Energy Efficient Cell Load-aware Coverage Optimization for Small-Cell Networks

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***Abstract*—Self-organizing network is a new capability envisioned for the near-future wireless cellular networks. Among the different use cases, here we tackle the coverage optimization with the objective of adjusting the power devoted for the pilot signal as a function of the load of the different small Node Bs (SNBs). The optimization is done with the objective of minimizing the total transmitted power for the pilot signals in the network, leading to a switch on/off SNBs solution as a particular case. In this paper we present a decentralized algorithm that is executed at UEs and SNBs, exploiting the messages reported by UEs.**

***Index Terms*—Coverage optimization, pilot power optimization**

I. Introduction

Radio coverage is one of the most important aspects in cellular communications: mobile terminals need to clearly receive the pilot signal of a Node B (NB) before operating. Coverage outage leads to an increase of the number of dropped calls, poor voice quality or poor data throughput. This issue is tackled at the cellular network planning phase, see for example [1],[2], but the coverage and capacity of the network should be dynamically controlled as a function of the actual long-term traffic demand from user equipments (UEs).

Nowadays, one of the solutions to deal with the large data traffic demand in wireless networks is deploying a large number of small Node Bs (SNBs), with reduced transmit power and coverage area, thus improving the frequency re-use factor and the efficiency of wireless systems. This solution increases the complexity of the network operation, conventionally based on semi-automatic supervised techniques. In this regard, the self-organizing network (SON) concept facilitates the management of complex networks [3]. For example, in [4] the power devoted to the cell-specific pilot signal is minimized subject to a coverage constraint by offline optimization techniques in an environment with multiple base stations. Furthermore, a heuristic algorithm for multi-sector joint beamforming that eliminates the poor coverage and

Likewise, pilot coverage optimization for traffic load balancing are topics covered by [6],[7],[8]. In the first reference, it is proposed a heuristic rule for improving the load and coverage: since adjusting the pilot power entails a larger or smaller cell size, the cell load is balanced among neighboring cells, provided that we can guarantee the coverage for the whole area. A decentralized algorithm is proposed in [7] for a joint coverage area optimization in a scenario with multiple SNBs. The heuristic algorithm updates the SNBs's pilot transmit power in order to balance the cell-load among collocated SNBs and combating the coverage holes. Finally, a cellular network that adapts to the dynamic offered traffic loads and reduces the total energy consumption by extending the cell coverage is designed in [8]. The proposed algorithm creates inner and outer cell regions, thanks to the vertical sectorization and adaptive tilting of outer cell antennas to expand and contract the cell coverage. Each cell might operate in three modes: *normal* mode, in which the cell maximizes the throughput of its associated users, *contract/sleep* mode, in which the cell is switched off and its users are passed to neighboring cells, and *expand* mode, in which the cell is expanded by tilting its outer cell antenna directionality towards the contracted cell area. The main objective is to switch off a percentage of cells and reduce the energy consumption and the interference level in the network.

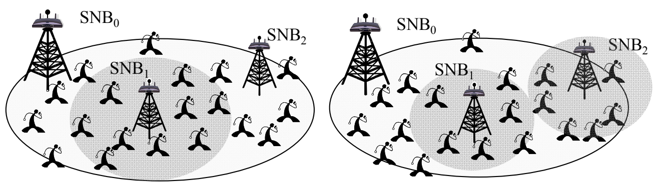

Fig. 1. Coverage area provided by Small Node B (SNB) network. Left) SNB$_2$ is switched-off, while SNB$_0$ and SNB$_1$ have 10 and 9 UEs, respectively. Right) By switching-on SNB$_2$, the overload of the system is reduced: here SNB$_0$, SNB$_1$, and SNB$_2$ provide coverage to 7, 6, and 6 UEs, respectively.

In this work we propose a heuristic algorithm to dynamically control the coverage area in the downlink depending on the long-term load of the system (number of UEs associated per SNB). The algorithm forces that a given UE is able to listen a certain number of SNB, although the UE is only associated to just one serving cell. When an SNB starts to be congested, for example SNB$_0$ and SNB$_1$ in Fig. 1-left, the SNB requests to its associated UEs to increase the number of listened SNBs. The messages reported by UEs indicate how the network has to increase the pilot transmit power of neighboring SNB. In such a case, UEs associated to the congested SNBs might associate to any of the less-congested neighboring cells (see SNB$_2$ in Fig. 1-right). In contrast, if a given SNB is lightly loaded, it requests to its current associated UEs to reduce the number of SNBs to be listened,

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so that the messages reported by UEs help to the network in deciding how to reduce the pilot transmit power.

