Planning for Energy-Aware Wireless Networks

Silvia Boiardi, Antonio Capone, Brunilde Sansò

***Abstract*—The paper proposes a fundamental modeling and optimization framework for the planning of energy-aware wireless networks. The key idea is that, in order to produce an energy-efficient network operation, energy awareness should be introduced at the planning stages. Cellular as well as mesh wireless examples are considered.**

I. Introduction

The rapid spread of mobile telecommunications has pushed not only for the design of new advanced systems, but also for the development of mathematical models and optimization algorithms to support planning and management decisions. Formal optimization methods improve the way the limited resources (e.g., radio spectrum, base stations, antennas, backhauling) are used, and enhance the service quality (e.g., throughput, delay, service accessibility). An important optimization problem is the general *coverage planning*, which consists in determining where to locate the radio access devices and selecting their configuration so that every client in a given area is served. This is usually the main problem addressed by the optimization modules included within mobile operators' software tools for radio propagation estimation and network planning. The typical goal is to minimize the total antenna installation cost while guaranteeing service coverage and quality. A nice view that helps understand the importance of network design optimization for system performance is presented in [1], where some modeling approaches for wireless network planning problem are analyzed. [2] presents an optimization framework for access station location and configuration selection in real size cellular networks, while [3] tackles the network deployment from the Wireless Local Area Network (WLAN) perspective. We refer the reader to the references of the cited papers for more examples.

This paper approaches the wireless network planning from a very different and novel perspective that accounts for *energy efficiency*. In recent years, the rising demand for pervasive information access has in fact underlined the growing ICT power consumption and global warming impact. Almost 50% of the power consumed by the telecommunication industry is due to the network operation (including WLANs, LANs, mobile and fixed line systems). Also, Wireless Access Networks (WANs) are pointed out as the most energy hungry component of the mobile radio segment, being responsible for over 80% of its power absorption [4]. As a consequence, *green networking* has emerged as a new way to design and manage communication networks to reduce power consumption.

Focusing on current mobile access networks, major technical drawbacks have been identified. First, WANs are *over-provisioned* since they are developed to satisfy service and quality requirements in peak traffic conditions. Second, the efforts toward energy awareness come often at the price of a worsening of the QoS, making the analysis of the *trade-off between performance and energy efficiency* a primary issue. There have been some attempts to consider the energy-aware management of wireless networks by first planning a traditional network and then optimizing its power management performance (see Section II). In this article, we convey the new and fundamental idea that energy awareness must be *incorporated at the network planning stages*. Our aim is to demonstrate that the resulting network topology and its operation are different than if planning was carried out in a traditional fashion, leaving the energy management optimization at a later stage. The proposed approach is based on the fact that, when power management is considered, the level of *flexibility* provided by the network topology is essential to adapt the system capacity to the varying traffic load by turning on and off unused access stations.

The framework was applied to both *Cellular Networks* (CNs) and *Wireless Mesh Networks* (WMNs). In what follows, after a brief review of the green network design and management techniques proposed in the literature, we introduce the philosophy underlying the so-called JPEM (Joint Planning and Energy Management) problem. Then, the considered mobile systems are described, underlining the characteristics which make them good candidates to illustrate our JPEM approach. Also, some

Silvia Boiardi is with the Department of Electronics and Information of the *Politecnico di Milano*, Italy, and with the Départment de Génie Électrique of the *École Polytechnique de Montréal*, Canada. Antonio Capone is with the Department of Electronics and Information of the *Politecnico di Milano*, Italy. Brunilde Sansò is with the Départment de Génie Électrique of the *École Polytechnique de Montréal*, Canada.

details regarding the optimization model formulation and its possible variations are presented, as well as the adopted resolution approach and some example results. Our final remarks conclude the paper.

II. Energy efficiency in wireless networks

In recent years, there has been a lot of work on power efficiency in wireless networks. Three macro areas can be identified as the main focus of the research community:

- *Energy-aware network design*, involving issues as the deployment of heterogeneous networks, the use of relays and cooperative communications;
- *Energy-aware network management*, including, for instance, efficient routing techniques able to perform traffic aggregation on a subset of links and devices, cell switch-off, transmission rate switch and multi-RAT (Radio Access Technology) coordination;
- *Energy-aware radio technologies and hardware*, consisting of methods to, among others, improve power amplifiers efficiency (responsible alone for more than half of the access device power consumption), deactivate device components and decrease the energy consumption of spacial diversity techniques.

