions opened by the Cell on-Demand paradigm.

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