The main contributions of this work are the following:

- A decentralized algorithm is proposed to balance the load among cells and guarantee coverage, and on its turn to minimize the total power devoted to pilot signals in a SNB-based network.
- The algorithm is executed by UEs and SNBs, adjusting dynamically the coverage area as a function of the long-term traffic demand, obtaining the conditions to switch-on/off a set of SNBs.

II. System Model

The considered scenario consists of a single NB that is always active and provides a large coverage area, N_{SNB} SNBs with smaller coverage areas that can be switched on/off as a function of the user distribution and traffic generation, and N_u users. The NB and SNBs are equipped with Network Listen (NWL) modules that allow scanning the downlink (DL) transmissions of neighboring SNBs. Consequently, they can be considered as additional virtual users in DL, but without receiving its own DL signal. Hence, the total number of listening terminals is: $N_{UE} = N_u + N_{SNB} + 1$. The total number of DL transmitters is $N_{SNB} + 1$.

All SNBs can communicate among them thanks to an existing backhaul connection. Additionally, each UE can only communicate with its serving SNB, but it might detect the transmitted pilot signals of neighboring SNBs. Therefore, all information exchanged with neighboring SNBs must go through the serving SNB and the backhaul link.

Every SNB is able to discover its neighbors, described by the set $\mathcal{X}_j$ at the *j*-th SNB. The way this set is built is not considered here. The set of UEs associated to the *j*-th SNB is defined as $\mathcal{U}_j$ in the sequel. The load of SNBs in terms of number of active associated UEs is classified in three states:

- *over-loaded*: $card\left(\mathcal{U}_j\right) > \delta_{up}$,
- *normal*: $\delta_{low} \le card\left(\mathcal{U}_j\right) \le \delta_{up}$, and
- *under-loaded*: $\delta_{low} > card\left(\mathcal{U}_j\right)$

where *card*(.) is the cardinality or number of elements in a set, and $\delta_{up}, \delta_{low}$ denote the thresholds to indicate the over-loaded and under-loaded states, respectively.

Finally, we define $\mathcal{F}_f$ as the set of SNBs active at the *f*-th carrier frequency. The power used by each SNB for pilot and data transmissions is $\left\{P_j^{pilot}, P_j^{data}\right\}$, respectively. Thus, the equivalent noise-plus-interference power at the *i*-th UE when it is listening the pilot signal of the *j*-th SNB that operates at the *f*-th carrier frequency is:

$$\sigma_{ij}^2 = \sigma_0^2 + \sum_{k \ne j, k \in \mathcal{F}_f}^{N_{SNB}} \frac{1}{L_{ik}} P_k^{data} + \frac{\alpha_{or}}{L_{ij}} P_j^{data} \tag{1}$$

where σ_0^2 is the power of additive white Gaussian noise, the second term denotes the interference generated by the data transmission of neighboring SNBs, α_{or} stands for the orthogonality factor that describes the interference generated by the *j*-th SNB, and L_{ij} accounts for the pathloss between the *j*-th SNB and the *i*-th UE. Notice that this model subsumes non-orthogonality between pilot and data transmissions from the same transmitter (like in WCDMA systems) if $\alpha_{or} \ne 0$, orthogonality between pilot and data transmissions between different transmitters $\left\{P_j^{data} = 0\right\} \forall j$, and non-orthogonality between pilot signals using variable *f*, like in LTE systems where there are 6 orthogonal pilot transmission patterns (cell specific reference signals), see chapter 10 of [9].

A given UE can decode correctly the pilot signal transmitted by the *j*-th SNB at the *f*-th carrier frequency if the signal-to-noise-plus-interference ratio (SNIR) satisfies,

$$SNIR_{ij}\left(P_j^{pilot}, \mathbf{P}_{-j}^{pilot}\right) = \rho_{ij} P_j^{pilot} \ge SNIR_t, \quad j \in \mathcal{F}_f$$
$$\rho_{ij} = \frac{1}{L_{ij}} \frac{1}{\sigma_{ij}^2 + I_0\left(\mathbf{P}_{-j}^{pilot}\right)}, \qquad I_0\left(\mathbf{P}_{-j}^{pilot}\right) = \sum_{k \ne j, k \in \mathcal{F}_f}^{N_{SNB}} \frac{1}{L_{ik}} P_k^{pilot} \tag{2}$$

where σ_{ij}^2 is the equivalent noise-plus-interference due to data traffic defined in (1), P_j^{pilot} is the power devoted for the pilot signal transmitted by the *j*-th SNB, $\mathbf{P}_{-j}^{pilot}$ is the set of pilot power values used by all SNBs except the *j*-th one, and $SNIR_t$ is the required minimum SNIR to be satisfied.