Excellent surveys which extensively treat those and other energy efficiency topics can be found in [5] and [6].

Being this paper centered on network planning and management and not energy-efficient radio technologies and components, we address the interested reader to the cited papers and their references for more information. Regarding the network design research area, different studies on energy-aware cellular networks tackle the efficiency of a radio coverage obtained with the deployment of macro and micro cells. In [7], for example, the authors compare the power efficiency of large vs. small cell deployments on a service area using two performance indicators: the energy consumption ratio, defined as the energy per delivered information bit, and the energy consumption gain, quantifying the possible savings that can be obtained by using small cells instead of big ones. [8] evaluates the benefits of a joint deployment of macro cells and residential femtocells showing that, for high user data rates, a mixed deployment can save up to 60% of the annual energy consumption of the network. A similar analysis in [9] considers an area where uniformly spread users are served by a macro cell system and estimate the impact of introducing a certain number of micro access stations in each cell. Their results show that, in case of peak traffic scenarios, the power savings are moderate and depend on the offset power of the access devices. A non uniform user distribution is used in [10], where the problem studied is that of finding the number and the location of micro stations in order to minimize the long term energy consumption. The results are compared to the case of a single macro cell serving the total number of users, and great power savings are shown for the tested scenarios.

In the research area of energy-efficient network management, the field studying new device switch-off procedures constitutes one of the most beaten track. The minimum power consumption of a Base Station (BS) can be significant, due to processing circuits and air conditioning systems. Thus, an effective cell energy management must try to turn off as many devices as possible. Another method is cell zooming, that allows cell size variations to guarantee an effective area coverage while limiting the energetic waste.

Summarizing, most green techniques are related to power control systems for coverage and energy consumption optimization (see the references in [4]). However, up to now only a few papers proposed a practical approach to address the *energy-aware operation problem in relation to the network deployment*. An example comes from [11], where a two-stage greedy approach aims at installing and managing micro BSs over a previously deployed macro cell layer to upgrade the network capacity while limiting the capital expenses. Similarly, in [12] the authors use a genetic algorithm to design network topologies according to three different strategies: minimization of the number of BSs, of the consumed power or of both of them. A set of BSs in the total number of installed devices is then selected to be always on, while the remaining stations are managed to save power during off-peak periods.

An interesting, completely new approach to the architecture of mobile networks is currently being investigated by the BCG^2 (Beyond Cellular Green Generation) project of the GreenTouch initiative (www.greentouch.org), where the separation of signaling and data functions at the radio interface allows to increase flexibility in the use of radio resources and to turn it into higher energy efficiency [13].

III. The JPEM Framework

In Figure 1, a toy topology made of three cells is depicted. As it happens in real life, we assume that it will be deployed according to a minimum installation cost criterion. The black, bold profile circles represent the area coverage of the turned-on access stations, while thin profile circles stand for turned-off devices. Mobile

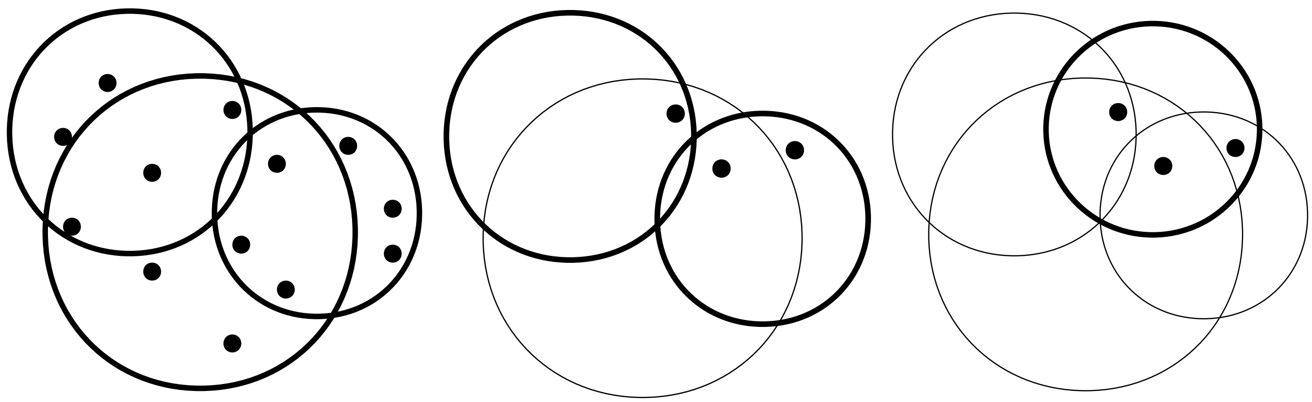


Fig. 1: Effect of flexibility on network operation management.

