

Base Station Placement Based on Force Fields

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Abstract—Network planning and optimization becomes more and more important in cellular mobile communications due to the growing complexity of the networks. Besides taking new key performance indicators into account such as energy efficiency, the augmented heterogeneity, caused by a variety of radio access technologies (e.g., 3G and beyond as well as WiFi) and network node types (e.g., micro and femto cells), leads to an exploding dimension of the planning process. On the other hand, the degrees of freedom increase as well, giving rise for new optimization techniques.

In this paper a novel approach for optimizing cellular deployments is presented. The model is based on characterizing the interrelations (among base stations and between base stations and the environment) by force fields, motivated by the physics of multiple particles in a closed system. Further, an algorithm is proposed which tracks the trajectory of base station locations under the presence of forces, focusing on finding a balanced state with minimal net force. Also, it is elaborated on how to combine different force types in order to capture different quality aspects of a network.

I. INTRODUCTION

Cellular network planning set in to become important from operators' point of view with the introduction of 2G networks. The evolution to 3G and 3.5G amplified the need for reasonable planning and optimization strategies significantly, ranging from frequency pattern optimization to site selection and parameter optimization such as antenna downtilt and transmit power. Where at the beginning the considered parameter space was comparably small, it has increased and is still increasing, especially with the introduction of LTE and LTE-A. This is due to new network topologies with rising heterogeneity, where the heterogeneity comes twofold. Firstly, the number of radio access technologies (RAT) is increased - nowadays a mobile user can be served via cellular networks like GSM and WCDMA but also via WiFi and WiMAX where available, introducing the notion of Multi-RAT. Secondly, heterogeneity is also increased due to the growing number of network node types, e.g., micro and pico base stations for outdoor and femto base stations for home coverage. Further, the design and operation of future architectures entail the integration of new aspects in the planning and optimization process. For instance, due to the diversity of cells with different signal propagation conditions, the interference becomes momentous and needs to be considered carefully.

For network optimization there exists a variety of optimization approaches. The major differences are due to strategies and techniques and sets of parameters which are considered. What most of them share is the problem of finding optimal base station locations, whereas only a smaller part elaborates on optimal network management parameters with a fixed placement of network nodes. The basic problem of finding optimal base station locations is typically dealt with by using a discrete optimization approach as in [1], [2]. The site selection strategy, which is often described by binary programs, targets on choosing a certain number of base stations from a predefined set of possible locations, so called candidate sites. Integrating additional parameters leads to mixed integer programs a good many times. They can be solved by means of integer programming techniques or by heuristics such as tabu search [3], [4]. Stochastic approaches are also used when the base station locations are not subject to a discrete subset of the area of interest, e.g., by particle swarm optimization [5], by some genetic algorithm [6], or by some other heuristic approach as in [7].

The novel technique for deployment optimization illustrated in this paper has its seeds in the work [8]. The authors' approach to solve the facility location problem is based on the application of an optimization technique called AGOP (a new global optimization algorithm) from [9]. The optimization strategy samples the parameter space and iterates to a global optimum using forces, where those forces are defined by means of the samples and their objective values. The major difference between this approach and the one described in this paper is that in the former the forces act between deployments (samples) while in the latter the forces act directly between parts of a deployment, which makes sampling the parameter space redundant and, thus, decreases complexity.

In this paper, the force field method will be introduced and explained focusing on base station placement while ignoring other parameters such as antenna downtilt and main lobe directions for sake of simplicity. Nevertheless, the model can be easily extended to incorporate a variety of parameters. As in [8], the optimization is done for continuous variables, hence avoiding any discretization and its involved increase in solution complexity.

The remainder of the paper is organized as follows. In Section II the force field approach is described, beginning with the interference and load model and continuing with the main concepts leading to an equivalent of a Newtonian system. Following, Section III shows numerical results based on force field examples defined in the main section. Section

¹This work was supported in part by European Community's Seventh Framework Programme (FP7/2007- 2013) under grant agreement n° 247733.

²This work was supported in part by the German Federal State of Saxony in the excellence cluster Cool Silicon within the frame of the project Cool Cellular under grant number 14056/2367.