Let us define $\mathcal{B}_i$ as the tentative set of neighboring SNBs to be listened by the *i*-th UE, which depends on the list of neighbors at each SNB ($\mathcal{X}_j$). This set might include SNBs detected by the current *i*-th UE.

$$\mathcal{B}_i = \bigcup_{j \in \mathcal{W}} \mathcal{X}_j \quad \mathcal{W} = \left\{\forall\ j \mid \quad SNIR_{ij} \ge SNIR_t\right\} \tag{3}$$

III. Coverage Optimization

With the objective of optimizing the coverage area dynamically, we propose to exploit the feedback from UEs in the decision process. We impose that each UE has to listen a certain number of neighboring SNBs, (n_i^{listen}), which is tied to the cell-load of the current SNB to which the UE is associated. This constraint will entail an increase/decrease of the pilot transmit power of neighboring SNBs.

The proposed algorithm is described in Table I. First, UEs become associated to a given SNB using a policy that takes into account the current number of UEs already associated to the SNB. For example, and by no means this is essential to the proposed technique, the *i*-th UE selects the SNB received with the largest SNIR and additionally has less UEs attached:

$$j^* = \arg\ \underset{j}{\text{maximize}} \left(\frac{SNIR_{ij}}{card\left(\mathcal{U}_j\right)} RE_j\right) \tag{4}$$

where $RE_j \ge 1$ is the range expansion linear factor that allows to a UE to be associated to low-power SNBs, see for example [10]. Each SNB updates the set of UEs $\mathcal{U}_j$ accordingly. In the next step of the algorithm, the number of SNBs to be listened by the *i*-th UE, n_i^{listen}, is updated according to the current state of the *j*-th SNB (*over-loaded* or *under-loaded*):

$$n_i^{listen} = \begin{cases} \min\left(n_i^{listen}+1, |\mathcal{B}_i|\right) & if \quad card\left(\mathcal{U}_j\right) > \delta_{up} \\ \max\left(n_i^{listen}-1, \eta\right) & if \quad card\left(\mathcal{U}_j\right) < \delta_{low} \\ n_i^{listen} & otherwise \end{cases}, \forall i \in \mathcal{U}_j \quad (5)$$

where UEs attached to the NB might not be required to listen any additional SNB in case the cell is slightly loaded,

$$\eta = \begin{cases} 0 & if \quad i = \text{NWL of NB} \\ 1 & otherwise \end{cases} \quad (6)$$

TABLE I. COVERAGE OPTIMIZATION

1. User association, see eq. (4)
2. Each SNB updates the list of associated UEs $\{\mathcal{U}_j\}$
3. Each UE updates the list of neighboring SNB $\{\mathcal{B}_i\}$, see eq. (3)
4. Each SNB defines the number of SNBs to be listened by its associated UEs, see eq. (5)
5. Pilot transmit power optimization, see Table II in section IV
6. Go to 1

Finally, the power devoted to the pilot signal has to be updated so that each UE listens n_i^{listen} SNBs. How the power is adjusted is investigated in the next section, where we propose a decentralized algorithm where SNBs take into account information sent by UEs assuming:

- The pathloss for a SNB-UE link is only known if the pilot signal of the respective SNB can be detected at the UE;
- The requested number of SNBs to be listened must be feasible, which requires a proper definition of the list of SNBs, $\mathcal{B}_i$.

IV. PILOT TRANSMIT POWER PROBLEM FORMULATION

The power devoted to the pilot is usually a small fraction of the total downlink transmitted power, so its impact on the energy consumption is in general negligible. Therefore, the reduction in energy consumption comes mainly by switching-off SNBs, provided they are not needed to guarantee service coverage. We propose to optimize the pilot transmit power by all transmitters in such a way that switching-off SNBs is obtained as a solution of the problem, expressed in this way:

$$\begin{aligned} \mathbf{P0}: & \underset{\{x_{ij}\}\{P_j^{pilot}\}}{\text{minimize}} \sum_{j=1}^{N_{SNB}} P_j^{pilot} \\ \text{s.t.} \quad & -SNIR_{ij}\left(P_j^{pilot}, \mathbf{P}_{-j}^{pilot}\right) + x_{ij} SNIR_t \le 0 \quad \forall i, j \in \mathcal{B}_i \\ & -\sum_{j \in B_i} x_{ij} + n_i^{listen} \le 0 \quad \forall i, \\ & P_j^{pilot} - P_j^{\max} \le 0 \quad \forall j, \\ & x_{ij} \in \{0,1\}, \quad P_j^{pilot} \ge 0 \end{aligned} \quad (7)$$

where the x_{ij} is a discrete variable indicating that the i-th UE is listening the j-th SNB, $SNIR_{ij}$ function is defined in (2), $P_j^{\max}$ is the maximum power allowed for pilot transmission in the j-th SNB, and n_i^{listen} is the number of SNB to be listened by the i-th UE.

