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► **To cite this version:**

Hussein Al Haj Hassan, Loutfi Nuaymi, Alexander Pelov. Small Cells Deployment for Cost Reduction of Hybrid-Energy Cellular Networks. 84th IEEE Vehicular Technology Conference (VTC 2016 Fall), Sep 2016, Montréal, Canada. 10.1109/VTCFall.2016.7881226 . hal-01656071

HAL Id: hal-01656071

<https://hal.science/hal-01656071v1>

Submitted on 25 Apr 2024

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Small Cells Deployment for Cost Reduction of Hybrid-Energy Cellular Networks

Hussein Al Haj Hassan, Loutfi Nuaymi, Alexander Pelov

Departement Réseaux, Sécurité et Multimédia (RSM). Telecom Bretagne. Rennes, France

Email:firstname.lastname@telecom-bretagne.eu,

Abstract—Energy efficiency of wireless cellular networks is a well-studied domain and many proposals have been done following different amelioration paths. In this paper, we analyze the efficient use of small cells in a renewable energy context and considering real-time price of grid energy. This is typically the case when the mobile network is powered by the Smart Grid, in addition to renewable energy when available. We study the use of an algorithm adapted for this context and analyze it in simulation. Our results show that a suitable number or density of small cells gives better cost and energy savings performance, if we take grid energy cost into account.

Index Terms—Cellular networks, Smart Grid, Energy efficiency, Renewable energy, Small cells.

I. INTRODUCTION

Due to the tremendous increase in mobile traffic, cellular network operators are deploying more base stations (BSs) to satisfy the needs of their users [1]. However, this comes with an increase in the network Carbon emissions and energy consumption. The latter is of great importance knowing that the energy cost can reach more than 32% of the total operational cost [2].

Taking into account that the radio access part is responsible of 75% to 80% of the total network energy demand [3], optimizing the radio energetic performance is a prerequisite for an energy-efficient network. To achieve this, several techniques have been proposed such as radio resource management, BS switch-off and heterogeneous deployment [4]. Another path explicitly considers powering cellular BSs with renewable energy (RE) sources [5]. By using RE powered BSs, cellular network operators can further reduce the consumption of non-green energy and thus reduce their Carbon footprint.

In this paper, we analyze the usage of RE in powering heterogeneous cellular networks (Hetnets). In contrast to most of the existing studies that aims at maximizing the service availability or reducing non-green energy consumption [6], [7], [8], we aim at studying the effect of deploying small cells on the network energy cost in RE context while considering real-time price of grid energy.

The rest of the paper is structured as follows. We present the background and related work in Section II. We describe the system model and the problem formulation in Section III. The simulated algorithms are presented in Section IV. In Section V, results are presented and discussed before concluding in Section VI.

II. BACKGROUND AND RELATED WORK

The rising energy demand and Carbon footprint of cellular networks have stimulated the need for addressing their energy efficiency, and many strategies have been proposed for performing this [4], [9]. One possible strategy is adjusting the cell sizes of BSs to the traffic distribution using switching-off and cell-breathing schemes. Another strategy considers heterogeneous deployment of macro/small cells [10]. Small cells can enlarge the capacity of a macro cell deployment without a high increase of energy consumption, by avoiding the introduction of new macro BSs to extend coverage and availability.

Some of the recent works start taking explicitly into account the availability and the specificities of RE sources in the functioning of the cellular network infrastructure. For example, Piro et al. investigate the possible role of RE in the deployment and operation of the next generation cellular networks [11]. Their study shows that it is economically suitable and environmental friendly to use RE sources in powering BSs, and that these resources can serve as basis for new business models.

Furthermore, energy efficiency techniques have been exploited to increase the utilisation of RE. In [12], Han et al. propose to adjust the cell size and switch-off BSs based on the availability of RE. Radio resource allocation problem of a single BS, powered by RE and the power grid, is studied in [13]. Maximizing the number of accepted users in a 2-tier Hetnet solely powered by RE is tackled in [6], where adaptive user association based on RE availability is proposed. In [7], the authors study the availability of BSs in a k-tier Hetnets. A BS is considered available when it has enough RE to serve at least one user. In [8], the call completion problem of a two-tier Hetnets with energy harvesting BSs is tackled. Results show that macro BSs energy harvesting parameters have the dominant impact on the call completion probability. The problem of user association in Hetnets powered by RE and the power grid to reduce the grid power is studied in [14]. A distributed user-association scheme is proposed where the BS measures the traffic load and harvested energy, and advertise the BS energy-latency coefficient. The user selects the corresponding BS based on this coefficient.