traffic is concentrated in traffic aggregators, called Test Points (TPs) and symbolized by black dots, which have to be served (i.e., lie in the coverage area of a switched-on device) at all times. Subfigures 1(a) and 1(b) report examples of network operation during high and low traffic load, respectively. As we can see in Subfigure 1(a), the number of active users during the peak period (say, for instance, around lunch time) requires all access devices to be turned on; on the other hand, Subfigure 1(b) shows that during the off-peak period (for instance, late at night), one BS can be turned off to save energy while the other two remain active to serve the user demand. So, in this case, the operational savings correspond to the power spared by switching off the biggest BS. Would it be possible to further decrease the energy consumption of the toy topology? Our answer to this question is represented in Subfigure 1(c), where we display the principle of the optimization framework we propose. Knowing the position of the TPs and the variation of their requirement during the day, we exploit this information to deploy a network topology which will be able to better take advantage of the demand fluctuation. If the future operation management is considered during the planning stage as in 1(c), an additional BS should be installed at the cost of a slight increase in installation expenses, so as to be able to switch off a higher number of network devices in off-peak periods (in the picture, three turned-off BSs instead of just one). Our framework philosophy is that, by applying an energy-aware management mechanism on a topology *specifically designed to be power efficient*, the power savings can be highly increased. Therefore, differently from previous work on energy-awareness in wireless networks, we do not assume a pre-existing infrastructure; conversely, to improve the power management effectiveness, we argue that networks should be designed considering the next energy efficiency requirements in the operation phase. The topologies resulting from the application of our method demonstrate our assertions, showing that a real energy-efficient operation strongly depends on the network coverage structure and on the radio planning decisions taken during the design phase.

The JPEM modeling framework is based on exploiting the variety in the types of Cellular Network access stations and the dynamic features of Wireless Mesh Networks to design a system that is not only cost-effective, but also follows the demand in an energy-efficient way during normal operation. To the best of our knowledge, no previous modeling exist in which energy management is incorporated into wireless network planning optimization. The operating principle of our framework is represented in Figure 2, where the proposed problem is depicted as a box having some network information as entry parameters. Such elements constitute the basic information required as input by the JPEM framework: TP and potential BS locations are fixed and known a priori, as well as the estimation of daily traffic patterns and the traffic requirements in the considered time periods. Also, the types and features (power consumption, coverage, transmitted power, installation cost) of the available network devices are specified. Different factors are decisive in the network topology creation. The main objective of the JPEM is to minimize at the same time the installation costs (Capital Expenditures, or *CapEx*), in order to limit the initial investments of the network operator, and the energy spent in the operation phase (Operational Expenditures, or *OpEx*), so as to guarantee a green, power-aware network behavior. Nonetheless, the complete coverage of the area as well as the satisfaction of the users demand have to be guaranteed at all times. Given these guiding factors, the outcome of the proposed framework consists in

