Improved models and algorithms for UMTS radio planning

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Abstract—
Classical coverage models based on signal predictions, adopted for second generation cellular systems, are not suitable for planning UMTS base station location since the area actually covered by each base station depends on the traffic distribution, the power control mechanism as well as the signal quality constraints. In a previous paper [2] we presented a discrete optimization model for the UMTS base station location problem. In this paper we propose enhanced models which consider the Signal-to-Interference Ratio (SIR) as quality measure and capture at different levels of detail the specific power control mechanism of the CDMA air interface. Moreover, we propose a Tabu Search algorithm for the uplink (mobile to base station) direction. The different models and algorithms are compared on realistic instances generated using classical propagation models.

I. Introduction

With the extraordinary success of mobile communication services, in recent years service providers have afforded huge investments to develop network infrastructures using second generation systems technologies. Due to the high costs and the scarcity of radio resources, an accurate and efficient mobile network planning is of outmost importance. With the advent of third generation systems, such as UMTS (Universal Mobile Telecommunication System), this need is now more acute due to the increased complexity of the system and the number of parameters that must be considered [4].

The planning of second generation cellular systems adopting a TDMA-based access scheme can be simplified subdividing the problem into a coverage planning and a frequency planning phases which are driven by coverage and capacity criteria, respectively [15], [8]. In the coverage planning phase, base stations (BSs) are placed so that the signal strength is high enough in the area to be served [16], [17], [14]. In the frequency planning phase, a number of channels has to be assigned to each BS [6]. Therefore the traffic load as well as the level of service measured as the Signal-to-Interference Ratio (SIR) are taken into account.

With the W-CDMA (Wideband Code Division Multiple Access) air interface of UMTS this two-phase approach is not appropriate basically because the bandwidth is shared by all active connections and no actual frequency assignment is strictly required. The capacity of each cell has not a hard limit, but it depends on the actual interference levels which determines the achievable SIR values. As these values depend on user and BS positions, the area actually covered by each BS is heavily affected by the traffic distribution. Therefore, BS location in UMTS networks cannot only be based on coverage but it must also be capacity driven [4]. In this context the *power control* (PC) mechanism plays a crucial role since it adjusts the emitter powers according to interference and propagation conditions and, therefore, affects system capacity.

The planning phase of cellular networks usually takes as input the following three main types of information related to the service area: i) a set of candidate sites where BSs can be installed, ii) the traffic distribution estimated by using empirical prediction models and iii) the propagation description based on approximate radio channel models or ray tracing techniques. The main purpose of planning is then to select the sites where to install the BSs taking into account different aspects such as costs, signal quality and service coverage.

Recently, some optimization planning schemes have been proposed for CDMA systems and in particular for UMTS. However, while some works still adopt a classical coverage approach [5], [13], the others do not account for some fundamental features of the SIR constraints or of the PC mechanism of the CDMA air interface [7], [9].

In [2] we presented a first discrete optimization model that takes into account these UMTS specific aspects. In this paper we propose enhanced models for the uplink direction (mobile to base station) which capture at different levels of detail the SIR constraints and the PC mechnism. Moreover, we propose a Tabu Search algorithm for the uplink (mobile to base station) direction which takes into account installation costs, signal quality and service coverage. We compare the different models and algorithms by means of realistic instances generated by using classical propagation models.

In Section II we propose and discuss the different formulations of the UMTS base station location problem, while in Section III we propose a Tabu Search heuristic for its solution. Computational results obtained with realistic instances are reported and discussed in Section IV. Finally, Section V contains some concluding remarks.