The previous studies succeed in increasing the availability of service in case of stand-alone bases stations (powered only

by RE) and decreasing the grid energy consumption for hybrid energy BSs (powered by RE and the power grid). However, considering heterogeneous deployment in RE context and Smart Grid environment is rarely considered. In the Smart Grid environment, many parameters, such as electricity price or CO_2 release, vary with time and bring the need for new definition of RE utilization [15]. For example, in [16], we verify that the problems of reducing the energy operational cost and reducing the energy consumption are not identical when the price of energy varies through the day. Moreover, we found that significant cost reduction can be achieved even with low amount of generated RE.

In this paper, we extend our work in [16] by considering heterogeneous deployment in real-time price of grid energy. In particular, we consider the deployment of small cells due to their low energy demand, which is a big advantage in the context of RE powered cellular networks. For example, powering a femto BS needs less than $1m^2$ of solar panels as illustrated in [11]. Thus, it is interesting to study the effect of adding small cells on the energy behaviour of cellular networks knowing that small cells can be purely powered by RE.

III. SYSTEM MODEL AND PROBLEM FORMULATION

Figure 1 presents the system model. We consider a cellular network composed of N_m macro BSs and N_s small BSs serving a set of mobile users M . The macro BSs are located in a grid form and the small BSs follow Poisson point process distribution. The macro BSs are powered by RE sources and/or the power grid, while the small BSs are powered solely by RE sources. We consider that BSs are equipped with energy storage. The real-time price of grid energy is periodically sent by the grid. We consider an interval of time divided into p periods each of duration T . Harvested RE is stored in the storage and then allocated to each BS at instant t_i corresponding to the beginning of period T_i . We assume that BSs always have data to transmit.

The problem of minimizing the network's energy operational cost while considering real time price of grid energy can be expressed as follows:

$$\min(\sum_{b,i} Cost_{b,i}) \quad b \in [1, N_m] \quad (1)$$

subject to :

$$R_j \geq R_{j,thr} \quad \forall j \in M \quad (2)$$

$$\frac{\sum_j n_{j,b}}{n_{b,max}} \leq 1 \quad \forall b \in [1, N_m] \quad \text{or} \quad b \in [1, N_s] \quad (3)$$

$$E_{a,b,i} \leq E_{s,b,i} \quad b \in [1, N_m] \quad (4)$$

where all calculations refer to BS b and time slot i , $Cost_{b,i}$ is the grid energy cost of macro BSs (small BSs are solely powered by RE). $Cost_{b,i} = G_{b,i} \times Price_i$, $G_{b,i}$ is the grid energy consumed by macro BS b in period i , $Price_i$ is the grid energy unit price, R_j is the bit-rate of user j . The

achieved bit-rate depends on the user association. For a user j associated with BS b , the bit-rate is calculated following modified Shannon formula as applied in [17] and expressed in Equation 5.

$$R_{j,b} = n_{j,b} \times BW_{RB} \times BW_{eff} \times \log_2(1 + \frac{SINR_{j,b}}{SINR_{eff}}) \quad (5)$$

$n_{j,b}$ is the allocated resource blocks by the corresponding BS b to user j , BW_{RB} is the bandwidth of a resource block, BW_{eff} is the bandwidth efficiency, $SINR_{j,b}$ is the signal to interference plus noise ratio of the user j , $SINR_{j,b}$ is expressed as follows:

$$SINR_{j,b} = \frac{Pr_{j,b}}{N_{j,b} + I_{j,b}} \quad (6)$$

$Pr_{j,b}$ is power received by user j from BS b . $N_{j,b}$ is the thermal noise and is defined as:

$$N_{j,b} = K \times Tem \times n_{j,b} \times BW_{RB} \quad (7)$$

K is the Boltzmann constant, Tem is the temperature in Kelvin. $I_{j,b}$ is the interference and is calculated as the sum of the received power of the first tier of neighbor BSs. $SINR_{eff}$ is the SINR implementation efficiency of LTE. $R_{j,thr}$ is the minimal (threshold) bit-rate guaranteeing the QoS, $n_{b,max}$ is the total number of available resource blocks and is related to the system design of BS b , $E_{a,b,i}$ is the allocated RE for macro BS b in i^{th} stage, $E_{s,b,i}$ is the available energy in the storage of macro BS b at beginning of i^{th} stage and $E_{s,b,i} = E_{s,b,i-1} + Eh_{b,i-1} \times S_{eff} - E_{a,b,i-1}$, $Eh_{b,i-1}$ is the harvested RE during period $i-1$ and S_{eff} is the energy storage efficiency.