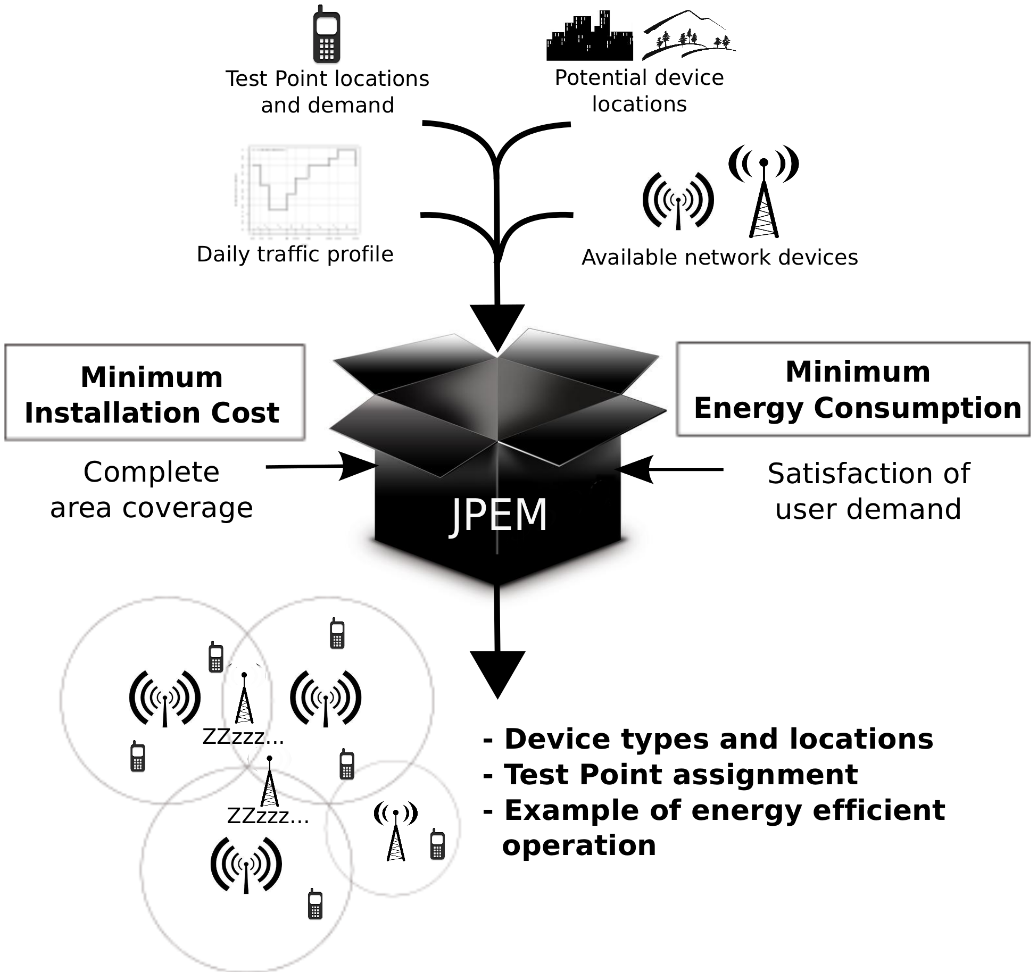


Fig. 2: Operating principle of the JPEM framework.

an heterogeneous network deployment, where different types of access stations are employed to provide the topology with the flexibility required by a truly energy-efficient operation. Test Points are assigned to the most convenient access station, according to a distance or signal strength criterion. Also, the JPEM model produces as outcome an example of energy-aware operation of the chosen topology where, in line with the daily traffic pattern, unused BSs are switched off to reduce the power consumption.

IV. Examples

Two examples illustrate how the JPEM framework can be used to design energy-aware wireless networks and to analyze the trade-off between installation cost and power efficiency. They are based on Cellular Networks, which are the most important and popular wireless access technologies, and Wireless Mesh Networks, that add the issue of multi-hop coverage.

Cellular Networks

The reference system for the Cellular Network model can be described as follows. Given an area to be served, a set of *Traffic* Test Points (TTPs) representing traffic centroids is picked out. Besides, a new set of *Coverage* Test Points (CTPs) is introduced. Differently from the former, they do not produce any traffic; rather, they are disposed on a regular grid overlaying the area to ensure the total coverage in the dimensioning phase even in the off-traffic regions. Together with the TPs, a set of available Candidate Sites (CSs) where the BSs are allowed to be positioned is identified. Since the signal propagation between any pair of TP and CS can be measured or evaluated, the subset of TPs reached by a sufficiently strong signal is assumed to be known for a BS installed in any CS. In particular, we calculated the median path loss by mean of the COST-231 Hata model. Shadowing and fast fading effects are neglected, which is a common assumption in network design modeling. The framework is however general enough to accept other types of propagation models.