II. Base station location models

A. Basic model

Consider a territory to be covered by an UMTS service. Assume that a set of *candidate sites* $S = \{1, \dots, m\}$ where a BS can be installed, is given and that an installation cost c_j is associated with each candidate site j, $j \in S$. A set of *test points* (TPs) $I = \{1, \dots, n\}$ is also given. Each TP $i \in I$ can be considered as a centroid where a given amount of traffic d_i (in Erlang) is requested and where a certain level of service (measured in terms of SIR) must be guaranteed [17]. The required number of simultaneously active connections for TP i, denoted by u_i, turns out to be a function of the traffic demand, i.e., $u_i = \phi(d_i)$. The actual definition of the function ϕ is a degree of freedom of the planning process. It can simply correspond

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to the average number of active connections or to the number of simultaneous connections not exceeded with a given probability p. The connection activity factor can be considered as well.

The propagation information is also supposed to be known. In particular let $G = \{g_{ij}\}_{1 \le i \le n, 1 \le j \le m}$ be the propagation gain matrix, where g_{ij}, $0 < g_{ij} < 1$, is the propagation factor of the radio link between TP i and a candidate site j.

In the W-CDMA UMTS base station location problem one wishes to select a subset of candidate sites within the set S where to install BSs, and to assign the TPs to the available BSs taking into account the traffic demand, the quality requirements in terms of SIR and the installation costs.

Let us define the two following classes of decision variables:

$$y_j = \begin{cases} 1 & \text{if a BS is installed in } j \\ 0 & \text{otherwise} \end{cases}$$

for $j \in S$ and

$$x_{ij} = \begin{cases} 1 & \text{test point } i \text{ is assigned to BS } j \\ 0 & \text{otherwise} \end{cases}$$

for $i \in I$ and $j \in S$. The core of the basic integer linear programming model that we propose for the uplink case is the classical uncapacitated facility location model:

$$\min \quad \sum_{j=1}^{m} c_j\, y_j + \lambda \sum_{i=1}^{n} \sum_{j=1}^{m} u_i \frac{1}{g_{ij}}\, x_{ij} \tag{1}$$

$$s.t. \quad \sum_{j=1}^{m} x_{ij} = 1 \qquad i \in I \tag{2}$$

$$x_{ij} \le y_j \qquad i \in I; j \in S \tag{3}$$

$$x_{ij}, y_j \in \{0,1\} \qquad i \in I; j \in S. \tag{4}$$

The first term in the objective function corresponds to the total installation cost. Since $1/g_{ij}$ is proportional to the power emitted from TP i when assigned to BS j, the second term aims at favoring assignments which require a smaller total emission power. $\lambda \ge 0$ is a trade-off parameter between these two objectives. Constraints (2) make sure that each TP i is assigned to a single BS. Constraints (3) impose that TPs are only assigned to sites where a BS is installed. Note that by restricting the assignment variables x_{ij} to take binary values, it is required that in every feasible solution all active connections out of any TP must be assigned to a single BS.

To account for the power limit on the user terminals, we need to include, for each pair of TP $i \in I$ and candidate site $j \in S$, the following constraint:

$$\frac{P_{target}}{g_{ij}}\, x_{ij} \le P_{max}\, y_j \tag{5}$$

where P_{max} is the maximum emission power and P_{target}/g_{ij} corresponds to the emission power required by a mobile station in TP i to guarantee the target received power P_{target} in site j. Note that if $g_{ij}\, P_{max}/P_{target} < 1$ the TP i cannot be assigned to candidate site j due to power limits, and therefore the variable x_{ij} can be omitted from the model. Otherwise constraint (5) is implied by the corresponding constraint (3).

The fundamental aspect to be taken into account is the quality of the signal received by each BS. A commonly adopted simplified model assumes that the interference due to the neighboring cells (I_{out}) can be expressed as a fraction f of the interference due to the other transmissions in the same cell [18]. For each connection, the quality constraint $SIR_{uplink} \ge SIR_{min}$ can then be rewritten as

$$SF\, \frac{P_{received}}{I_{in}(1+f)} \ge SIR_{min} \tag{6}$$

Considering a power-based PC mechanism, the power received $P_{received}$ at BS j from each mobile station in a TP assigned to it is equal to P_{target} and the quality constraint amounts to imposing an upper bound on the number N_j of connections that can be assigned to that BS. Specifically, we have