The power model of the BSs follows the EARTH model [18]. The power demand (input power) of BS b in period i consists of a static part $P_{b,0}$ and a load dependent part related to the transmitted power $P_{T_{b,i}}$. Moreover, the power demand depends on the number of active resource blocks. It can be expressed as:

$$P_{b,i} = N_{b,trx} \times (P_{b,0} + \frac{n_{b,i}}{n_{b,max}} \times \Delta P_b \times P_{T_{b,i}}) \quad (8)$$

where $N_{b,trx}$ is the number of transceiver chains of BS b , $n_{b,i}$ is the number of active resource blocks and ΔP_b is the slope of the load dependent power part. The BS is active if at least one user is associated. If not, the BS will switch into sleep mode and the input power of such BS is as follows:

$$P_{b,i} = N_{b,trx} \times P_{b,sleep} \quad (9)$$

where $P_{b,sleep}$ is the sleep mode power demand.

IV. SIMULATED ALGORITHMS

In order to study the effect of deploying small cells powered by RE on the network energy behaviour, we simulate several algorithms. The algorithms, presented next, are used to manage the macro BSs. For the three algorithms, users are first associated with the small BSs if a minimum bit-rate is achieved. Then, the remaining of the users are associated based on the algorithm used to manage the macro BSs. It should be noted

Power grid

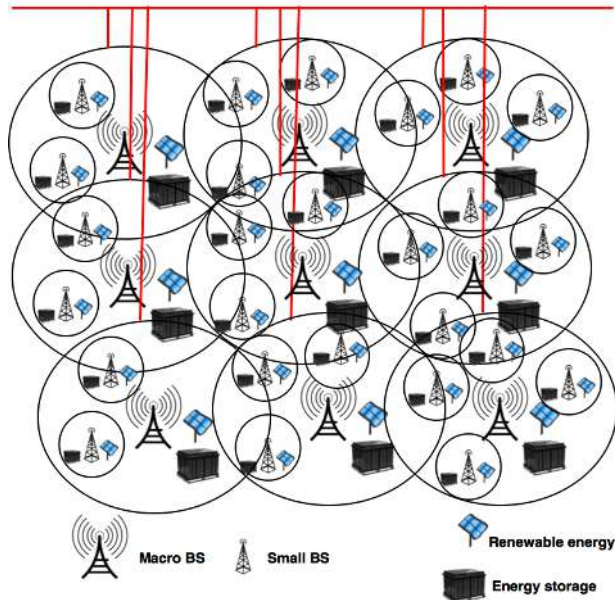


Fig. 1. Network of macro BSs powered by RE and the power grid overlapped by small BSs powered by RE.

that non of the algorithms would lead to QoS degradation as all users should be satisfied as presented in Equation 2.

- 1) Strong Signal First (SSF): This algorithm is used as the reference user association for different results. BSs do not switch-off and users are associated with the BS with strongest received power. Moreover, RE is used in a basic way, i.e. RE is consumed when available. Excess generated energy is stored and then used when RE is not available.
- 2) Cell Size Optimizing (CSO) [12]: The algorithm is an iterative approach combining RE allocation and adjustment of the BSs cell size. RE is allocated based on the storage level, and cell size is adjusted by changing the beacon transmitting power. When the approach converges, BSs whose energy consumption per user is larger than a predetermined threshold are switched-off.
- 3) Electric bill reduction (EBR-RRA): In [16], we propose EBR-RRA to manage a network of hybrid-energy macro BSs. EBR-RRA decides the usage of RE for macro BSs depending on grid energy price and storage state. Then, the algorithm switches-off BSs with the lowest amount of allocated RE. This step minimizes the number of BSs that rely on grid energy. However, it is not always possible to switch-off a BS due to capacity constraint and/or quality of service (QoS) demand of users. In this regard, EBR-RRA is designed to match the BSs energy demand with the amount of allocated RE by adjusting the transmitting power of BSs and re-allocating RE based on this adjustment. This leads to different cell sizes depending on RE availability and allocation. As a final step, EBR-RRA determines the number of active resource blocks for each BS based on its cell size and

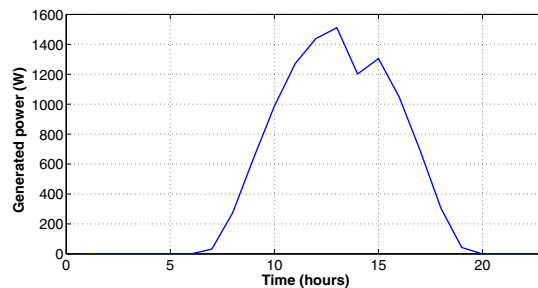


Fig. 2. Example of renewable energy generated by solar panels.

traffic intensity, which will further reduce the energy consumption of the network.