To account for traffic load fluctuation typical of real networks, a *daily pattern* reflecting mobile user habits and representing the active user percentage at each time is considered. The day is then split in periods where the TTP's traffic demand, given by a random value uniformly chosen between a minimum and maximum values, is considered unchanged. Alternatively, TTPs can be in idle state if no traffic is requested. Note that long term demand variations are not taken into account. However, the method is applicable independently of the characteristics of the traffic changes.

Finally, according to the key idea that flexibility is a fundamental characteristic for a power-efficient network, we decided to exploit the diversity offered by the market in terms of cell dimension. Therefore, several *BS configurations* are made available, having different installation cost, capacity, consumed power, transmitted power and so covering ray.

Wireless Mesh Networks

Wireless Mesh Networks (WMNs) are a type of dynamically self-organized and self-configured communication infrastructures that offer wireless connectivity through the use of cheap and low transmission power devices. Each node in WMNs works as a host as well as a router, forwarding packets on behalf of other nodes that may not be in the transmission range of their destinations. Thus, the nodes automatically establish mesh connectivity among themselves, creating in effect an ad-hoc network.

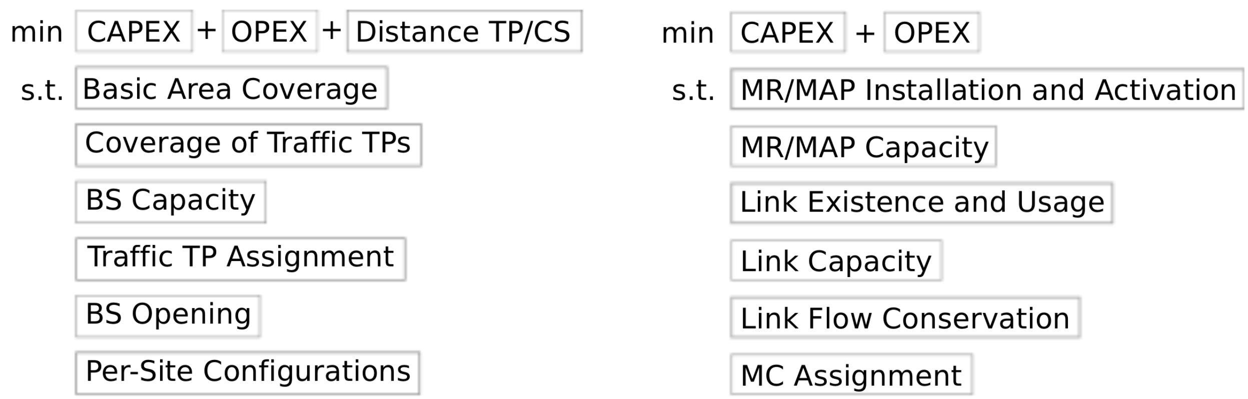
In the JPEM framework, the mesh reference system is made up of Mesh Routers (MRs) and Mesh Access Points (MAPs), which communicate through dedicated wireless channels with other access devices residing in their coverage radius. Routers and gateways (generally referred to as BSs) can be installed only in predetermined CSs. Both kinds of BSs provide network access to mesh users; in addition, MAPs, representing only a restricted set of routers, behave as gateways toward the wired backbone, enabling the integration of WMNs with other networks (typically the Internet). Concerning Mesh Clients (MCs), they can be assigned to only one BS, being the closest active one, and are connected to the Internet through multi-hop communications.

The day is also divided in time periods during which Mesh Clients require a fixed amount of traffic. Again, the traffic profile is defined as the percentage of active users typical of every time interval, but in this case two different congestion levels are considered. In addition to the *standard* profile, a *busy* profile has been tested, characterized by a higher value of the minimum user demand.

JPEM Implementation

Let us analyze first the case of Cellular Networks. From the perspective of power consumption per unit of covered area, a network topology based on small and low-power cells is generally considered more convenient than one deploying only high-power cells. However, since per-site fixed installation expenses tend to prevail, a small cell topology involves high deployment costs. Now, considering that active users must be provided with network service at all time, a cellular system only based on small cells may not be the most energy efficient option; in this case, all cells would be necessary to provide full area coverage and none of them could be switched off during low-traffic periods. Conversely, the availability of different network configurations, employing a set of BSs with different capacity and energy consumption, is what we point out as the key issue to enable effective power management strategies. Such a topology can be obtained only if network planning and operation management are incorporated in the same optimization framework.

