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Radio planning and coverage optimization of 3G cellular networks

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Abstract Radio planning and coverage optimization are critical issues for service providers and vendors that are deploying third generation mobile networks and need to control coverage as well as the huge costs involved. Due to the peculiarities of the Code Division Multiple Access (CDMA) scheme used in 3G cellular systems like UMTS and CDMA2000, network planning cannot be based only on signal predictions, and the approach relying on classical set covering formulations adopted for second generation systems is not appropriate.

In this paper we investigate mathematical programming models for supporting the decisions on where to install new base stations and how to select their configuration (antenna height and tilt, sector orientations, maximum emission power, pilot signal, etc.) so as to find a trade-off between maximizing coverage and minimizing costs. The overall model takes into account signal-quality constraints in both uplink and downlink directions, as well as the power control mechanism and the pilot signal.

Since even small and simplified instances of this NP-hard problem are beyond the reach of state-of-the-art techniques for mixed integer programming, we propose a Tabu Search algorithm which provides good solutions within a reasonable computing time. Computational results obtained for realistic instances, generated according to classical propagation models, with different traffic scenarios (voice and data) are reported and discussed.

Keywords 3G · UMTS · CDMA2000 · Radio planning · Base stations · Location · Configuration · Signal quality constraint · Mathematical programming models · Tabu Search

1 Introduction

In the last years 3G systems, such as UMTS [16, 30] and CDMA2000 [23], which are based on a more flexible but also more complex Wideband Code Division Multiple radio Access scheme (W-CDMA) [22], have been standardized and network deployment has started. Since providers and vendors have to face with the huge costs of the service licenses and the market situation has dramatically changed, there is an acute need for planning tools that help designing networks with good service coverage in a cost efficient way.

Due to the peculiarities of W-CDMA, the radio planning problem cannot be decomposed into a coverage problem and a frequency allocation problem, like it is the case for planning second generation cellular systems with a Time Division Multiple Access scheme (TDMA) [24–26, 31]. Indeed, in W-CDMA the bandwidth is shared by all active connections and no frequency assignment is required. Moreover, the area actually covered by a base station (BS) also depends on the signal quality constraints, usually expressed in terms of

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Signal-to-Interference Ratio (SIR), and on the traffic distribution [10]. Since *SIR* values depend on emission powers, the specific power control mechanism and the power limitations must be also taken into account.

To address the network planning problem for systems with W-CDMA air interface, the following data are usually supposed to be known: (i) a set of candidate sites where BSs can be installed, (ii) a set of possible configurations of each base station (sector orientation, tilt, height, maximum power, pilot power, etc.), (iii) the traffic distribution estimated by using empirical prediction models and (iv) the propagation description based on approximate radio channel models or ray tracing techniques and antenna diagrams. Although there clearly are some similarities with the problem of locating and configuring base stations in second generation systems, the above-mentioned peculiarities of W-CDMA air interface must be considered for 3G systems.

In earlier work [6] we proposed discrete optimization models and algorithms to support decisions in choosing the location of new BSs. In that work we considered signal quality constraints in the uplink direction (mobile to base station) and fixed BS configuration only, since the focus was on the viability of the approach.

That choice was justified by the fact that the uplink direction is more critical than the downlink one (base to mobile station) in the case of symmetrical traffic such as voice calls (see e.g. [22]). However, 3G systems are especially intended to provide data services which are expected to have a substantial impact on the downlink direction (e.g., web-browsing) and to yield asymmetrical traffic. This suggests that the downlink direction must be also considered [8]. Moreover, not only BS locations but also BS configurations and sector orientations have a strong impact on the traffic covered and the connection quality [5, 7].

In real system planning, optimizing BS configuration can often be more critical than BS location since service providers may have a very limited set of candidate sites due to authority constraints on new antenna installation and on electromagnetic pollution in urban areas [12]. Maximizing the coverage with the existing set of BSs by modifying their configurations, and adding new BSs only when they are strictly needed, can be one of the main objective of the planner. Due to the many issues that affect system performance, the network designer's task is quite complex and software planning tools based on optimization models and algorithms can make a substantial difference.

In this paper we investigate mathematical programming models for 3G radio planning which account for both uplink and downlink directions as well as for relevant BS configuration issues such as antenna height, tilt, and sectors orientation. Pilot signals, which are emitted by base stations so as to broadcast system information and to allow mobile terminals to select the best serving base stations, are also considered.

To evaluate *SIR* constraints, we consider power control (PC) at two levels of detail using: a power-based PC model, which assumes that emission powers are adjusted to guarantee a target received power, and a more sophisticated *SIR*-based PC model that assumes that emission powers are adjusted to guarantee a *SIR* target value to all active links.

Since even small and simplified instances of these NP-hard problems are beyond the reach of state-of-the-art techniques for mixed integer programming, we propose a Tabu Search algorithm for tackling the overall model with uplink and downlink directions. A simple but important idea is to exploit the insight gained from the simplified models to drastically reduce the computational time required to find good approximate solutions of the overall 3G base station location and configuration problem. This is achieved by deriving good initial feasible solutions of the overall model with a sophisticated *SIR*-based PC mechanism from the approximate solutions obtained for the uplink model with a simpler power-based PC mechanism.

Computational experiments have been carried out on realistic instances with signal predictions generated according to classical propagation models and with different traffic scenarios (voice and data).

The paper is organized as follows. In Section 2 we briefly summarize the most important issues of W-CDMA that affect coverage and capacity (see [6] for a more detailed description) and review the most relevant related work. The new base station location and configuration problem and optimization models are presented in Section 3, while our Tabu Search algorithm is described in Section 4. Computational results are reported in Section 5 where the solutions provided by the simplified models are compared for different scenarios. Finally, Section 6 contains some concluding remarks.

2 Radio planning for W-CDMA systems

2.1 Coverage and capacity

In W-CDMA cellular systems, the amount of traffic that can be served by each BS is not limited a priori by a fixed channel assignment as in TDMA (Time Division Multiple Access) systems, but it is implicitly limited by the interference levels in the service area [18]. This allows for a flexible use of radio resources depending on propagation conditions and interference sources distribution, but it makes the problem of radio network planning more complex since signal quality rather than signal strength must be considered to evaluate system coverage [10].

The signal quality is usually measured by the *SIR*. Signal quality constraints impose that the *SIR* exceeds a minimum value τ, which depends on the communication service considered (e.g., voice, video, packet data).

The *SIR* can be expressed as:

$$SIR = SF\frac{P_{received}}{\alpha I_{in} + I_{out} + \eta} \tag{1}$$

where $P_{received}$ is the received signal power, I_{in} is the total interference due to the signals transmitted by the same BS (intra-cell interference), I_{out} is that due to signals of the other BSs (inter-cell interference), and η the thermal noise power. α is the orthogonality loss factor ($0 \leq \alpha \leq 1$), which accounts for the orthogonality properties of spreading codes. In the uplink case, no orthogonality must be accounted for and $\alpha = 1$, while in the downlink case usually $\alpha \ll 1$. For the sake of simplicity, in the sequel we refer to the *SIR* before despreading and require that it is greater than $SIR_{min} = \tau/SF$.