IV concludes the paper and provides an outlook for future research.

II. FORCE FIELD MODEL

A. Assumptions

Let $\mathcal{A} \subseteq \mathbb{R}^2$ denote a given set which describes the area where a cellular network shall be deployed. For this area information about landscape and buildings are assumed to be available. The spatial user distribution in the area is denoted by δ where $\int_{\mathcal{A}} \delta(u) du = 1$ holds.

Consider a deployment in \mathcal{A} consisting of a certain number of cells. For each cell i , the corresponding cell area $\mathcal{A}_i \subseteq \mathcal{A}$ is defined by the maximum receive power association rule, i.e.,

$$\mathcal{A}_i := \left\{ u \in \mathcal{A} \mid P_{\text{rx},i}(u) = \max_j P_{\text{rx},j}(u) \geq P_{\text{rx},\min} \right\} \quad (1)$$

where $P_{\text{rx},i}(u)$ and $P_{\text{rx},\min}$ denote the receive power in u from base station i and the receiver sensitivity, respectively. Note that the terms cell and base station (BS) are used interchangeably, i.e., a base station is assumed to serve exactly one sector. Given a total offered traffic T in \mathcal{A} , the traffic intensity in cell i can be defined by means of the user distribution δ as

$$T_i := T \int_{\mathcal{A}_i} \delta(u) du. \quad (2)$$

The achievable rates of the users heavily depend on the interference generated by the base stations, which, in turn, is determined by the load conditions. For instance, a highly loaded base station will be responsible for a lot more interference in neighboring cells compared to a lowly loaded cell, since in the former case the base station would be transmitting for a larger fraction of the time. The interference and load in the network is modeled based on [10], where users are assumed to arrive according to a Poisson process with intensity $\frac{T_i}{\Omega}$ with some arbitrary mean flow size Ω . The signal-to-interference-and-noise-ratio (SINR) γ_i of a user in location $u \in \mathcal{A}_i$ is defined by

$$\gamma_i(u, \eta) := \frac{P_{\text{rx},i}(u)}{\sum_{j \neq i} \eta_j P_{\text{rx},j}(u) + N} \quad (3)$$

where N denotes the noise. This yields achievable user rates

$$r_i(u, \eta) = W \log_2(1 + \gamma_i(u, \eta)) \quad (4)$$

with W denoting the system bandwidth. According to the model, the load conditions η_i of the cells are connected via the fixed point equation

$$\eta_i = \min \left\{ 1, T_i \int_{\mathcal{A}_i} \frac{1}{r_i(u, \eta)} \delta_i(u) du \right\} \quad (5)$$

where δ_i describes the user distribution within cell \mathcal{A}_i . The fixed point (also denoted by η), which is shown to exist, then provides the cell capacities

$$C_i = \left(\int_{\mathcal{A}_i} \frac{1}{r_i(u, \eta)} \delta_i(u) du \right)^{-1} \quad (6)$$

which correspond to the harmonic mean of the achievable user rates in the individual cells. As a result, the served traffic in the cells can be computed as

$$\bar{T}_i := \min \{T_i, C_i\}. \quad (7)$$

B. The Notion of Forces

The interference model is only one example which underlines the strong interrelations among base stations in a network, where a local parameter adjustment (at one or more base stations) has a global effect on the network performance. For instance, to decrease the load in one cell, the downtilt of the corresponding base station antenna can be increased. This results in less interference and, possibly, in increased loads of neighboring cells due to increased cell sizes. In turn, such cells have to compensate for the higher load as well.

Now associate base stations with particles in a closed system. Due to the interrelations among the particles and between the particles and the system, these particles kind of jiggle around. The notion of forces is now motivated by describing the jiggling as effect of some virtual force field in the background. In physics, there exist different kind of forces. With regard to the model described in this paper, force fields similar to the concepts of attractive and repulsive forces and external forces are defined. While the first are modeled both to be caused by and to effect on base stations, the latter is described to originate from the environment.

Before going into detail on how to convert the physics of multiple particle systems to deployment optimization, the technique for defining reasonable forces is explained exemplarily by introducing two different force fields which act on the location of base stations.