The problem P0 in (7) is a non-convex problem involving binary variables. In case $\sigma_{ij}^2 \gg I_0\left(\mathbf{P}_{-j}^{pilot}\right)$, see (2), the problem is transformed into a mixed-integer linear programming (MILP) problem that can be solved numerically in a centralized way. Nevertheless, it is possible to find closed-form solutions for x_{ij} and P_j by transforming problem P0 using the following two concepts:

- Perspective function $x\log(1+a/x)$ on the constraint of the received pilot signal,

$$-x_{ij}\log\left(1+\frac{1}{x_{ij}}SNIR_{ij}\left(P_j^{pilot}, \mathbf{P}_{-j}^{pilot}\right)\right) + x_{ij}\log\left(1+SNIR_t\right) \le 0 \quad (8)$$

  Notice that when $x_{ij} = \{0,1\}$ this constraint subsumes the first constraint in (7).

- Relaxing variable x_{ij}, i.e. $0 \le x_{ij} \le 1$

A. Centralized optimization problem

With the previous transformations, problem P0 in (7) is cast into the following set of equations,

$$\begin{aligned} \mathbf{P1}: & \underset{\{x_{ij}\}\{P_j^{pilot}\}}{\text{minimize}} \sum_{j=1}^{N_{SNB}} P_j^{pilot} \\ \text{s.t.} \quad & \left(\lambda_{ij}\right): -x_{ij}\log\left(1+\frac{1}{x_{ij}}SNIR_{ij}\left(P_j^{pilot}, \mathbf{P}_{-j}^{pilot}\right)\right) + \\ & \qquad + x_{ij}\log\left(1+SNIR_t\right) \le 0 \quad \forall i, j \in B_i \\ & \left(\omega_i\right): -\sum_{j \in B_i} x_{ij} + n_i^{listen} \le 0 \quad \forall i, \\ & \left(\nu_j\right): P_j^{pilot} - P_j^{\max} \le 0 \quad \forall j, \\ & \left(\underline{\alpha}_{ij}\right): -x_{ij} \le 0. \quad \left(\overline{\alpha}_{ij}\right): x_{ij} \le 1 \quad \forall i, j \\ & P_j^{pilot} \ge 0 \quad \forall j \end{aligned} \quad (9)$$

where $\{\lambda_{ij}\}, \{\omega_i\}, \{\nu_j\}, \{\underline{\alpha}_{ij}\}, \{\overline{\alpha}_{ij}\}$ are the Lagrange multipliers associated to the different constraints. Problem P1 in (9) is still not convex due to the interference, but we can use the tools developed for interference management in [11] to achieve a local optimal solution. It turns out that problem P1 can be solved by iterative solving problem P2 (defined in the following), and updating parameters $\{\psi_j, \rho_{ij}\}$ accordingly,

$$\begin{aligned} \mathbf{P2}: & \underset{\{x_{ij}\}\{P_j^{pilot}\}}{\text{minimize}} \sum_{j=1}^{N_{SNB}} \left(1+\psi_j\right) P_j^{pilot} \\ s.t. \quad & \left(\lambda_{ij}\right): -x_{ij}\log\left(1+\frac{\rho_{ij}}{x_{ij}}P_j^{pilot}\right) \\ & \qquad + x_{ij}\log\left(1+SNIR_t\right) \le 0, \forall i, j \in B_i \\ & \left(\omega_i\right): -\sum_{j \in B_i} x_{ij} + n_i^{listen} \le 0 \quad \forall i, \\ & \left(\nu_j\right): P_j^{pilot} - P_j^{\max} \le 0 \quad \forall j, \\ & \left(\underline{\alpha}_{ij}\right): -x_{ij} \le 0. \quad \left(\overline{\alpha}_{ij}\right): x_{ij} \le 1 \quad \forall i, j \\ & P_j^{pilot} \ge 0 \quad \forall j \end{aligned} \quad (10)$$

where ρ_{ij} is defined in (2), and ψ_j is the interference cost,

$$\psi_j = \sum_i \frac{\pi_{i,-j}}{L_{ij}},\ \pi_{i,-j} = \sum_{k\neq j} \frac{\lambda_{ik}\rho_{ik}P_k^{pilot}}{\left(\sigma_{ik}^2 + I_0\left(\mathbf{P}_{-k}^{pilot}\right)\right)\left(1+\frac{\rho_{ik}P_k^{pilot}}{x_{ik}}\right)} \quad (11)$$