The *SIR* level of each connection depends on the received powers. The PC mechanism dynamically adjusts the emitted power according to the propagation conditions so as to reduce the interference and satisfy quality constraints. For W-CDMA systems a *SIR-based PC mechanism* is usually adopted: the emitted power is adjusted through a closed-loop control procedure so that the *SIR* is equal to a target value SIR_{target} [30]. According to this scheme the power emitted by each station is strictly related to that emitted by all the others. A simpler *power-based PC model,* in which the emitted power is adjusted so that the power received on each channel is equal to a given target value P_{target}, can be also considered. In this case the emitted power for each connection simply depends on the attenuation between source and destination. Given any set of *SIR* constraints, the power-based PC mechanism yields higher powers compared with the more complex *SIR*-based PC one. Thus, from the network planning point of view, considering a power-based PC mechanism instead of a *SIR*-based PC one may lead to a more conservative dimensioning of the system [6].

Note that, with both PC mechanisms in the uplink direction, the powers received by a given BS from all mobile terminals in the cell are at the same level. The only difference is that the power-based PC uses the same power level for all BSs, while the *SIR*-based PC adjusts the received power level of each BS according to the inter-cell interference.

In the downlink direction, it can be observed that the two mechanisms lead to quite different behaviors. Indeed, the interference received by users connected to the same BS may be quite different. Therefore, *SIR*-based PC needs to set different received-powers for each mobile station to keep the *SIR* at the target value, while the power-based PC sets received-powers to a given value for all users.

Moreover, in the downlink case a power limitation on the total power emitted by each BS must be accounted for. However, to avoid that most of the BS power is used for transmission toward mobile terminals with bad propagation conditions, also a limit to the power used for each downlink transmission is usually adopted [22].

In the presence of symmetrical traffic such as circuit switched voice/video calls, the system capacity obtained considering only the uplink *SIR* constraints is in general smaller than that obtained considering only the downlink constraints. This is mainly due to the different levels of inter-cell interference (α values), see e.g. [22]. However, 3G cellular systems can also provide high-rate packet-switched data services with different speeds in uplink and downlink. In the presence of asymmetrical traffic due to applications, such as web browsing or e-mail, the system capacity may clearly be also limited by the downlink *SIR* constraints.

Besides base station location, also antenna configuration has a strong impact on the traffic covered and the connection quality. For instance, the interference in each cell of a three-sector antenna depends on its horizontal orientation which can be optimized taking into account traffic distribution. Since the vertical radiation diagram is not uniform, also the vertical orientation (tilt) of the antenna affects the *SIR* values. Smaller tilt angles tend to increase not only the coverage range but also the captured interference. Also the BS maximum power affects the area actually covered: a higher power allows to cover a wider area, but it also increases the interference generated towards the other cells. The above-mentioned parameters as well as antenna height can thus be tuned in order to maximize traffic coverage.

2.2 Related work

In [33] the modelling approach that describes the traffic distribution in terms of *demand nodes* is firstly proposed. Demand nodes (or *test points)* represent the center of an area characterized by a given traffic demand (usually expressed in Erlang). This approach is the most diffused in the wireless network planning literature.

In many contexts, radio planning is formulated in terms of minimum set covering problem [20, 25, 32]: the coverage problem is defined by considering the signal level in each test point from all BSs, and requiring that at least one level is above a fixed threshold. In [27, 28] explicit traffic capacity constraints are added for each base station. A different coverage model is adopted in [31] where the position of transmitters is chosen in a continuous 3-D space. Some works address network planning problems for CDMA systems but still rely on variations of the classical coverage approach [11, 14, 24].

In [17] a simplified model for locating BSs in CDMA-based UMTS networks is proposed and a Polynomial Time Approximation Scheme is presented. This model attempts to take into account interference, however, only the intra-cell interference is considered while the interference among BSs (inter-cell one) is neglected.

In [1] an optimization model for base station location and configuration is presented. The approach is quite different from those presented in most of the other works since it does not include the installation cost into the objective function being fixed the number of base stations whose location and configuration must be optimized. The model considers the uplink direction only, power-based PC and includes pilot signals, however it assumes that base station locations are continuous decision variables. The problem is solved using branch-and-bound and numerical results obtained for a set of example networks are presented.

In [2] an Automatic Cell Planning (ACP) tool for 3G networks based on genetic algorithms is presented. Unfortunately, no detail on the optimization model and the algorithms is provided.

In [15] the work carried out in the European project MOMENTUM on UMTS optimization is described. In particular various modelling aspects of the UMTS radio planning are discussed and a mathematical program is presented. As stated in the paper, the focus is to provide a model which includes as many system details as possible without considering, at least in the first stage, the difficulties in solving the problem. As a result the mathematical programs proposed are huge and beyond the reach of state-of-the-art MIP (Mixed Integer Linear Programming) solvers except for very small instances. As already mentioned, this approach is different from our approach since we decided to start from simple models adding complexity step-by-step. However, the model proposed in that paper is very interesting; it considers both network cost and service quality in the objective function and includes uplink and downlink SIR constraints, SIR based power control, the number of codes assigned to each connection, pilot signals, and antenna configuration.

3 Base station location and configuration problem

The base station location and configuration problem takes as input a set of *candidate sites* (CSs) $S = \{1, \dots, m\}$ where BSs can be installed, and for each candidate site $j \in S$ a set $K_j = \{1, \dots, l_j\}$ of possible BS configurations. Moreover, an installation cost c_{jk} is associated with each candidate site $j \in S$ and BS configuration $k \in K_j$, since the installation cost may vary with the BS location and configuration. 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 [32]. 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 to the average number of active connections or to a given percentile of the number of simultaneous calls. Function ϕ can also consider the connection activity factor.

The propagation characteristics of the radio channels between every pair of CS and TP are also supposed to be an input of the problem. They can be estimated by using prediction tools (e.g., the simple Hata's models, statistical models or ray tracing [29]) or obtained by actual measurements. Let $G = [g_{ijk}]$ be the propagation matrix, where g_{ijk}, $0 < g_{ijk} \leq 1$, is the gain factor of the radio link between TP i, $i \in I$, and a BS installed in CS j, $j \in S$, with configuration k, $k \in K_j$. We assume that all the characteristics of the radio link contribute to the propagation factor, including propagation from source to destination over multiple paths and radiation pattern of BS antenna.

In each CS j it is possible to install a BS with configuration k equipped with s identical sectors, for instance three 120 degree sectors. Let the index set $I_{jk}^{\sigma} \subseteq I$ denote the set of all TPs i that fall within the sector σ of the BS installed in CS j with configuration k. Obviously, for every pair j, k, $I_{jk}^1 \cup I_{jk}^2 \cup \cdots \cup I_{jk}^s = I$ and the index sets I_{jk}^{σ} with $\sigma = 1, \dots, s$, are disjoint if we assume that the antenna propagation factor is negligible outside the sector.