$$N_j \le \frac{SF}{SIR_{min} \cdot (1+f)} + 1. \tag{7}$$

For the typical values $f = 0.4$, $SF = 128$ and $SIR_{min} = 6$ dB used in the literature, we obtain an upper bound of 23.97 on the maximum number of connections that can be serviced by any single BS. Thus for each candidate site $j \in S$ the signal quality constraints can be rewritten as:

$$\sum_{i=1}^{n} x_{ij} \le 23\, y_j. \tag{8}$$

The resulting model falls into the class of standard capacitated facility location problem which have been extensively studied in the Operations Research literature (see [12]). Medium-size instances of such NP-hard problems turn out to be very difficult to solve even using state-of-the-art optimization techniques. However, the capacity constraints (8) do not capture the distinctive features of the CDMA technology and, as we shall see in Section IV, in most practical cases the above basic model provides meaningless solutions.

B. Enhanced model with power-based PC

To make the model more realistic, inter-cell interference needs to be considered explicitly and independently from intra-cell interference. The use of pseudo-random spreading codes implies that, for a specific uplink connection between TP i and BS j, there is no significant difference in the two types of interference.

In the presence of power-based PC mechanism, for each candidate site $j \in S$ we consider the following quality constraint:

$$\frac{P_{target}}{\sum_{h=1}^{n} u_h\, g_{hj} \sum_{t=1}^{m} \frac{P_{target}}{g_{ht}}\, x_{ht} - P_{target}} \ge SIR_{min}\, y_j, \tag{9}$$

where the thermal noise η has been omitted as in other works focusing on this type of PC mechanism (see e.g. [18]). This constraint enforces that if a BS is installed in site j (i.e., $y_j = 1$), the resulting SIR must exceed the given SIR_{min}. More specifically, the double summation in the denominator corresponds to the total interference due to all connections and the P_{target} term that is subtracted amounts to the received power associated to a single connection assigned to j. Note that for any TP h the only term of the inner summation (over index t)

that is nonzero corresponds to the site to which h is assigned. Thus the contribution to the outer summation of any TP h assigned to site j amounts to $u_h P_{target}$. The bilinear constraints (9) can be linearized as follows:

$$1 + M(1 - y_j) \geq SIR_{min} \cdot \left(\sum_{h=1}^{n} \sum_{t=1}^{m} u_h \frac{g_{hj}}{g_{ht}} x_{ht} - 1 \right) \quad (10)$$

for a large enough value of M.

By analyzing the quality constraints (9), one can establish a simple but important property of the underlying assignment subproblem of the BS location problem: given any set of active BSs $\overline{S} \subseteq S$ and set I of TPs that can all be serviced, only assignments of TPs to "closest" active BSs need to be considered, where "closeness" is meant in terms of the required emission power (see [1] for a proof of this property).

C. Model with SIR-based PC

In the presence of a more sophisticated PC mechanism aiming at constant estimated SIR for all mobile to base station connections, the discrete optimization model is more involved since the signal powers p_i, needed to connect TP $i \in I$ to the candidate site it has assigned to, must be considered as explicit variables. The core model is then as in (1-4) except that in the second term of the objective function $1/g_{ij}$ is replaced by p_i. Constraints (5) are replaced by $0 \leq p_i \leq P_{max}$. Moreover, for each pair of TP $i \in I$ and candidate site $j \in S$, the quality constraint is now:

$$\frac{p_i \, g_{ij}}{\sum_{h=1}^{n} u_h \, g_{hj} \sum_{t=1}^{m} p_h \, x_{ht} - p_i g_{ij} + \eta} \geq SIR_{min} \, x_{ij} \quad (11)$$

assuming that the SIR target value is equal to SIR_{min}. Note that this third order constraint enforces that, if TP i is assigned to site j (i.e., $x_{ij} = 1$), the transmission powers must be tuned so that the resulting SIR exceeds the given SIR_{min}. Unlike in the power-based PC case, in this context the thermal noise η is usually included to guarantee convergence of the closed-loop PC mechanism used in real systems [19].