where $\pi_{i,-j}$ measures the impact of the P_j^{pilot} over the *i*-th UE when it is listening any SNB different from the *j*-th one. Notice that the KKT conditions of problems P1 and P2 are the same, but problem P2 is convex over all the optimization variables given $\left\{\psi_j, \rho_{ij}\right\}$. The optimal value for x_{ij} is found solving the Lagrangian of problem P2,

$$x_{ij} = \frac{\rho_{ij}P_j^{pilot}}{\exp\left(\frac{\rho_{ij}P_j^{pilot}}{x_{ij}+\rho_{ij}P_j^{pilot}} + \log\left(1+SNIR_t\right) - \frac{\omega_i + \underline{\alpha}_{ij} - \overline{\alpha}_{ij}}{\lambda_{ij}}\right) - 1} \quad (12)$$

Additionally, by applying hypothesis testing, see section 7.3 of [12], over variable x_{ij} ($x_{ij}=0$, $x_{ij}=1$, $0<x_{ij}<1$) we obtain a criterion to set $x_{ij}=1$ as a function of the Lagrange multiplier ω_i (tied to the number of SNBs that are listened) and λ_{ij} ,

$$x_{ij} = 1 \quad if \quad 1+\log\left(1+SNIR_t\right) < \frac{\omega_i}{\lambda_{ij}} \quad (13)$$

Finally, the optimal value of the power transmitted by the *j*-th SNB, using the Lagrangian of problem P2, must satisfy,

$$1+\psi_j+\nu_j = \sum_i \lambda_{ij}x_{ij}\frac{\rho_{ij}}{x_{ij}+\rho_{ij}P_j^{pilot}} \quad (14)$$

The solution to problem P2 is given by (12) and (14). In the following, we propose some modifications to the obtained solutions in order to provide simple expressions and force the constraint $x_{ij}=\left\{0,1\right\}$.

B. Adjusting the transmitted power at each SNB

We propose the following dynamic power allocation

$$P_j^{pilot}(n) \approx (1-\alpha)P_j^{pilot}(n-1) + \alpha\ \min\left(\frac{\sum_{i,j\in\mathcal{B}_i}\lambda_{ij}x_{ij}}{1+\psi_j}, P_j^{\max}\right) \quad (15)$$

where α adjusts power dynamics in every update. Notice that (15) is a valid approximation to the solution shown in (14) in case $x_{ij} \ll \rho_{ij}P_j^{pilot}$, i.e. for SNIR>0 dB. However, this is not always the case and we keep this approximation at the cost of certain inaccuracies. The positive aspect of the proposed solution is two-fold: a) The power allocated to the pilot of the *j*-th SNB depends on variables $\left\{\lambda_{ij}\right\},\left\{x_{ij}\right\}$, but not on the pathloss of the link between the *i*-th UE and the *j*-th SNB; b) The value of $\left\{\lambda_{ij}\right\}$ contains implicit information about the feasibility of the problem that will be discussed in section IV.E.

C. Updating lambda at each UE

Variable $\left\{\lambda_{ij}\right\}$ is updated using a sub-gradient approach [13],

$$\lambda_{ij}(n) = \max\left(\lambda_{ij}(n-1)+\mu\xi_{ij}, 0\right) \quad (16)$$

where μ is the step-size of the gradient and ξ_{ij} is defined as,

$$\xi_{ij} = \begin{cases} \kappa & if \quad x_{ij}=1\ and\ \rho_{ij}P_j^{pilot} < SNIR_t \\ \log\left(\frac{1+SNIR_t}{1+\rho_{ij}P_j^{pilot}}\right) & if \quad x_{ij}=1\ and\ \rho_{ij}P_j^{pilot} \geq SNIR_t \\ 0 & otherwise \end{cases} \quad (17)$$

and κ is a constant value to be defined, which imposes an increase of the variable $\left\{\lambda_{ij}\right\}$ when the *i*-th UE tries to listen to the *j*-th SNB ($x_{ij}=1$) but it is not detected, so that $\rho_{ij}P_j^{pilot}$ is not known. Moreover, the second term in (17) corresponds to the first constraint of problem P2, (10).