A force typically consists of two parts, namely a direction and a magnitude. In the case of attractive or repulsive forces, which act among base stations, the direction is inherently defined to lie on the line connecting the corresponding base station locations. The first and most simple force is connected to interference and is called interference force. Naturally, it can be modeled as repulsive force with a magnitude corresponding to the accumulated (weighted) interference power in the considered cell received from a neighboring base station. More precisely, define

$$F_j^i := \frac{x^i - x^j}{\|x^i - x^j\|} \int_{\mathcal{A}_i} P_{\text{rx},j}(u) \delta_i(u) du \quad (8)$$

as the interference force acting from base station j on base station i . The location of base station i is denoted by x^i . Superimposing all forces acting on base station i yields the net force

$$F^i = \sum_{j \neq i} F_j^i - \sum_{j \neq i} F_i^j \quad (9)$$

where the second summation accounts for Newton's 3rd law (actio et reactio).

The following coverage force is modeled as external force. It is based on the (spatial) traffic demand distribution described

by δ and originates from the non-covered areas $\mathcal{A} \setminus \bigcup_i \mathcal{A}_i$ of the network. Let denote

$$\bar{\mathcal{A}}_i := \left\{ u \in \mathcal{A} \mid P_{\text{rx},i}(u) = \max_j P_{\text{rx},j}(u) < P_{\text{rx},\min} \right\} \quad (10)$$

that area, where users would be associated to cell i if the maximum receive power exceeds the receiver sensitivity. Hence, the system of sets $\{\mathcal{A}_i\}_i$ and $\{\bar{\mathcal{A}}_i\}_i$ constitutes a partitioning of the whole area. The direction of the coverage force acting on base station i is determined by the (weighted) center c^i of each non-covered area $\bar{\mathcal{A}}_i$ calculated as

$$c^i := \frac{\int_{\bar{\mathcal{A}}_i} u \delta(u) du}{\int_{\bar{\mathcal{A}}_i} \delta(u) du} . \quad (11)$$

Defining the magnitude of this force by the accumulated offered traffic in $\bar{\mathcal{A}}_i$ yields the coverage force described as

$$F^i := \frac{c^i - x^i}{\|c^i - x^i\|} T \int_{\bar{\mathcal{A}}_i} \delta(u) du . \quad (12)$$

C. The Mass Concept

The modeling of repulsive forces requires Newton's 3rd law of motion. In order to have a proper conversion of the mechanical behavior of multiple particles to network planning, Newton's 2nd law of motion is considered. For this, an entity representing the mass is needed.

Introducing a (varying) mass in combination with forces entails two properties contemporaneously. Besides translating the acting forces to an acceleration of the base stations, it further brings inertia to the system. Meaning, the mass relativizes the total force. In this context, the mass of a base station should somehow represent its quality with regard to the network. Typically, the quality is determined by some selected key performance indicators (KPIs). Regarding network planning, a cell is considered of high quality, if it provides good coverage and is able to serve the traffic demand while consuming as little energy as possible. Combining those aspects would lead to a mass of cell i defined by

$$m_i := \frac{|\mathcal{A}_i| + 1}{|\mathcal{A}| + 1} \frac{\bar{T}_i + 1}{T_i + 1} \frac{P_{\text{in},\min,i}}{P_{\text{in},i}} \frac{1}{T_i + 1} \quad (13)$$

where $|\cdot|$ denotes the volume operator. The actual and minimal energy consumption of base station i is denoted by $P_{\text{in},i}$ and $P_{\text{in},\min,i}$, respectively, where the latter is assumed to be nonzero which corresponds to a minimal energy consumption due to some sleep mode. The last term in (13) sees to it that the mass is bounded above by 1. The additional '+1' terms ensure that the mass is finite and positive. A base station's mass becomes 1 if and only if this base station covers the whole area and serves the total offered traffic with minimal power. The lower bound is established by served traffic tending to zero with offered traffic increasing to the total traffic demand in the whole network while consuming maximal energy (i.e., maximum transmit power and maximal load). This yields $m_i \in (m_{\min}, 1]$ with some $m_{\min} > 0$ which prevents having to deal with zero masses which are difficult to handle.