D. Different planning objectives

Although the generic objective function proposed in (1) takes into account the installation costs and the total emission power, the appropriate choice depends on the specific planning objectives. According to the traffic requirements and distribution, the number of candidate sites and their locations as well as the mobile station maximum power, the signal quality constraints (9) or, respectively, (11) can be infeasible. In this case, it is reasonable to assume as objective of the optimization process the maximization of the fraction of traffic that is actually serviced. To this purpose, the assignment constraints (2) can be relaxed as follows:

$$\sum_{j=1}^{m} x_{ij} \leq 1 \qquad i \in I \quad (12)$$

so as to allow some TPs not to be assigned. Then the objective function must drive towards solutions satisfying a maximum fraction of the traffic demand, thus the additional term $\sum_{i \in I} u_i \sum_{j \in S} x_{ij}$ has to be added to the objective function with an appropriate weight parameter.

III. Tabu search algorithm

Since the UMTS BS location problems defined in the previous section contain the uncapacitated facility location problem as a special case, they turn out to be NP-hard.

In [2] we described greedy and reverse greedy randomized procedures that iteratively activate and, respectively, disactivate BSs (*Add* and *Remove* procedures). In this section we present a more sophisticated Tabu Search heuristic.

Tabu Search (TS) is a *metaheuristic* that guides a local search procedure to explore the solution space of optimization problems beyond local optima [10]. The idea is to use the history of the search process through an appropriate memory scheme to prevent cycling (running into feasible solutions that have already been generated) and to direct it towards regions of the solution space that are promising in terms of the objective.

The basic ingredients of a general TS strategy can be described as follows. Starting from an initial feasible solution $\mathbf{s}^0$, a set of neighboring solutions $N(\mathbf{s}^0)$ are generated by applying a set of possible "moves" to $\mathbf{s}^0$. Then the best solution in the "neighborhood" $N(\mathbf{s}^0)$ is selected as the next iterate $\mathbf{s}^1$ even if it does not strictly improve the value of the objective function and the process is repeated to gnerate a sequence of solutions $\{\mathbf{s}^k\}$.

In order to prevent cycling and to try to escape from local optima a list of "tabu moves" is maintained. The purpose of this list is to forbid to make the opposite move that has been made at a given step for a certain number of iterations. A move that is added to the list remains tabu for a number of iterations that corresponds to the length L of the list. According to the "aspiration criteria", tabu moves can be clearly made if they lead to an improved solution. The best solution encountered is stored as the algorithm proceeds and it is returned after a maximum number of iterations max_{it}. max_{it} and L are two parameters of the method. Not surprisingly the efficiency and performance of a TS procedure strongly depend on the way the moves are defined and how well they exploit the actual structure of the problem at hand.

A. Basic algorithm for the model with power-based PC

As initial solution we consider the set of active BSs $\overline{S} \subseteq S$ provided by the Add or the Remove procedures together with an assignment $\mathbf{x}$ of the TPs to their closest active BS, whenever they are serviced. Note that the current solution is in a sense fully characterized by the set $\overline{S} \subseteq S$ of active BSs. Besides the *add* and *remove* moves used in the randomized greedy procedures, we do also define *swap* moves that amount to installing a new BS in one of the empty sites while deleting one of the active BSs. Exploring all possible swap moves for any given current solution would of course be very time consuming even for small-size instances. But, due to the actual structure of the problem, it is reasonable to focus on swaps between candidate sites that are relatively close to each other. For each active BS we evaluate the swap for nb available sites. First we select the $nb \cdot q$ ones with the largest propagation gains, where $0 < q < 1$, and then we pick randomly the others by considering the empty sites by nonincreasing gain.

The objective function used to guide our Tabu Search is the same function U_r adopted for the Remove procedure in [2]. As to the implementation of the tabu list, BSs that are installed (disactivated) cannot be disactivated (reinstalled) during L iterations. Although this imposes stronger restrictions on the search process than just avoiding considering solutions that have already been generated, it provides better experimental results since it forces to explore a larger region of the solution space.