V. SIMULATIONS AND RESULTS

We consider 25 macro BSs located on a 5x5 grid, with 2000 m inter-cell distance. Small cells are distributed following Poisson point process, and the number of small cells is variable through our simulations. Mobile users are uniformly distributed, with maximum number of users equal to 450. The traffic intensity through a day is estimated based on [19]. We assume that the network has complete knowledge of users' positions. BSs operate with 2 GHz carrier frequency and 10 MHz bandwidth. We adopt Cost 213 Walfisch-Ikegami for path loss [20] and consider the noise figure as 9 dB. Moreover, log-normal shadowing is considered with 8 dB standard deviation. We consider that users receive interference only from macro BSs and interference from small cells are neglected (due to their small transmitting power). All BSs are equipped with solar panels and a storage system. The generated energy at a BS site follows the same pattern presented in Figure 2. We also

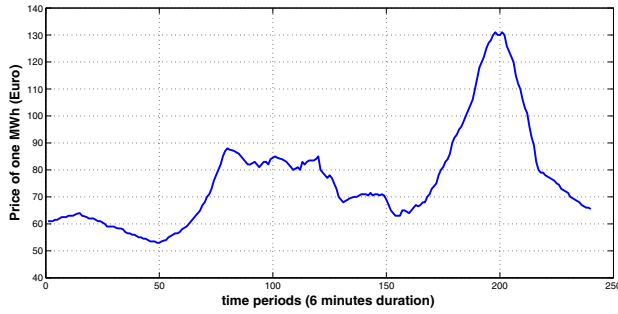


Fig. 3. An example of real time pricing of electricity for a day in France [21].

TABLE I
PARAMETERS' VALUES AND ASSUMPTIONS.

Parameters	Values and assumptions
Number of macro BSs	25
Number of sectors in a BS	3
Number of periods p	240
Period T	6 min
Carrier frequency	2GHz
Bandwidth	10 MHz, FDD
Inter-cell distance of Mmacro BSs	2000 m
Distribution of macro BSs	Grid
Distribution of small BSs	Poisson Point Process (PPP)
Number of resource blocks	50
Resource block bandwidth	180kHz
$SINR_{eff}$	1.2
BW_{eff}	0.83
Maximum number of users	450
User distribution	Uniform
User bit-rate (R_{th})	360 Kb/s
Path loss	Cost 231 Walfisch-Ikegami [20]
Scheduler	Round Robin
Noise figure	9 dB
BS power model	EARTH [18]
Lognormal shadowing	standard deviation 8 dB

consider small variations in the production due to temporary conditions (clouds for example). An example of real time price variation of grid energy [21] through time is presented in Figure 3. Parameters' values and assumptions of the system are summarized in Table I. Simulations are carried for a 24-hour scenario divided into 240 periods of 6 min duration. The results, presented next, are for the case where RE sources (at macro BS sites) produce 20% and 40% of the macro BSs total energy demand. This would allow to generalize the results for different locations, where same RE sources would have different amount of generated RE. Simulations are repeated many times and the results are the average value of these simulations.

Figure 4 presents the energy reduction of the network of macro BSs according to the density of small cells. Energy reduction (ER) is calculated as follows:

$$ER = \frac{(E_{SSF} - E_{alg}) \times 100}{E_{SSF}} \quad (10)$$

where E_{SSF} is the energy demand of the network that associates user based on the reference algorithm SSF and E_{alg}

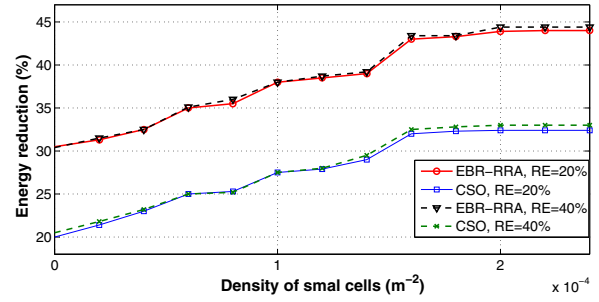


Fig. 4. Energy reduction according to density of small cells.