In the UMTS base station location and configuration problem one wishes to select a subset of candidate sites where to install directive BSs as well as their configurations, and to assign the TPs to the available BSs so as to maximize the traffic covered and/or minimize the installation costs.

To describe the mixed integer programming model, we consider the two following classes of binary variables:

$$y_{jk} = \begin{cases} 1 & \text{if a BS is installed in } j \text{ with configuration } k \\ 0 & \text{otherwise} \qquad\qquad \forall j \in S,\ k \in K_j \end{cases}$$

$$x_{ijk} = \begin{cases} 1 & \text{if TP } i \text{ is assigned to BS } j \text{ with configuration } k \\ 0 & \text{otherwise} \qquad\qquad \forall i \in I,\ J \in S,\ k \in K_j \end{cases}$$

If we assume a *SIR*-based PC mechanism, we also need for each TP $i \in I$ the continuous variables p_i^{up} to indicate the power emitted by the mobile in TP i towards the BS it is assigned to (uplink direction) and p_i^{dw} to indicate the power received at each TP i from the BS it is assigned to (downlink direction).

Note that by restricting the assignment variables x_{ijk} to assume binary values, it is required that in every feasible solution all active connections must be assigned to a single BS. Therefore, we do not consider soft-handover which requires that a TP can be assigned to more than one BS. Since soft-handover tends to increase *SIR* values, we may be too conservative, but this can be at least partially compensated for by decreasing the value of SIR_{min}. Moreover, we assume that the number of connections assigned to any BS does not exceed the number of available spreading codes. In uplink, there is a very large number of nonorthogonal codes, while in downlink, where there are at most *SF* orthogonal codes, standard cardinality constraints can be easily added to the model.

Although a budget could be imposed on the total installation costs, if we aim at a tradeoff between maximizing the total traffic covered and minimizing the total installation costs, we maximize:

$$\sum_{i\in I}\sum_{j\in J}\sum_{k\in K_j} u_i x_{ijk} - \lambda \sum_{j\in J}\sum_{k\in K_j} c_{jk} y_{jk} \tag{2}$$

where $\lambda \geq 0$ is a trade-off parameter between the two contrasting objectives.

The first three groups of constraints ensure the coherence of the location and assignment variables. Each TP i can be assigned to at most one BS:

$$\sum_{j\in S}\sum_{k\in K_j} x_{ijk} \leq 1 \quad \forall i \in I. \tag{3}$$

and at most one BS configuration can be selected for CS *j:*

$$\sum_{k\in K_j} y_{jk} \leq 1 \quad \forall j \in S. \tag{4}$$

If for a given CS j we have $y_{jk} = 0$ for all $k \in K_j$, no BS is installed in CS j.

A TP i can be assigned to a CS j only if a BS with some configuration k, $k \in K_j$, has been installed in j:

$$\sum_{k\in K_j} x_{ijk} \leq \sum_{k\in K_j} y_{jk} \quad \forall i \in I, \ \ j \in S \tag{5}$$

In uplink, the power emitted by any mobile terminal at TP i cannot exceed a maximum power $P_i^{max\text{-}up}$:

$$0 \leq P_i^{up} \leq P_i^{max\text{-}up} \quad \forall i \in I. \tag{6}$$

In downlink, besides the limit on the total power emitted by each BS j ($P_j^{tot\text{-}dw}$), we also consider an upper bound on the power used for each connection:

$$0 \leq p_i^{dw} \leq \sum_{j\in S}\sum_{k\in K_j} P^{max\text{-}dw} g_{ijk}\, x_{ijk} \quad \forall i \in I, \tag{7}$$

where $p^{max\text{-}dw}$ denotes the maximum power per connection. Thus BSs cannot use too much of their power for transmission towards mobiles with bad propagation conditions [22].

For the downlink direction, we also introduce for each CS j, $j \in S$, the power $\hat{p}_j$ of the pilot signal emitted by the BS installed in j. These pilot powers can either be considered as variables or, as a first approximation, be taken as equal to a fraction of the total power $P_j^{tot\text{-}dw}$ emitted by the BS:

$$\hat{p}_j = \delta_k P_j^{tot\text{-}dw} \quad \forall_j \in S \tag{8}$$

where δ_k is a parameter of the BS configuration k (for instance $\delta_k = 0.15$). Then the limit on the total power emitted by each BS j can be expressed as:

$$\sum_{i\in I}\sum_{k\in K_j} \frac{p_i^{dw}}{g_{ijk}} x_{ijk} + \hat{p}_j \leq P_j^{tot\text{-}dw} \sum_{k\in K_j} y_{jk} \quad \forall_j \in S. \tag{9}$$

Now let us turn to the *SIR* constraints, which express the signal quality requirements, and consider first the uplink direction. Given the *SIR*-based PC mechanism, for every triple of BS $j \in S$, configuration $k \in K_j$ and TP $i \in I$ we have the uplink *SIR* constraint:

$$\frac{p_i^{up} g_{ijk} x_{ijk}}{\sum_{h\in I_{jk}^{\sigma_{ijk}}} u_h p_h^{up} \cdot g_{hjk} \sum_{t\in S}\sum_{l\in K_t} x_{htl} - p_i^{up} g_{ijk} + \eta_j^{bs}} = SIR_{tar}\, x_{ijk}, \tag{10}$$

where η_j^{bs} denotes the thermal noise at BS j and $I_{jk}^{\sigma_{ijk}}$ denotes the set of all TPs in I that fall within the sector σ_{ijk} containing TP i. For any single connection between a TP i and a BS installed in CS j with configuration k, the numerator of the left-hand-side term corresponds to the power of the relevant signal arriving from TP h at CS j with BS configuration k while the denominator amounts to the total interference due to all other active connections in the system. The triple summation term expresses the total power received at the BS in j with configuration k from all TPs h that are served. Indeed, $p_h^{up} g_{hjk}$ indicates the power received at the BS j from TP h and, according to (3), $\sum_{t\in S}\sum_{l\in K_t} x_{htl}$ is equal to 1 if and only if TP h is assigned to a BS, namely is served. The total interference is then obtained by just subtracting the received power of the relevant signal.