In the experiments described in Section IV, Tabu Search is applied in two different settings. On the one hand, we use 200 TS iterations in a multistart Add or Remove context as a local search procedure to improve the solutions obtained with each one of the 10 runs of the greedy method. On the other hand, the same total number of iterations, namely 2000, of TS are carried out starting from a single initial solution provided by Add or Remove. Note that the advantage of generating a starting solution with Remove is that one also checks whether all traffic demand can be satisfied.

B. *Extension for the model with SIR-based PC*

Although in the SIR-based case assigning TPs to closest BSs is no longer guaranteed to yield the best possible SIR values, we make this simplifying assumption which reflects a conservative point of view in the sense that there might exist an assignment of TPs to active BSs involving a smaller number of active BSs. Given a current set of active BSs $\overline{S} \subseteq S$ and an assignment $\mathbf{x}$, to compute the emitted powers p_i it would be necessary to solve the system composed of constraints (11) for each active connection between TP and BS subject to the maximum power bounds. Since the resulting system contains n constraints (11) in the n variables p_i, a solution satisfies all of them with equality. Assuming that TPs are assigned to closest active BSs, the system can then be simplified by reducing the number of variables as well as the number of equations. For every TP i assigned to a given active BS j, all corresponding equations are equivalent when considered as function of $p_i g_{ij}$. Denoting the common received power by $p'_j = p_i g_{ij}$, the equations can be rewritten as:

$$\frac{p'_j}{\sum_{h=1}^{n} u_h \, g_{hj} \sum_{t=1}^{m} \frac{p'_t}{g_{ht}} x_{ht} - p'_j + \eta} = SIR_{min} \qquad (13)$$

for all $j \in \overline{S}$. The size of the resulting system is thus equal to the number of active BSs which is at most m and usually much smaller than the number n of TPs. This size reduction is absolutely necessary to make our algorithms applicable to the more accurate model. Given the assignment $\mathbf{x}$ and the solution $\mathbf{p}'$ of the the above system, the emission power at the TPs are derived by setting $p_i = p'_j / g_{ij}$ if $p_i \leq P_{max}$ and otherwise $p_i = P_{max}$.

IV. Computational results

To evaluate the performance of the proposed algorithms we have considered the same three families of synthetic instances (with a small, medium and large service area) used in [2] and generated according to Hata's propagation model [11]. In this section we present the highlights of our results, the reader is referred to [3] for the details.

A. *Comparison between different SIR formulae*

The first computational effort has been directed towards a comparison between the simplified power-based PC model (i.e., including constraints (8)) and the enhanced power-based PC one with SIR constraints (9) in which inter-cell interference is explicitly considered. For the above-mentioned values of f and of the other parameters, in the simplified model the number of users per BS is upperbounded by 23. The resulting models for the small instances have been solved to optimality by using the Mixed Integer Programming solver CPLEX 7.0. In all cases, the simplified model yields solutions with 5 activate BSs (which corresponds to the lower bound, since $95/23$ is about 4.1), while the optimal solution of the enhanced model always activates just 4 BSs.

For a fair comparison between the solutions provided by the simplified and enhanced models, we changed the value of parameter f (setting it to 0.35) so that also the simplified model returns solutions with only 4 active BSs.

To evaluate the quality of the solutions provided by the simplified model, we considered the active BSs and the assignments of TPs, we evaluated the SIR values of each BS using the power-based PC mechanism and the SIR-based PC mechanism. Typical results obtained for one of the small instances (instance SU-3 in [2]) are reported in Table I. In the power-based setting the SIR drops far below any acceptable value, while in the SIR-based setting it has not even been possible to find a feasible value for the received powers, meaning that the PC mechanism does not converge to a stable solution.