In case not all KPIs are taken care of by network planning using the force field approach, the definition of the mass can be shortened such that neglected KPIs are removed. For instance, when focusing on coverage only, the mass might also be modeled as $m_i = \frac{|\mathcal{A}_i| + 1}{|\mathcal{A}| + 1}$.

D. The Newtonian System

The fundamental basis for describing the reaction of particles due to acting forces is Newton's 2nd law of motion stated as

$$F = \frac{dp}{dt} = \frac{d(mv)}{dt} = \frac{dm}{dt}v + m \frac{dv}{dt} = ma . \quad (14)$$

Here, p , v , a , m , and t denote the linear momentum, velocity, acceleration, mass, and time, respectively. The last equals sign is based on the assumption of the mass being constant. In fact, it involves some kind of approximation, since the mass concept introduced in the previous section consists of varying base station masses. Using this approximation yields that the acceleration of a base station is determined by the net force and the mass.

In general, the quantities in (14) all depend on the time via the base station locations. Thus, in order to obtain the trajectories of the base station locations, a second order ordinary differential equation has to be solved. Due to the complex nature of the quantities force and mass, the problem can only be tackled numerically. The following approach shall describe how the continuous trajectories are tracked by approximation.

E. Base Station Trajectories

Let t denote a given time. For a sufficiently small time step Δt assume that $F^i(t + \Delta t) \doteq F^i(t)$ and $m_i(t + \Delta t) \doteq m_i(t)$ holds, i.e., the force and the mass are constant. Consider a uniformly accelerated motion of base station location i in the time interval $[t, t + \Delta t]$ which gives

$$x^i(t + \Delta t) \doteq x^i(t) + v^i(t) \Delta t + \frac{a^i(t)}{2} \Delta t^2 . \quad (15)$$

The assumption of a vanishing initial velocity, i.e., $v^i(t) = 0$, is motivated by a dead start motion, where the base stations are regarded to be in an inoperative state and experience an acceleration due to constant forces. Thus, the motion of each base station's location in the given time interval is on a straight line. Under these assumptions, the displacement of base station i can be computed as

$$\Delta x^i(t) := x^i(t + \Delta t) - x^i(t) = \frac{\Delta t^2}{2m_i(t)} F^i(t) . \quad (16)$$

Following the continuous trajectory by the discrete one described above, the system is supposed to converge to a balanced state where the net forces vanish, i.e.,

$$F^i = 0 \quad \forall i . \quad (17)$$

The basic algorithm based on the force field approach which generates base station trajectories using the dead start motion is summarized in Alg.1. Note that the algorithm presented there should only illustrate the principal nature and lacks any numerical details.

Algorithm 1 Force field algorithm for optimal BS placement.

Require: $x^i, \Delta t$
initialize $t \leftarrow 0, x^i(t) \leftarrow x^i$
while $\sum_i |F^i(t)| \neq 0$ **do**
 compute $F^i(t)$ and $m_i(t)$
 $x^i(t + \Delta t) \leftarrow x^i(t) + \frac{\Delta t^2}{2m_i(t)} F^i(t)$
 $t \leftarrow t + \Delta t$
end while
return $x^i(t)$

F. Combination of Different Types of Force Fields

Base stations in a network are typically connected not only due to one KPI but many. In the context of the proposed force field method, different force fields have to be considered simultaneously. Taking a closer look at the force field examples in (8) and (12) shows that a straightforward superposition of different force types is not practical due to different orders of magnitude, which would yield the dominance of one force over the others. One way to solve this problem is to scale the forces such that their magnitudes are comparable, i.e., they are in a common range. Unfortunately, it is not clear how to arrive at such scaling functions. Another approach is based on considering different force fields sequentially. This requires to solve the problem of determining a reasonable sequence which is the focus of future research.