The JPEM for Cellular Networks (JPEM-CNs) is a binary linear programming model to *jointly* plan and manage Cellular Networks. The schematic of JPEM-CNs is reported in Figure 3(a), while we refer the reader to [4] for the mathematical formulation and further details. Through three sets of binary decision variables, identifying i) the BS configurations installed in the selected CSs, ii) the state (on/off) of every installed BS and iii) the assignment of TTPs to one of the turned-on BSs, the model attempts to minimize an objective function without violating a set of constraints on the variable values. The objective function can be broken down in two main terms. The first one, namely *CapEx term*, accounts for the installation cost of the chosen devices; the *OpEx term*, on the other hand, considers the energy consumption in the operational setting, summing up the power required by each BS during the time periods in which it is turned on. In the cellular context, a third term *Distance TP/CS*, to promote the assignment of TPs to the most convenient access device (in terms of distance or signal strength) was introduced in the objective function. Interestingly, that term was active only with GSM technology, whereas it did not have any impact for LTE networks. In order to fairly compare the OpEx term, consisting in a measure of power consumption, with the CapEx one, consisting in a high, one-time cost, the energy related expenses are calculated over the network lifetime (assumed to be 14 years). The trade-off between CapEx and OpEx is adjusted by a weight parameter β, which varies from 0 to any big integer



(a) Model for CNs

(b) Model for WMNs

Fig. 3: JPEM implementation for Cellular and Wireless Mesh Networks.

value (typically between 1 and 10). When CapEx are the only costs to be minimized, the value of β is set to 0 to exclude the OpEx term from the objective function: this way, the resulting network installs the minimum cost topology. On the other hand, by choosing higher values for β and introducing the OpEx in the objective function, the model is pushed by the energy management mechanism to reduce at the same time capital and operational expenses. The JPEM-CN framework seeks to minimize the objective function provided that some fundamental constraints are respected. Commonly used in network dimensioning problems, *coverage constraints* provide a basic and constant coverage of the service area, guaranteeing that all the TPs, being Coverage or Traffic ones, lay in the coverage ray of at least one switched-on BS (coverage constraints can be relaxed when architecture based on signaling and data separation [13] are considered). *Assignment constraints* ensure that every TTP is served by one BS in each time period. Traffic TPs in idle state (i.e., that are not requesting traffic in a certain time interval) are as well assigned to a BS, but they do not contribute to fill its capacity. Also note that for Coverage TPs, which never provide traffic, the explicit assignment to an access station is not required. Each access station can route the traffic of a limited number of Traffic TPs, depending on its capacity and therefore on the chosen configuration. So, *capacity constraints* guarantee that active BSs are able to satisfy the traffic demand of the assigned TTPs at any time. Other sets of constraints are introduced in the model formulation, relating the values of different decision variables and fixing their binary domain.

The joint framework for Wireless Mesh Networks (JPEM-WMNs)(see Figure 3(b) for a schematic and [14] for the complete formulation) utilizes the same set of decision variables as JPEM-CNs: device installation, activation and user assignment. Furthermore, new variables are introduced to keep track of the wireless link existence and usage between MRs, MAPs and the Internet. Once again, the objective function represents the trade-off between the CapEx, corresponding to the installation costs of MRs and MAPs, and the OpEx, calculated as the power expenses of the active devices in any time interval. In this case, the parameter δ weights the relative importance of the two terms by assuming values in the [0,1] interval. Starting from $\delta = 1$, when just capital expenses are minimized, we gradually reached the opposite case of $\delta = 0$ (minimization of power costs only) after evaluating intermediate values. Due to the difference between cellular and mesh system structures, in addition to the well-known sets of *coverage*, *assignment* and *capacity constraints*, different sets of *link* and *traffic flow constraints* are added to the WMN formulation.

V. Main results

In order to illustrate the advantages in energy savings achievable by the new planning framework, we show two examples of CN and WMN application. The results are obtained by solving the described linear binary models with CPLEX branch and bound solver, which produced optimality gaps below 5%. Resolution time varied from a few seconds to about half an hour.