BS id.	**number of TPs per BS**	**power based setting SIR (dB)**
0	23	4.8
6	24	4.97
8	24	5.09
13	24	5.22

TABLE I

Solution quality of the simplified model, $f = 0.35$

All our experiments show that the model with the simplified SIR formula is not suitable for locating BSs in UMTS networks since it fails to capture the fundamental characteristics of third generation systems.

B. *Comparative results for model with power-based PC*

In this subsection some typical results obtained with the Tabu Search algorithm for the enhanced power-based PC model are reported and compared with those provided by Add and Remove.

Table II reports the results obtained with the Add and Remove algorithms (50 runs) and with Tabu Search algorithms for medium-size instances with a service area of 1×1 km, $m = 120$, $n = 400$, and u_i geometrically distributed with mean equal to 2, for all $i \in I$. Out of the 10 instances mentioned in Table II, 5 have been generated using the Hata formula for urban areas (MU) and 5 using that for rural areas (MR). Multistart TS consists of 50 runs of Add (A) or Remove (R) followed by 200 iterations of Tabu Search while single run TS consists of Remove followed by 2000 iterations of tabu search. The solutions found always provided full traffic coverage.

We observe that the solutions provided by the TS procedures require a few BSs less than the randomized greedy algorithms. Although there is no significant difference among the three TS procedures, single run TS provides in all but one cases the best solution and it always does so at lower computational cost.

C. *Comparison between models with power or SIR-based PC*

We now discuss the results obtained with the SIR-based PC model pointing out the differences with respect to those from

	Add	Remove	multi TS (A)	multi TS (R)	TS
MU-1	47	50	46	48	47
MU-2	46	46	43	43	43
MU-3	45	43	41	41	41
MU-4	45	44	42	42	42
MU-5	44	46	42	42	42
MR-1	44	42	40	41	40
MR-2	44	45	43	43	43
MR-3	43	44	41	41	41
MR-4	45	45	42	42	42
MR-5	44	46	42	42	42

TABLE II

Power-based model: minimum number of BSs obtained with the Add, Remove ($\delta = 0.3$), multistart TS and single run TS for medium-size urban (MU) and rural (MR) instances.

the power-based PC models. Multistart TS was applied with 10 runs. Each run starts from a solution provided by one of the randomized greedy algorithm (Add or Remove) and is followed by 200 iterations of TS. TS was also applied in a single long run involving 2000 local search iterations. For each of the medium-size instances the multistart TS took about 15 hours (PC PIII 1.2 GHz) while the single run TS took about 9 hours. On the same instances the same type of algorithms applied to the enhanced power-based PC models took 2:30 hours and, respectively, 1:20 hours. This clearly indicate the considerable additional computational load required to compute the power values at each iteration.

Table III shows the numerical results for the ten medium-size instances.

	multistart TS (R)	TS
MU-1	39	39
MU-2	37	36
MU-3	35	35
MU-4	36	36
MU-5	36	36
MR-1	35	36
MR-2	37	36
MR-3	35	35
MR-4	36	36
MR-5	36	36

TABLE III

SIR-based model: number of installed BSs with tabu search algorithms

Comparing the number of active BSs yielded by the enhanced power-based PC model with that obtained by the SIR-based PC model on the same instances we observe that the SIR-based PC model allows for a saving of at least 5 BSs. This is mainly due to the fact that TPs can emit lower powers with respect to those in the power-based PC case, and thus they generate lower interference towards all BSs they are not assigned to. This allows the system to support more connections per BSs and, in practice, it is like if it would increase the capacity of the overall network.

V. Conclusions

We have proposed discrete optimization models for the UMTS BS location problem that capture at different level of detail the SIR contraints and the peculiarities of the PC mechanism. Starting from two randomized greedy heuristics that we presented in [2], we have devised a Tabu Search algorithm that, both in a multistart and single run setting, provides improved solutions in terms of costs and coverage. These algorithms have been extended to the SIR-based model and it has been shown that the solutions obtained with this model have substantially lower costs than those from the power-based model.

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