In the downlink direction, the *SIR* constraints must also take into account the pilot powers. For every triple of TP $i \in I$ and BS $j \in S$ with configuration $k \in K_j$, we have the downlink *SIR* constraint:

$$\frac{p_i^{dw} x_{ijk}}{\alpha\left(\sum_{h\in I_{jk}^{\sigma_{ijk}}} u_h g_{ijk} \frac{p_h^{dw}}{g_{hjk}} x_{hjk} - p_i^{dw}\right) + \sum_{\substack{l\in S\\ l\neq j}}\sum_{z\in K_l}\sum_{h\in I_{lz}^{\sigma_{ilz}}} u_h g_{ilz} \frac{p_h^{dw}}{g_{hlz}} x_{hlz} + \hat{P}_i + \eta_i^{mt}} = SIR_{tar}\, x_{ijk} \tag{11}$$

where

$$\hat{P}_i = \alpha \hat{p}_j g_{ijk} + \sum_{\substack{l \in S \\ l \neq j}} \sum_{z \in K_l} \hat{p}_l g_{ilz} y_{lz} \qquad (12)$$

amounts to the interference at TP i due to all pilot signals. η_i^{mt} denotes the thermal noise of mobile terminal at TP i. For any single connection between a BS located in CS j with configuration k and a TP i falling in one of its sectors (denoted by σ_{ijk}), the numerator of the left-hand-side term corresponds to the power of the relevant signal received at TP i from the BS j (definition of p_i^{dw}) and the denominator amounts to the total interference due to all other active connections in the system. The interpretation of (11) is similar to that of (10) except for the pilot powers and for the orthogonality loss factor α in the *SIR* formula (1), which is strictly smaller than 1 in downlink.

Thus, summarizing, constraints (10) and (11) ensure that if a connection is active between a TP i and a BS j with configuration k (i.e., $x_{ijk} = 1$) then the corresponding *SIR* value is equal to SIR_{tar}.

Finally, for each triple BS j with configuration k and TP i, we have to consider an additional downlink *SIR* constraint regarding the pilot signal:

$$\frac{\hat{p}_j\, g_{ijk}\, x_{ijk}}{\alpha\left(\sum_{h \in I_{jk}^{\sigma_{ijk}}} u_h g_{ijk} \frac{p_h}{g_{hjk}} x_{hjk}\right) + \sum_{\substack{l \in S \\ l \neq j}} \sum_{z \in K_i} \hat{p}_l g_{ilz} y_{lz} + \sum_{\substack{l \in S \\ l \neq j}} \sum_{z \in K_l} \sum_{h \in I_{lz}^{\sigma_{ilz}}} u_h g_{ilz} \frac{p_h}{g_{hlz}} x_{hlz} + \eta_i^{mt}} = SIR_{\text{tar}}\, x_{ijk} \qquad (13)$$

The numerator of the left-hand-side term corresponds to the pilot power received at TP i from the BS j and the denominator amounts to the total interference due to all other signal including all other pilot powers.

The model that maximizes (2) subject to (3)–(13) is a non linear mixed integer program. Indeed nonlinear *SIR* constraints (10)–(13) contain products of assignment variables (x_{ijk} and y_{jk}) and power variables (p_i^{up} and p_i^{dw}).

It is worth pointing out that, if we assume a power-based PC mechanism instead of a *SIR*-based one, the model can be substantially simplified. Indeed, the powers p_i^{up} emitted from any TP i in uplink and the powers p_i^{dw} received at any TP i from the BS are given and they are no longer variable. Since all emitted powers are adjusted so as to guarantee a received power of P_{tar}, p_i^{up} and p_i^{dw}, for all $i \in I$, just depend on the value of P_{tar} and on the propagation factor of the corresponding radio links. To obtain the simplified model, we take into account that:

$$p_i^{up} = \sum_{j \in S} \sum_{k \in K_j} \frac{p_{tar}}{g_{ijk}} x_{ijk}, \quad p_i^{dw} = P_{tar} \qquad (14)$$

and in the *SIR* constraints we require that the left-hand-side terms of Eqs. (10), (11), and (13) are greater or equal to $SIR_{min} x_{ijk}$. The resulting *SIR* constraints, which have the general form

$$\frac{P_{tar}}{(\alpha I_{in} + I_{out} + \eta)} \geq SIR_{min} x_{ijk} \qquad (15)$$

where P_{tar} is a constant, and I_{in} and I_{out} are linear functions in the x and y variables, can be linearized as follows:

$$(\alpha I_{in} + I_{out} + \eta) \leq \frac{1}{SIR_{min}} + M_{ijk}(1 - x_{ijk}) \qquad (16)$$

for large enough values of the constants M_{ijk}.

It can be shown that the optimization problem in the power-based PC case is similar to the classical capacitated facility location problem [6] since the quality constraints amount to imposing an upper bound on the number of connections that can be assigned to that BS. As new users are added to the system, the *SIR* values of all the other users decrease until one falls below the lowest acceptable quality level SIR_{min}

4 Tabu Search algorithm

Since even small instances of the problem are often beyond the reach of state-of-the-art mixed integer programming techniques, we have developed a Tabu Search (TS) algorithm [19] to find good approximate solutions in a reasonable amount of time.

To provide starting solutions to the TS a simple constructive heuristic has been implemented. BSs are iteratively added to a set of active BSs $\bar{S}$, starting from $\bar{S} = \emptyset$ (i.e., $y_{jk} = 0, \forall j \in S,\ k \in K_j$). At every iteration, all remaining candidate sites $s \in S \backslash \bar{S}$ are added one at a time to the active set $\bar{S}$ selecting a possible configuration c. The corresponding variables y_{sc} are set to 1 and the associated assignment variables $x_{ijk}, \forall i \in I,\ j \in S,\ k \in K_j$, are calculated. For each possible configuration c, the objective function (2) is evaluated and that providing the best value is taken as utility function $U(\bar{S} \cup \{s\})$. At every iteration one $s' \in S \backslash \bar{S}$ is randomly selected among a pre-defined fraction of those that yield the highest value of U. The procedure stops when the addition of a new BS worsens the current solution value according to objective function U.

TS is a meta-strategy for guiding local search to overcome local optimality; it uses the history of the search process through an appropriate memory scheme to prevent cycling (exploring solutions that have already been generated) and examines regions of the solution space that are promising in terms of the objective function.

Our adaptation of TS to the BS location and configuration problem starts from an initial solution s^0 described by a set of active BSs $\bar{S} \subseteq S$. A set of neighboring solutions $N(s^0)$ is then generated by applying the following "moves" to s^0: *add*, which adds a BS in a CS with the best configuration according to the objective function, *remove,* which removes a BS installed in a given CS and *swap,* which installs a BS in a CS j_1 with the best configuration while deleting another in CS j_2. Note that changing the configuration of a single BS can be considered as a particular case of a *swap* move: in this situation a BS with a given configuration is substituted by the same BS with another configuration. The best solution in the "neighborhood" $N(s^0)$ is then selected as the next iterate s^1 even if it does not strictly improve the value of the objective function and the process is repeated to generate a sequence of solutions $\{s^k\}$.

In order to prevent cycling and try to escape from local optima a list of "tabu moves" is maintained: BSs that are installed (disactivated) cannot be disactivated (reinstalled) during L iterations, where L is the length of the Tabu list. Note that, according to "aspiration criteria", tabu moves are accepted if they lead to an improved solution with respect to the current best. Finally, the best solution encountered is stored as the algorithm proceeds and it is returned after a maximum number of iterations max_{it}.

To make this procedure computationally effective, several enhancements are needed.