Instead of mapping the forces onto some common range, the displacement in (16) can be scaled by factors $\alpha_i(t)$ such that the displacement is in a predefined range. This approach can be regarded as part of a step size control, where the maximal displacement is below a certain threshold. The adapted trajectory would then be computed as

$$\Delta x^i(t) = \alpha_i(t) \frac{\Delta t^2}{2m_i(t)} F^i(t) . \quad (18)$$

Let $\Delta x^{i,n}$ denote the displacement according to a force of type n , suppressing the time instance t for now. The total displacement Δx^i is then defined via

$$\Delta x^i := \sum_n \lambda_n \Delta x^{i,n} \quad \left(\lambda_n \in \mathbb{R}_+, \sum_n \lambda_n = 1 \right) \quad (19)$$

which is the convex combination of the individual displacements. The multipliers λ_n provide the opportunity to control the impact of the different forces or KPIs, respectively.

III. NUMERICAL RESULTS

The force field method summarized in Alg.1 is illustrated using the following system setup. Consider an area $\mathcal{A} = [-1000 \text{ m}, 1000 \text{ m}]^2$ and a randomly generated spatial user distribution (demand nodes) where each user is supposed to be indoor with equal offered traffic such that the traffic demand accumulates to 120 Mbps/km². Let an initial deployment consist of 5 three-fold symmetrically sectorized macro base stations with random main lobe directions, 70° horizontal beamwidth, 6° downtilt, 10° vertical beamwidth, 46 dBm

transmit power, and 14 dBi antenna gain. They are randomly placed and concentrated in the south-west of the area. For receive power calculations the urban non-line-of-sight macro path loss model from [11] with penetration loss of 20 dB is applied. The receiver sensitivity is chosen $P_{\text{rx},\text{min}} = -104$ dBm for a 10 MHz bandwidth system operating at 2.0 GHz.

The numerical base station trajectory is tracked for 500 iterations. Prior optimization, the magnitudes of the forces are estimated. The maximal allowed displacement of a base station is 100 m. In case it is exceeded, all displacements are rescaled such that the largest equals the threshold. For calculating the mass, definition (13) is used.

In Fig.1 the final positions of the base stations are visualized when considering coverage and interference force with equal weights simultaneously. The black triangles correspond to non-covered demand nodes. Base station associations are distinguished by different markers (squares, stars, diamonds), where identical colors refer to base stations sharing the same site. It can be observed that the coverage force distributes the base stations over the area. In the absence of the interference force, the balanced state would be reached if the union of non-covered areas corresponding to base stations sharing the same site are kind of uniformly distributed around the site location. Due to the presence of the interference force, the base station main lobes are directed such that interference in neighboring cells is minimized, leading to improved achievable user rates. The trajectory of the macro base station located in the south-west of the area is comparably short, since the non-covered area associated with the base stations sharing this site are almost empty due the coverage of the neighboring cells.

The progress in coverage for this scenario is shown in Fig.2 in comparison with the case of coverage force only. It can be seen that the interference force has an opposing effect on the coverage force such that the improvement in coverage is alleviated. A further increase in coverage with growing number

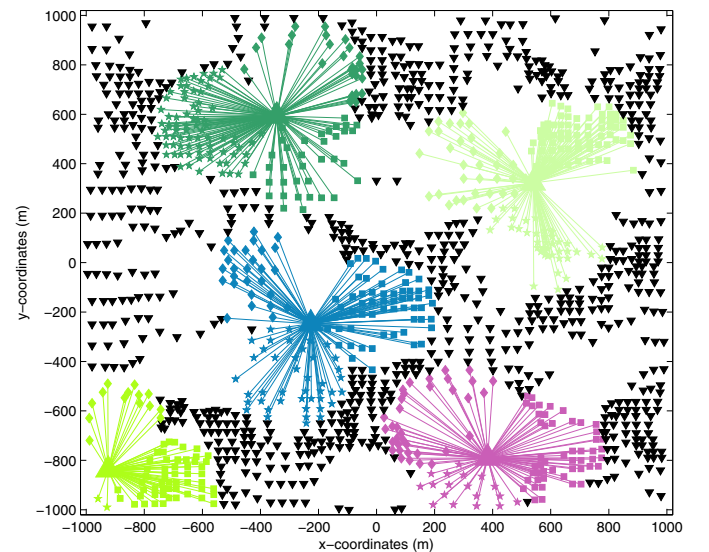


Fig. 1: Deployment according to coverage and interference force field with equal weights.