D. Adjusting the listening SNBs at each UE

Variables $\left\{x_{ij}\right\}$ are obtained as it is suggested by (12) but we have to consider if the *j*-th SNB is actually detected or not, and these variables have to be set to {0,1}. We propose to use,

$$x_{ij} = \begin{cases} 1 \quad if \quad \frac{\omega_i}{\lambda_{ij}} > 1+\log\left(1+SNIR_t\right) \\ 0 \quad if \quad \frac{\omega_i}{\lambda_{ij}} < 1+\log\left(1+SNIR_t\right)\ and\ \rho_{ij}P_j^{pilot} < SNIR_t \\ \left[\frac{\rho_{ij}P_j^{pilot}}{\exp\left(1+\log\left(1+SNIR_t\right)-\frac{\omega_i}{\lambda_{ij}}\right)-1}\right]_0^1 \quad otherwise \end{cases} \quad (18)$$

where operator [ ] denotes the *round* function and the third case assumes $x_{ij} \ll \rho_{ij}P_j^{pilot}$. Although this latter aspect is not always true, results reported in [16] shows a similar performance that using the ideal expression defined in (12). It turns out, that for given values of $\left\{P_j^{pilot},\lambda_{ij}\right\}$ the variable x_{ij} is found by optimizing ω_i in such a way that the second constrain in problem P2 is always satisfied. This can be done using the bisection method, see chapter 4 of [12].

E. Setting the maximum number of SNB to be listened

We are assuming that UEs know their neighboring SNBs, $\mathcal{B}_i$, by exchanging the lists available at each SNB, $\mathcal{X}_j$, see (3). Problem P2 in (10) assumes that the constraint over the number of SNBs that can be listened, $\left\{n_i^{listen}\right\}$, is always feasible. However, not all the SNBs in the list might be detected by a given UE because some of them might be switched-off or they can use a reduced transmitted power.

In the following we define a procedure to adjust the number of SNBs to be listened by a UE taking into account the equation of the pilot power defined in (15), which shows that the transmit power is proportional to λ_{ij}. In that case, this variable is increased in case the *i*-th UE is not detecting the pilot signal of the *j*-th SNB and the *i*-th UE would like to listen that SNB ($x_{ij}=1$), see (17). Therefore, the list of neighboring SNB at the *i*-th UE should be adjusted according to the current value of this variable,

$$\mathcal{B}_i = \begin{cases} \mathcal{B}_i \setminus \left\{j\right\} & if \quad \lambda_{ij} \geq \lambda_{\max} \quad and \quad SNIR_{ij} < SNIR_t \\ \mathcal{B}_i & otherwise \end{cases} \quad (20)$$

The number of SNB to be listened by the *i*-th UE is ,

$$n_i^{listen} \leq card\left(\mathcal{B}_i\right) \quad (21)$$

TABLE II. PROPOSED PILOT TRANSMIT POWER OPTIMIZATION

1. # *Inputs at UEs* : $\forall i = 1..N_{UE}$
2. $\boldsymbol{\lambda}_i = \left[\lambda_{i1} \ldots \lambda_{ij} \ldots \lambda_{icard(\mathcal{B}_i)}\right], \mathcal{B}_i, \mathbf{x}_i = \left[x_{i1} \ldots x_{ij} \ldots x_{i,card(\mathcal{B}_i)}\right], n_i^{listen}$
3. # *Inputs at SNBs* : $P_j^{pilot} \quad \forall j = 1..N_{SNB}$
4. # *Continuous processing at UEs*
5. Detection of new neighboring SNBs
6. Each UE updates $\boldsymbol{\lambda}_i$, see eq. (16)
7. Each UE updates $\mathcal{B}_i$, see eq. (20)
8. Each UE reads the parameter n_i^{listen} from its serving SNB
9. Each UE measures $\boldsymbol{\pi}_i = \left[\pi_{i,-1} \ldots \pi_{i,-j} \ldots \pi_{i,-card(\mathcal{B}_i)}\right]$, eq. (11)
10. Each UE measures pathloss $\mathbf{L}_i = \left[L_{i1} \ldots L_{ij} \ldots L_{i,card(\mathcal{B}_i)}\right]$,
11. Each UE calculates ω_i and $\mathbf{x}_i$, see section IV.D
12. Each UE reports, $\boldsymbol{\lambda}_i, \mathbf{x}_i$, $\mathbf{L}_i$, and $\boldsymbol{\pi}_i$ to the serving SNB
13. # *Continuous processing at SNBs*
14. Each SNB processes the reports send by associated UEs
15. Exchange parameters to other SNBs (via backhaul)
16. Each SNB computes ψ_j, see eq. (11)
18. Each SNB calculates the new P_j^{pilot} see eq. (15)
19. Go to 5 until convergence
20. # *Outputs* : $\boldsymbol{\lambda}_i, \mathcal{B}_i, \mathbf{x}_i \ \forall i = 1..N_{UE}, \quad P_j^{pilot} \ \forall j = 1..N_{SNB}$

F. Decentralized Pilot Optimization

After tuning the analytical solutions obtained for problem P2 throughout sections IV.B to IV.E we are able to propose a pilot transmit optimization procedure that is carried out in a decentralized manner at SNBs and UEs to solve problem P0.