Since exploring all possible swap moves for any given current solution would be very time consuming even for small-size instances, a first improvement can be achieved by focusing on swaps between candidate sites that are relatively "close" to each other. For each active CS j we consider the set $C_j \subseteq S$ of max_{swap} available sites that have the largest propagation gains with respect to j; then, set a parameter q such that $0 < q < 1$, we evaluate all the swaps involving the $max_{swap}q$ best sites, while the remaining sites in C are considered with a given probability q', $0 < q' < 1$.

Moreover, looking for even approximate solutions of the *SIR*-based model is very cumbersome computationally even for instances with a moderate number of TPs. Indeed, just computing the transmitted powers corresponding to a given assignment of TPs to BSs involves inverting a $n \times n$ matrix. This operation has to be done each time a single transmitted power has to be changed: clearly, this produces a great computational effort. Moreover, there is no straightforward way of handling power constraints (6) and (7): indeed, if some of the calculated powers p_i do not satisfy them, the solution cannot be considered as feasible. To cope with the above-mentioned problems, we adapted an iterative method to find the power levels [9]. This method, which is sketched below, allows for a substantial reduction of computational time. See also [13] for another fast computation algorithm recently proposed.

We assume that new users arrive one at a time and that, before each arrival, power levels are assigned so that all users achieve their SIR_{tar}. A new user i is given a starting power level that is just high enough to overcome the current interference. For instance, in the uplink direction we consider

$$p_i^{up} = \frac{SIR_{tar}}{g_{ij}} \left(\sum_{h \in I_j^i} u_h g_{hj} \sum_{t=1}^{m} p_h^{up} x_{ht} - p_i^{up} g_{ij} + \eta \right). \qquad (17)$$

Then all power levels are iteratively updated taking into account the additional interference due to the new user. Since power levels are monotonically increased during iterations, the procedure can only be applied if the initial value of the power assigned to the new user does not exceed its upper bound.

More precisely, emitted powers are adjusted as follows:

1. set the power p_i of the new user according to the interference level before the user arrival, namely according to Eq. (17) for uplink;
2. compute the *SIR* levels (SIR_j) of all users according to Eq. (10) for uplink or Eq. (11) for downlink;
3. iteratively adjust the emitted powers of all users j, including that of the new user i, according to:

$$p_j^{new} = min\left\{ p^{max}, \ \frac{p_j^{old} SIR_{tar}}{SIR_j^{old}} \right\}; \qquad (18)$$

4. the procedure stops if: (1) any power exceeds its upper bound; (2) all *SIR* levels are above the target value (a tolerance margin is considered). In the former case the problem is considered to be infeasible, while in the latter case it is feasible. If none of these conditions is verified within a maximum pre-defined number of iterations the procedure ends and the problem is considered infeasible.

A similar procedure is also used to estimate the emitted powers and pilot powers in the downlink direction.

5 Computational results

In this section we present some numerical results obtained from the application of our Tabu Search algorithm to some instances. The aim of these numerical experiments is not only to show the effectiveness of our algorithm on realistic instances but also to point out the impact of some modelling issues, such as BS configurations and traffic characteristics, on the solution obtained by using the complete model or simplified models which considers the power-based PC and/or the uplink direction only.

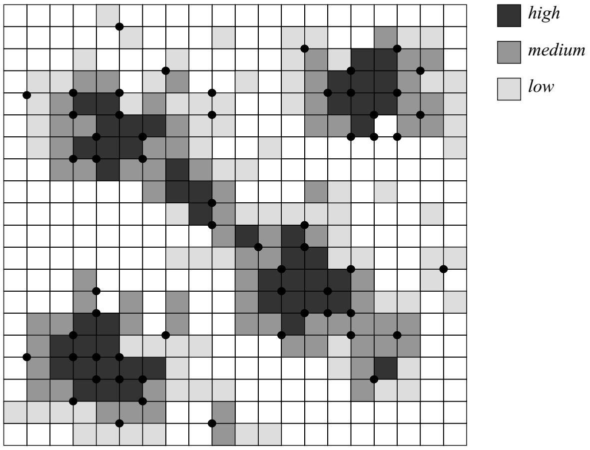

Fig. 1 Synthetic but realistic instances

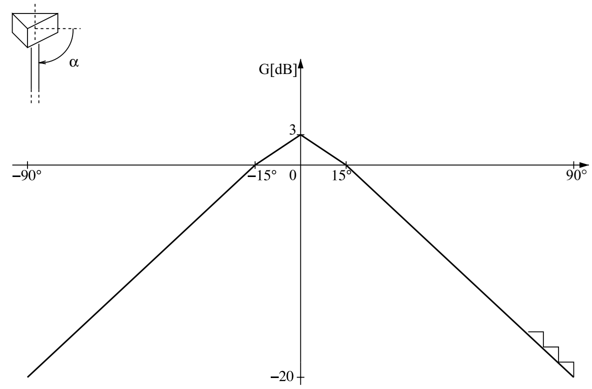

Fig. 2 Vertical antenna diagram

The propagation matrix **G** is obtained by using classical Hata's formulas [21] which give the attenuation A (loss) in dB due to signal propagation as a function of the distance between transmitter and receiver, the transmission frequency, and the base and mobile stations heights (see [3, 4, 6]). Moreover, we take into account the antenna tilt by considering a simplified vertical radiation diagram (see Fig. 2) and the angle in the vertical plane obtained considering the ray between the BS antenna (whose height is also a configuration parameter) and the mobile terminal (whose height is set to 2 m).

In the following sections we present the numerical results obtained with the above described instances. The computation times reported have been evaluated running the algorithms on a PC AMD-athlon 1000 MHz with 512 Mbyte RAM.

5.1 Instance generator

To test the proposed algorithm we have considered synthetic but realistic instances. To generate these instances we have developed an instance generator tool which aims at simulating the traffic distribution of urban areas surrounded by suburban areas and the candidate sites location which is usually selected by service providers considering traffic intensity in the area. For each instance we consider a square service area $D \times D$, a number m of candidate sites in which to locate three-sector antennas and a number n of TPs. To select the position of TPs and CSs we divide the area into $d \times d$ smaller regions through a regular grid (see Fig. 1). In each region we can locate a *high* (H), *medium* (M) or *low* (L) number of TPs, or even no TP at all. The number of regions with H, L, M TPs is set to $n_H,\ n_L,\ n_M$ respectively, so that $H \cdot n_H\ + M \cdot n_M + L \cdot n_L = n$.

Using a pseudo-random number generator we first select which regions are assigned a number H of TPs. To each region i is associated a weight w_i initially set to 1. Regions are iteratively picked with a probability $P_i = w_i/(\sum_i w_i)$. After each iteration the weight w_i of the selected region is set to zero, and the weights of the neighboring regions are increased by 1. Once all n_H TPs with high traffic have been selected, the n_M TPs with medium traffic and the n_L TPs with low traffic are selected with the same procedure. This mechanism produces realistic instances characterized by clusters of regions with high traffic surrounded by regions with lower traffic as usually observed in cities and their suburban areas. The position of CSs is also randomly selected in the set of crossing points of the regular grid. The procedure adopted is similar to the previous one: to each grid point is assigned a weight equal to the number of TPs in the four adjacent regions. After each iteration the weight of the selected point is set to zero and the weights of its neighboring points are increased by 1.