Tables I and II report the total CapEx required by the network deployment and the expected OpEx, calculated over a fourteen-year network lifetime by considering an energy-aware network operation management. Both values are expressed in thousands of Euro, while we assume an energy cost for business users of 0.2 Euro/kWh. The percentages in parenthesis show the CapEx increase and the OpEx reduction with respect to the minimum installation cost topology where no operation management is

TABLE I: Results from CN Scenario nr.1 with different values of β.

CN Scenario nr.1

	$\beta = 0$ (two-step)	$\beta = 1$ (joint)	$\beta = 10$ (joint)
CapEx (k€)	56	62 *(+11%)*	66 *(+18%)*
OpEx (k€, 14 years)	39 ***(-7%)***	19 ***(-55%)***	17 ***(-60%)***
Installed BSs	18	17	21
BS Type	Macro - 1 Micro - 1 Pico - 16	Macro - 0 Micro - 5 Pico - 12	Macro - 0 Micro - 5 Pico - 16

TABLE II: Results from WMN "Large" Scenario with different values of δ.

WMN "Large" Scenario

	$\delta = 1$ (two-step)	$\delta = 0.5$ (joint)	$\delta = 0.1$ (joint)
CapEx (k€)	9.6	10 *(+4%)*	12.4 *(+29%)*
OpEx (k€, 14 years)	15.6 ***(-9%)***	13.5 ***(-21%)***	13.1 ***(-23%)***
Installed MRs	44	46	50
Installed MAPs	2	2	6

performed. The next entries represent the number and type of installed BSs, being macro, micro or pico cells in the Cellular Network case or MRs and MAPs in the Wireless Mesh Network one.

Let us first report Table I, where the most important results for a Long Term Evolution (LTE) cellular system scenario are displayed. The service area is a 4 km^2 square, over which 40 CSs, 121 Coverage TPs and 30 Traffic TPs are located. Each traffic demand is a random value uniformly chosen between 20 and 40 Mb/s. The first column $\beta = 0$ represents a Cellular Network deployment based on the minimum CapEx network planning. Running costs are not taken into account during the design phase; however, to fairly evaluate our joint framework results, we *separately* optimized the network operation by applying an energy-aware management to the topology. Conversely, $\beta = 1$ and $\beta = 10$ correspond to the case of *joint* design and management optimization, where the value of the weight parameter symbolizes the relative importance of the OpEx term with respect to the CapEx one in the model objective function. The most important information included in the table regards the variations in the deployed network when the two-step or joint framework are adopted. By increasing the value of β, and so introducing energy-awareness in network planning, different types and numbers of BSs are installed. In particular, a higher number of medium or small BSs tend to be preferred to macro cells, which have high installation cost and power requirements. Also, from an energy point of view, macro BSs can hardly be turned off to save power during off-peak periods due to their large coverage radius. It appears straightforward that, when we allow the joint framework to account for the network energy consumption at the planning stage, great energy savings are enabled at the cost of a modest increase in CapEx. For instance, with easy calculations we find that when the trade-off parameter is set to 1, the extra capital investment, corresponding to 6000 €, can be recovered in slightly more than four years from the savings in network operation, amounting to 1450 € per year.

The same observations made for Cellular Networks apply to the Wireless Mesh Network instance reported in Table II. Here, when the trade-off parameter δ decreases, the proposed optimization model is pushed to optimize the network topology and operation in a joint way. On the other hand, if δ equals 1, the less expensive topology from the CapEx perspective is installed and an energy-aware management mechanism is carried out in a second stage. The "Large" WMN scenario displayed in the table includes 240 MCs, requesting a traffic between 1 and 10 Mb/s, and 64 CSs placed over a square area with side 2.5 km. As for Cellular Networks, we notice that a growing number of routers (MRs) is deployed when the operational savings assume more importance than the minimization of the CapEx. Also, when $\delta = 0.1$, four additional MAPs are selected: the power savings are further increased by adding Internet access points, this way limiting the number of hops (i.e., active MRs) necessary for the MC's traffic to reach its destination. Yet again, the OpEx saving percentages confirm the soundness of our framework. However, in this case, we note less striking results due to the fact that WMNs present a limited choice in the device selection, allowing just one configuration of router and one of access point to be deployed. This aspect validates further our initial claim that the network flexibility represents the most important element to enable an effective energy-efficient network behavior.

Results from different test scenarios and interesting framework variations (the relaxation of the total area coverage constraints, among others) can be found in our previous work [4] and [14].