This procedure is presented in Table II, denoting which actions are performed at the UEs and SNBs respectively. The variables updated at the UE are: i) the Lagrange multiplier associated to the constraint of the pilot reception from the j-th SNB, λ_{ij}, the Lagrange multiplier associated to the constraint of the number of SNB to be listened, ω_i, ii) The list of neighboring SNBs, $\mathcal{B}_i$, iii) the indicator if this UE is listening the j-th SNB, x_{ij}. Additionally, each UE should measure the pathloss with its neighboring SNBs, and parameter $\pi_{i,-j}$ which is connected with the interference generated by the j-th SNB when the UE listens to other SNB.

On the other hand, each SNB updates the pilot transmit power, P_j^{pilot}, and must process the received messages from neighboring SNBs (via backhaul) in order to get the interference cost of the j-th SNB, see (11).

In terms of implementation in current systems, the proposed algorithm needs to report a message containing $\left\{\lambda_{ij}\right\}, \left\{x_{ij}\right\}$, while the other parameters can be already known at the serving SNB. For example in 3G systems, see [14], UEs are able to report the pathloss, CPICH-Received Signal Code Power (RSCP) and CPICH-E_c/N_0, these latter two measurements allow obtaining $\rho_{ik} P_k^{pilot}$ and $\sigma_{ik}^2 + I_0\left(\mathbf{P}_{-k}^{pilot}\right)$, in (11). Similarly, in LTE systems, see section 5.11.2 of [15], we can employ the Reference Signal Received Power (RSRP) and the Reference Signal Received Quality (RSRQ).

V. RESULTS

Due to the lack of space, results for a LTE-based scenario are reported in section 5.4.4 of [16], where it is shown the similarities of problems P0 and P2, in case there is not interference. In this latter case, problem P0 can be solved using MILP techniques. In contrast, here we evaluate the proposed coverage optimization procedure in the 3G-based scenario depicted in Fig. 2 with the parameters defined in Table III and frequency reuse equal to one. We can observe that some UEs are able to listen up to 4 different SNBs, while others only detect one SNB.

TABLE III. SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
N_u	120	$P_{1,\max}^{pilot}$	3 W
N_{NB}	1	$P_{1,\max}^{data}$	7 W
N_{SNB}	$N_{NB}+8$	$P_{k,\max}^{pilot}$ $(k=2\ldots7)$	0.075 W
N_{UE}	$N_{SNB}+N_u$	$P_{k,\max}^{data}$ $(k=2\ldots7)$	0.176 W
$SNIR_t$	-20 dB	$P_{n,\max}^{pilot}$ $(n=8\ldots9)$	0.006 W
RE_1	1	$P_{2,\max}^{data}$ $(n=8\ldots9)$	0.014 W
RE_j $(j=2\ldots9)$	5	*Path-loss model*	Okumura Hata – open areas
Noise power	-102 dBm	*Carrier freq.*	850 MHz

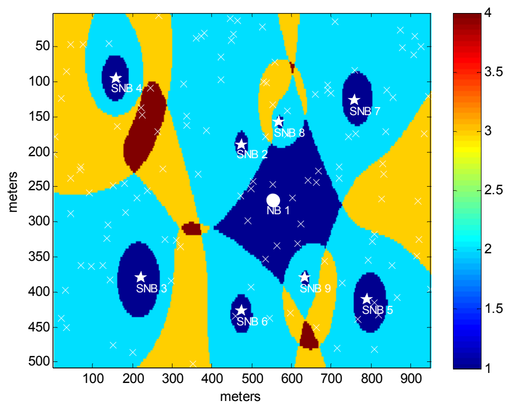

Fig. 2. Deployment of SNBs over a certain area, with 1 NB (solid circle) total P_{max}=40 dBm, 6 SNBs with total P_{max} =24 dBm (solid squares), 2 SNBs with total P_{max}=13 dBm, and 120 UEs (crosses). Color indicates the number of SNBs detected in a location (SNBs use 30% of its P_{max} for pilot transmission).

First, we evaluate the algorithm presented in Table II with the objective of minimizing the total pilot power used in the network and all UEs are able to listen at least $n_i^{listen} = 2$ SNBs. We impose that SNB_1 (i.e. NB) always transmit with its maximum pilot transmit power. Let us remark, that the proposed algorithm adjusts the pilot power and the feasible set of neighboring SNBs for every UE. In this regard, Fig. 3 shows the evolution of the total pilot power assuming that the feasible set of neighboring SNBs is either: a) known a priori (dotted line) or b) estimated during the pilot transmit power optimization (solid line), see section IV.E. We can observe that there are important fluctuations of the total power when we are estimating the feasible set of neighboring SNBs because we are considering unfeasible SNBs at that time. This is not observed when we work with a feasible set (dotted line). In Fig. 4 we show the optimized coverage areas where all UEs are listening at least 2 SNBs (if this is possible). We have observed savings in terms of pilot power equal to $[20\%, 92\%, 13\%, 95\%, 90\%, 44\%, 15\%, 52\%]$ for SNB_2 to SNB_9 with respect the initial unplanned pilot power allocation.