5.2 Tradeoff parameter

In the planning process, the balance between installation cost and coverage is extremely delicate. Indeed, depending on the importance that the planner gives to these two contrasting criteria, the model yields different solutions.

In Fig. 3 we show the trade-off between coverage and cost for an instance with $m = 45$ CSs and $n = 881$ TPs. Note that this type of curve, which provides useful insight into the best way to balance the two contrasting objectives, can be easily computed by adapting our Tabu Search algorithm so as to look for approximate solutions with a prescribed number of BSs. If none of the two objectives has a much higher priority than the other, one may be interested in non-dominated (Pareto-optimal) solutions.

In the following sections, to make the numerical results easily readable we have adopted the same cost for all BSs, and reported separately the coverage (No. of TPs served) and the cost (BSs installed). Clearly, the coverage and cost values also depend on the value of the trade-off parameter λ in (2). We selected a small λ so as to favour solutions with a good coverage.

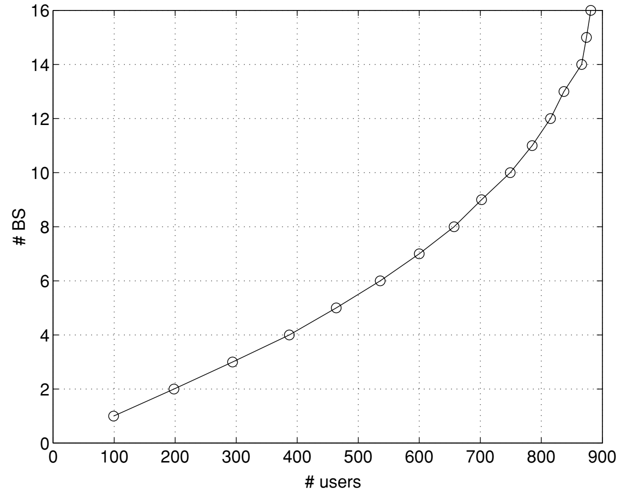

Fig. 3 Trade-off between the traffic coverage and the number of BSs installed: instance with 881 TPs and 45 CSs, BS location and horizontal sector orientation

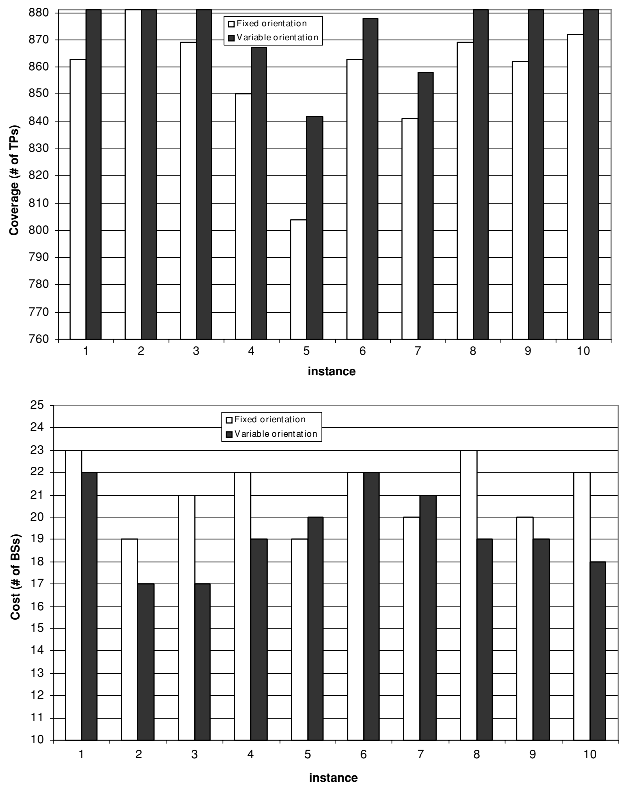

Fig. 4 Results obtained with fixed (white bars) and variable sector orientations (black bars): $n = 881$, $m = 45$

5.3 BS configuration

To evaluate the effect of optimizing BS configuration on the traffic coverage and the total installation cost we have considered the simplified model including the uplink quality constraints only. The following configurations have been taken into account: BS antenna height (which has an impact on **G** through Hata's formula), antenna tilt (whose impact on **G** is due to the translation of the vertical antenna radiation diagram), and sector orientation (which defines the sets I^{σ}_{jk}). More specifically, we consider 0, 30, 60 or 90 degree rotations, 10, 20, 30 or 40 degree tilts with respect to the vertical axis and 5, 10, 20, 30 meter heights above ground level. Note that we have selected these values due to the simplified propagation model and antenna diagram which are not very sensitive with respect to small changes. With more accurate models it is expected that even small differences in configuration parameters lead to relevant coverage variations.

We report some typical results obtained for randomly generated instances with $n = 881$ TPs and a 1005×1005 m service area which is subdivided into 225 square regions of about 67×67 meter. The number of regions with high, medium and low traffic, respectively, are: $n_H = 45$, $n_M = n_L = 68$, and the corresponding number of TPs per region are: $H = 9$, $M = 5$, and $L = 2$.

Figure 4 shows the results obtained with the Tabu Search algorithm considering either fixed sector orientations or variable ones (while tilts and heights are fixed). The reported ten instances consider $m = 45$ CSs. Notice that, in all the cases, optimizing the sector orientation yields a higher traffic coverage and/or a lower number of BSs installed. Of course the price to pay is a higher computation time. The computation

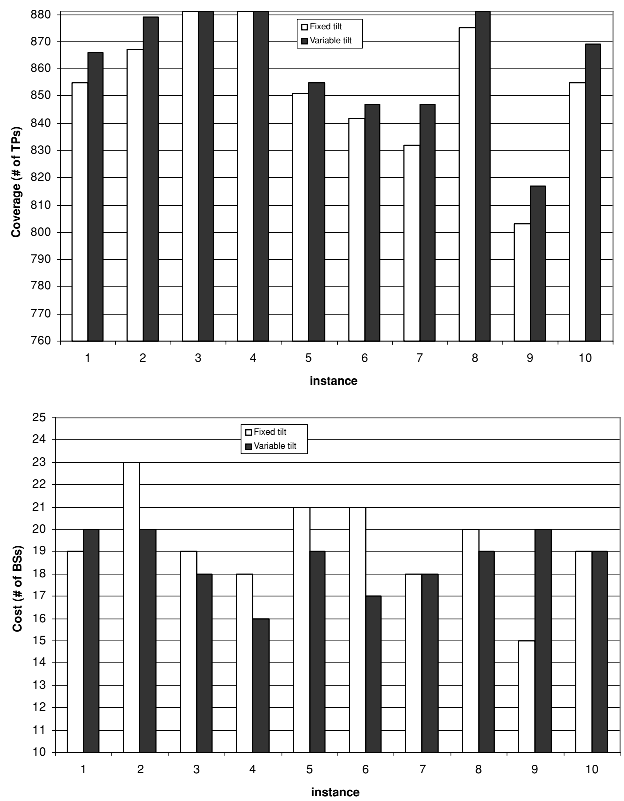

Fig. 5 Results obtained with fixed (white bars) and variable antenna tilt (black bars): $n = 881$, $m = 55$

time for the fixed orientation case is approximately 15 min, while that for the variable orientation is 4 h.