VI. Conclusions

Recent studies on green networking show that a network operation management that follows the traffic variations is one of the most useful instruments to reduce power consumption. In this paper we have shown that, by minimizing at the same time installation costs and operation power expenses, networks are designed for a more efficient energy-aware operation. With the help of some results from Cellular and Wireless Mesh Networks, we showed that an optimal topology from the installation cost point of view does not produce a network that is optimal for an energy-aware perspective. Conversely, the most power-efficient networks include different types of devices, providing the management mechanism with the required flexibility to adapt the network capacity to the user demand in different time periods.

Even though our proposal has specifically focused on energy-awareness on-off operation, it would still be valid for other type of operational issues, such as on-line antenna tilting, for instance [15]. In the end, our proposed framework can be summarized in adding and optimizing flexibility at the planning stages for a more efficient and cost-effective operation.

References

[1] A. Eisenblätter and H.-F. Geerdes. Wireless network design: Solution-oriented modeling and mathematical optimization. *Wireless Communications, IEEE*, 13(6):8–14, December 2006.

[2] S. Hurley. Planning effective cellular mobile radio networks. *Vehicular Technology, IEEE Transactions on*, 51(2):243–253, 2002.

[3] A. Eisenblätter, H.-F. Geerdes, J. Gross, O. Puñal, and J. Schweiger. A two-stage approach to WLAN planning: Detailed performance evaluation along the Pareto frontier. In *Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2010 Proceedings of the 8th International Symposium on*, pages 227–236, 2010.

[4] S. Boiardi, A. Capone, and B. Sansò. Radio planning of energy-aware cellular networks. *Computer Networks*, 57(13):2564 – 2577, 2013.

[5] D. Feng, C. Jiang, G. Lim, Jr. Cimini, L.J., G. Feng, and G.Y. Li. A survey of energy-efficient wireless communications. *Communications Surveys Tutorials, IEEE*, 15(1):167–178, 2013.

[6] A.P. Bianzino, C. Chaudet, D. Rossi, and J. Rougier. A survey of green networking research. *Communications Surveys Tutorials, IEEE*, 14(1):3–20, 2012.

[7] B. Badic, T. O'Farrell, P. Loskot, and J. He. Energy efficient radio access architectures for green radio: Large versus small cell size deployment. In *IEEE 70th VTC 2009-Fall*. IEEE.

[8] H. Claussen, L.T.W. Ho, and F. Pivit. Effects of joint macrocell and residential picocell deployment on the network energy efficiency. In *PIMRC 2008, IEEE 19th International Symposium on*.

[9] F. Richter, A.J. Fehske, and G.P. Fettweis. Energy efficiency aspects of base station deployment strategies for cellular networks. In *VTC '09*, 2009.

[10] P. Gonzalez-Brevis, J. Gondzio, Y. Fan, H.V. Poor, J. Thompson, I. Krikidis, and P.J. Chung. Base station location optimization for minimal energy consumption in wireless networks. In *Vehicular Technology Conference (VTC Spring), 2011 IEEE 73rd*.

[11] K. Son, E. Oh, and B. Krishnamachari. Energy-aware Hierarchical Cell Configuration: from Deployment to Operation. In *IEEE INFOCOM 2011 Workshop on Green Communications and Networking*, pages 289–294, 2011.

[12] L. Chiaraviglio, D. Ciullo, G. Koutitas, M. Meo, and L. Tassiulas. Energy-efficient planning and management of cellular networks. In *Wireless On-demand Network Systems and Services (WONS), 2012 9th Annual Conference on*, pages 159–166. IEEE, 2012.

[13] A. Capone, I. Filippini, B. Gloss, and U. Barth. Rethinking cellular system architecture for breaking current energy efficiency limits. In *Sustainable Internet and ICT for Sustainability (SustainIT), 2012*, pages 1–5. IEEE, 2012.

[14] S. Boiardi, A. Capone, and B. Sansò. Joint design and management of energy-aware mesh networks. *Ad Hoc Networks*, 10(7):1482 – 1496, 2012.

[15] D. Tipper, A. Rezgui, P. Krishnamurthy, and P. Pacharintanakul. Dimming cellular networks. In *IEEE GLOBECOM 2010*, pages 1–6, 2010.