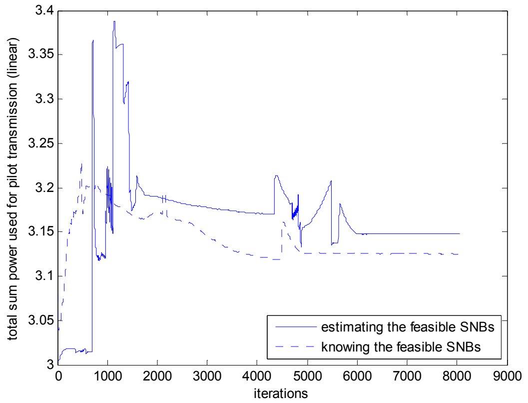

Fig. 3. Total pilot power (linear scale in W) assuming that $\mathcal{B}_i$ is known (dotted line) or estimated (solid line). $n_i^{listen} = 2 \quad \forall i$

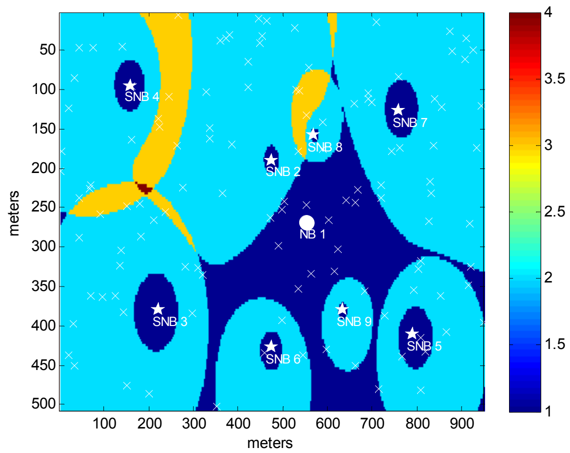

Fig. 4. Coverage area after imposing that all UEs should listen at least 2 SNBs. Color indicates the number of SNBs detected in a given location.

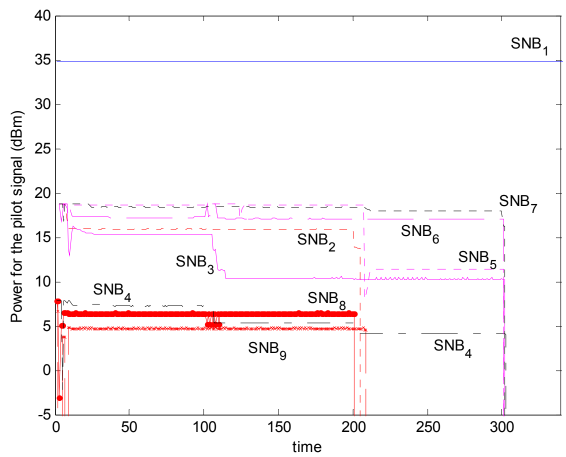

Fig. 5. Pilot power (in dBm) evolution of the different SNB when at t={0, 100, 200, 300, 400} there are N_u={120, 96, 60, 24, 6} active UEs.

On the other hand, Fig. 5 presents the evolution of the pilot transmit power of the different SNBs when the number of the UEs is changing over the time and the dynamic coverage optimization presented in Table I is applied at every time t, i.e. the decision on the variable n_i^{listen}, while the pilot optimization is carried out during the elapsed time between decisions. In particular we assume that only SNB_1 is switched on and all UEs are attached to it at the beginning. At time t={100, 200, 300, 400}, the active UEs are equal to N_u={96, 60, 24, 6}, respectively. We can observe that up to t<200 all SNBs are active, and afterwards, SNB_2, SNB_8, and SNB_9 are switched off. The remaining SNBs are switched off at t=300, where only the SNB_1 is active, and all UEs are associated to it.

VI. CONCLUSIONS

We have proposed a decentralized pilot power optimization that adapts the coverage area of the different SNBs in the network as a function of the corresponding load of the system. The proposed algorithm exploits the messages reported by UEs and informs to the network when SNBs need to be switched on/off or increase/decrease their coverage areas. The content of the messages reported by UEs is obtained with the objective of minimizing the total power in the network for pilot transmission, while maintaining the coverage constraints.

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