Figure 5 shows the results obtained with the Tabu Search algorithm considering either fixed or variable antenna tilts (while sector orientations and heights are fixed). The reported ten instances consider $m = 55$ CSs. Notice that, in all the cases, optimizing the antenna tilts yields a higher traffic coverage and/or a lower number of BSs installed. The computation time is approximately 15 min for the fixed tilt case, and 4 h and 30 min for the variable tilt.

Figure 6 shows a comparison between three scenarios: in the first one only sector orientations can be optimized, in the second one only antenna tilts while in the third one both set of parameters are simultaneously optimized (while heights are fixed). As expected, tuning sector orientations as well as tilts can yield substantial improvements in traffic coverage and/or installation cost. Again, this is paid with a higher computation time. The computation time is approximately 4 h for the variable orientation case, 4 h and 30 min for the variable tilt case, and 40 h for the case in which both tilt and orientation are optimized.

In Fig. 7, for a medium size instance ($m = 20$ CSs, $n = 390$ TPs and a 500×500 meter area), the solutions obtained by simultaneously optimizing BS location and con-

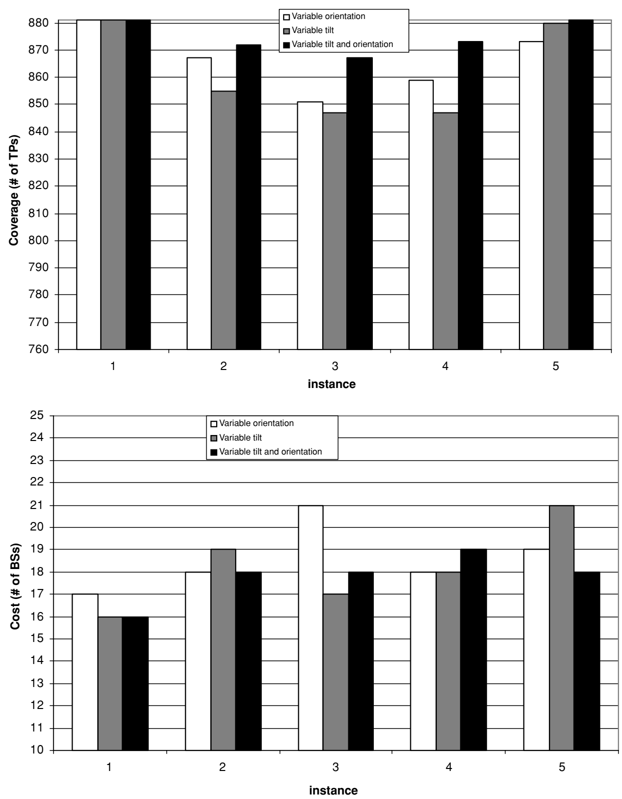

Fig. 6 Best solutions obtained with variable orientations (white bars), variable tilts (grey bars), and variable orientations and tilts (black bars): $n = 881$, $m = 55$

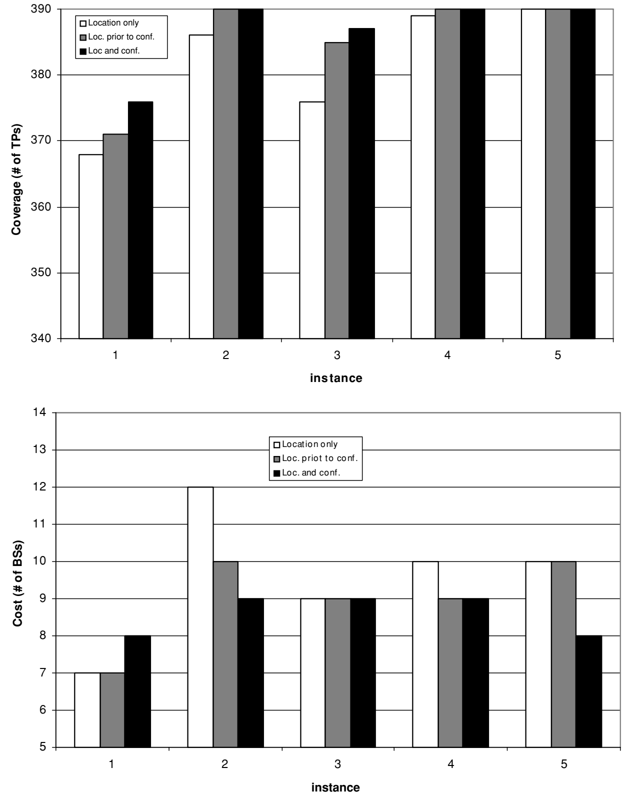

Fig. 7 Results obtained with location only (white bars), when location and configuration are separately optimized (grey bars) or simultaneously optimized by using the general model (black bars)

figuration (orientation and tilt, while heights are fixed) are compared to those resulting from location only and from a two-phase approach in which first the BS locations are selected and then the configurations are optimized. Notice that our general location-configuration model leads to better results even though similar Tabu Search procedures are used to separately optimize locations and configurations and require computation times only slightly higher (approximately 2 min for the location only, 2 h for the location prior to configuration case, and 2 h and 20 min for the location and configuration case).

5.4 Uplink and downlink SIR constraints

In this section we discuss the effect of uplink and downlink SIR constraints. In previous work [6] we discussed the importance of power control mechanisms in 3G network planning. Indeed, the *SIR* depends on the received powers which in turn depend on the transmitted ones: therefore, these powers have to be adjusted by the PC mechanism so as to minimize interference and guarantee quality.

As shown in [6], in uplink direction the power-based PC mechanism gives good results, even if it is more conservative than the *SIR*-based one. Yet, the latter needs extremely high

Table 1 Left columns: Results obtained with the Tabu Search algorithm for the overall model with uplink and downlink *SIR*-based constraints. Right columns: results obtained for a simplified uplink model with power-based PC and then evaluated with both uplink and downlink constraints

Uplink and downlink			Power-based uplink		
TPs dw	TPs up	No. of BSs	TPs dw	TPs up	No. of BSs
881	859	26	806	872	23
881	878	19	881	864	19
864	854	22	856	855	22
800	796	20	785	801	20
746	797	24	758	738	19
881	879	18	881	856	17
860	841	21	852	837	21
881	872	20	870	868	22
853	832	22	841	803	20
881	870	24	881	832	22

Table 2 Left columns: Results obtained with the Tabu Search algorithm for the overall model with uplink and downlink *SIR*-based constraints, sector orientation is also considered. Right columns: results obtained for a simplified uplink model with power-based PC and then evaluated with both uplink and downlink constraints, sector orientation is also considered

Uplink and downlink			Power-based uplink		
TPs dw	TPs up	No. of BSs	TPs dw	TPs up	No. of BSs
881	871	23	881	860	22
881	881	22	881	881	23
878	880	20	877	878	20
862	842	22	828	862	21
849	735	24	773	732	19
881	881	17	881	881	17
875	865	21	874	859	21
881	881	19	881	881	19
881	881	20	881	881	20
881	881	20	881	881	21

computational time, which is in uplink direction almost 10 times higher than the power-based one.