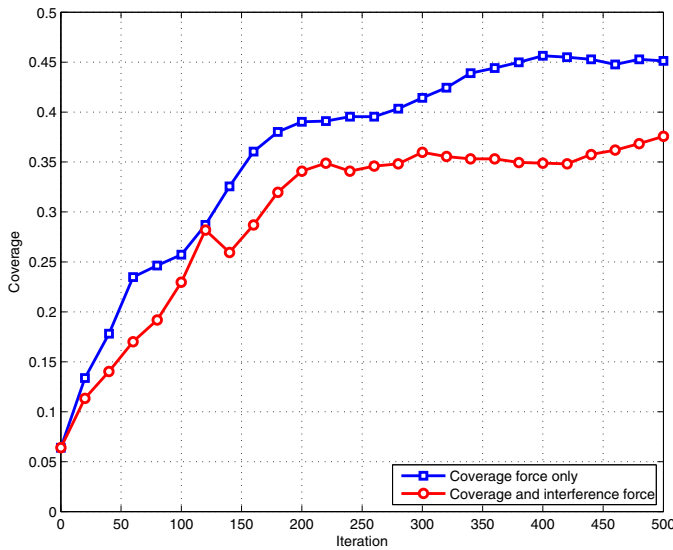


Fig. 2: Comparison of the coverage progress of the combined approach vs. the coverage force only scenario.

of iterations can not be observed since each displacement tends to zero, revealing a balanced state. In Fig.3 the norm of the coverage force for each macro base station is shown exemplarily.

IV. SUMMARY AND OUTLOOK

In this work a novel approach to solving the base station placement problem in cellular radio networks was presented. The model is based on the notion of force fields which converts ideas from interactions among particles in a closed system to interrelations among base stations in a network. The main elements of the model are attractive/repulsive and external forces and the mass concept. Combined under Newton's laws of motion, changes in the network can be characterized. Another novelty of the approach is the modeling technique of the interference conditions, emphasizing the load concept

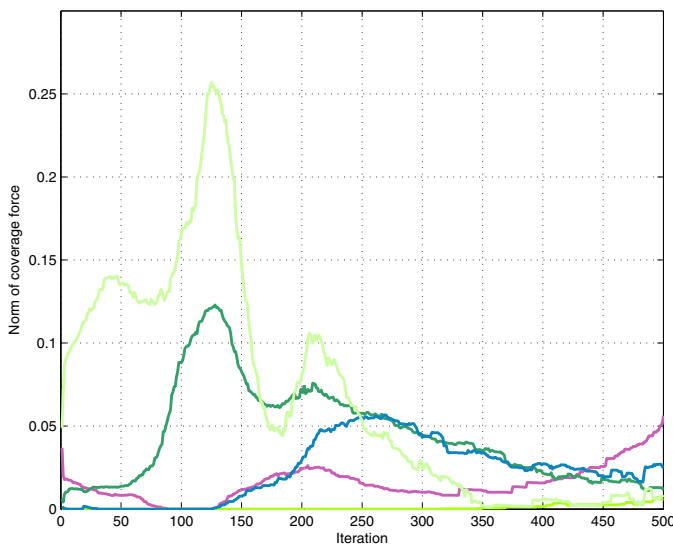


Fig. 3: Progress of coverage force in the combined coverage and interference scenario.

whose importance grows significantly for next generation cellular networks, especially with regard to energy efficiency aspects.

In this paper the focus was on base station locations due to motivating reasons. Nevertheless, the model can be extended such that other base station characteristics, e.g., transmit power and downtilt, are considered as well. It was shown that the forces defined exemplarily are reasonable. Further, a way how to combine different force fields was presented.

Next steps with regard to the force field model are to investigate the behavior of the model if a larger number of force fields is considered, e.g., load and SINR force fields. Moreover, it will be studied how this approach can be used for network planning and optimization, focusing on finding the optimal mix of different cell sizes/types, which is a discrete problem by nature. When fixing base station locations, the force field approach could be utilized for self-organizing networks which is the object of further investigations.

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