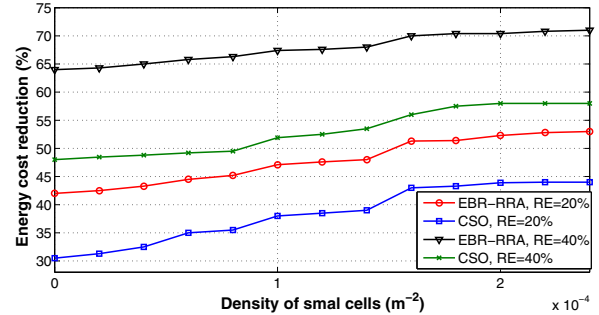


Fig. 5. Energy Cost reduction according to density of small cells.

is the energy demand of the network using a specific algorithm (CSO or EBR-RRA).

From Figure 4, results show that energy reduction is independent of the amount of RE generation for both CSO and EBR-RRA. Moreover, EBR-RRA leads to higher energy reduction than CSO. Adding small cells increases the energy reduction of the network for both algorithms. However, this reduction is not proportional to the density of small cells. When adding small cells in small densities, some macro BSs (with low load) can offload users and go to sleep mode. These BSs were not able to switch-off before adding small cells due to QoS constraints (minimum bit-rate for the users).

Increasing the density of small cells leads to more energy reduction. However, minor increase in energy reduction is obtained if we increase the density of small cells in some cases. This is because these small cells are not enough to switch-off more Macro cells. After additional increase of small cells, energy reduction starts to increase once again. This pattern is repeated as shown in Figure 4. For CSO, energy reduction reaches a limit where no more BSs can switch off due to coverage constraints. However, EBR-RRA still leads to slight increase in energy reduction, where EBR-RRA deactivate radio resource blocks when users are offloaded to small cells. This allow indirect energy sharing between macro BSs and small ones.

Figure 5 presents the energy cost reduction according to the density of small cells. Cost reduction (CR) is calculated by:

$$CR = \frac{(Cost_{SSF} - Cost_{alg}) \times 100}{Cost_{SSF}} \quad (11)$$

where $Cost_{SSF}$ and $Cost_{alg}$ are respectively the cost of grid energy using SSF and the specified algorithm (CSO or EBR-RRA), calculated using Equation 1.

Figure 5 shows that cost reduction follows the energy reduction presented in Figure 4. However, the energy cost reduction is not proportional to the energy reduction, and depends also on the time of energy reduction and usage of RE. For example, RE generation is high in certain periods (100-130), as shown in Figure 2. The price of grid energy is low in these periods, see Figure 3, and this justifies why EBR-RRA outperform CSO in terms of cost reduction for any density of small cells. EBR-RRA allocates RE for macro-BSs based on the price of grid energy and storage level, while CSO uses RE based only on the storage level. Although EBR-RRA outperforms CSO in terms of cost reduction, we see that adding small cells has more effect when it is used with CSO. For example, adding small cells in case of CSO (RE=20%) increases the cost reduction by 14 points, while it increases the cost reduction in the case of EBR-RRA (RE=20%) by 11 points. This is because the energy reduction caused by small cells in case of CSO allow macro BSs to store RE at low price periods to be used at high price periods.

Adding small cells in the case of EBR-RRA with RE=20% has more effect on cost reduction than the case with RE=40%. However, the cost reduction of EBR-RRA (RE=40%) without small cells is higher than that of EBR-RRA (RE=20%) with high density of small cells. This is due to dominant impact of macro-BSs on the energy operational cost of the network. Nevertheless, small cells enlarge the capacity of the network without significant increase in its energy demand, and macro BS sites might not have large available space to deploy large RE sources. Adding small cells powered with RE sources in such environment (e.g. urban) is a suitable solution for decreasing the energy operational cost of cellular networks while increasing its capacity.

VI. CONCLUSION

Powering base stations with renewable energy is one of the promising solutions for the increase in energy demand and Carbon footprint of cellular networks. This solution can be further enhanced by exploiting energy efficiency techniques to better utilize the harvested renewable energy. In this paper, we analyze the efficient use of small cells in a renewable energy context while considering real-time price of grid energy. Results show that adding green-powered small cells can reduce the network energy operational cost of up to 71% even with low amount of generated renewable energy. In future work, we aim at considering data delay and studying the trade-off between energy operational cost and delay experienced by users. Moreover, it is interesting to study these trade-offs considering the capital cost of small cells powered by renewable energy sources.

ACKNOWLEDGEMENT

The authors would like to acknowledge the support of the French Ministry of Industry for funding this work under

SooGreen European Project.

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