In downlink direction the difference between the results obtained with *SIR*-based PC mechanism and power-based one becomes more relevant than in uplink direction: with the addition of the pilot signals this difference is still more increased [8].

This substantial difference is mainly due to the wide range in which the emitted power levels may vary in downlink direction, thus generating high intra-cell and inter-cell interference. In the presence of a power-based PC mechanism the emission powers, which are selected to guarantee a P_{tar} level at the receiving end, are often much higher than needed to yield *SIR* values equal to SIR_{min}, thus producing high interference levels. On the contrary, with a *SIR*-based PC the emission powers are selected in order to have a signal quality exactly equal to SIR_{tar}, thus keeping the interference levels under limited values. This in turn leads to solutions having excellent coverage with a limited number of BSs.

Due to the above considerations, we focused our attention on the joint uplink and downlink model with *SIR*-based PC.

In Table 1 we report in the three left-hand-side columns the results obtained with our Tabu Search algorithm for the overall model with *SIR*-based PC on realistic large-size instances including pilot signals but with fixed configurations. There are $m = 45$ CSs and 881 points where a total of $n = 1762$ TPs are located, 881 producing voice traffic in the uplink direction and 881 receiving traffic on the downlink direction.

In three right-hand-side columns of Table 1 we report the solutions produced by a simplified uplink model with power-based PC subsequently evaluated considering the uplink and downlink model with SIR-based PC presented in Section 3. The results are quite similar to that in the left part of the table since in the considered scenario only uplink constraints limit system capacity even with the uplink and downlink model. This confirms that in the presence of symmetric traffic the most relevant direction from a planning point of view is the uplink one (see also [8]). But above all, it suggests that the computational load required to find good solutions to the overall model is substantially lower when exploiting the solutions of the simplified model (two-stage approach)

Table 3 Results obtained for downlink (fixed configurations) assuming *SIR*-based PC with pilot signal and without pilot signal: $n = 881$, $m = 45$

SIR-based downlink with pilot signal		*SIR*-based downlink without pilot signal	
Served TPs	No. of BSs	Served TPs	No. of BSs
814	12	881	9
872	20	881	14
709	11	881	8
881	16	881	11
825	16	881	10
760	16	881	11
881	16	881	10
860	17	881	12
868	17	881	12
881	18	881	13

than when directly applying Tabu Search to the overall model. The Tabu Search algorithm for the uplink model with power-based PC is indeed about 50 times faster than the version for the overall model: it requires approximately 5 min in the first case and 4 h and 15 min in the second one.

Table 2 is the analogue of Table 1 for the case with configurable sectors orientation (fixed tilts and heights). When also antenna rotations are optimized, one can clearly achieve a higher traffic coverage and/or install a lower number of BSs.

Finally, Table 3 shows the impact of the introduction of pilot signals in 3G planning: these signals considerably reduce the available power at BSs, thus worsening the quality of the results obtained without them. Moreover, pilot signals themselves have to satisfy some *SIR*-constraints (see 13): again, this produces a degrading of the quality of the results.

6 Concluding remarks

We have presented a mathematical programming model to optimize the location and configuration of BSs in 3G networks taking into account both uplink and downlink directions, with pilot signals included, and assuming a *SIR*-based PC mechanism. A Tabu Search algorithm, which starts from the solutions provided by a randomized greedy algorithm, has been proposed to find good approximate solutions within a reasonable amount of computational time. To make the algorithm computationally effective, we adapted iterative method to find the power levels of the signals emitted by TPs or BSs.

Unlike for the uplink model with power-based PC, in downlink the more accurate model with *SIR*-based PC is required. Moreover, the results obtained with the combined model including uplink *SIR*-based as well as downlink *SIR*-based constraints indicate that by starting from the solutions provided by the simplified uplink model with power-based PC, computing times are reduced by a factor of fifty without heavily affecting the solutions' quality. Besides, the introduction of pilot signals obviously worsen the solutions' quality in downlink direction but makes the results more realistic.

Finally, we can assert that the fact of considering and studying separately the uplink and downlink direction models as well as a power-based PC mechanism or a *SIR*-based one has yielded a striking improvement from the computational point of view and has given us a better insight into the overall BS location and configuration problem.

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References

1. R.G. Akl, M.V. Hegde, M. Naraghi-Pour and P.S. Min, Multicell CDMA network design, IEEE Trans. on Vehicular Technology 50(3) (2001) 711–722.
2. Z. Altman, J.M. Picard, S. Ben Jamaa, B. Fourestie, A. Caminada, T. Dony, J.F. Morlier and S. Mourniac, New challenges in automatic cell planning of UMTS networks, in: *Proceedings of IEEE Vehicular Technology Conference Fall (VTC Fall, 2002)* (2002)
3. E. Amaldi, A. Capone and F. Malucelli, Discrete models and algorithms for the capacitated location problem arising in UMTS network planning, in: *Proceedings of the 5th International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIAL-M)* (ACM, 2001) pp. 1–8.
4. E. Amaldi, A. Capone and F. Malucelli, Improved models and algorithms for UMTS radio planning, in: *Proceedings of IEEE VTC Fall, 2001* (2001).
5. E. Amaldi, A. Capone and F. Malucelli, Optimizing UMTS radio coverage via base station configuration, in: *The 13th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIRMC'02),* Vol 1 (2002) pp. 315–319.
6. E. Amaldi, A. Capone and F. Malucelli, Planning UMTS base station location: Optimization models with power control and algorithms. IEEE Transactions on Wireless Communications 2(5) (2003) 939–952.
7. E. Amaldi, A. Capone, F. Malucelli and F. Signori, UMTS radio planning: Optimizing base station configuration, in: *Proceedings of IEEE VTC Fall 2002,* Vol. 2 (2002) pp. 768–772.
8. E. Amaldi, A. Capone, F. Malucelli, and F. Signori, Optimization models and algorithms for downlink UMTS radio planning, in: *Proceedings of IEEE Wireless Communications and Networking Conference (WCNC'03)* (2003).
9. M. Berg, *Radio Resource Management in Bunched Personal Communication Systems*. Technical Report, Kungl Tekniska Hogskolan (KTH), Stockholm, Sweden (2002).
10. E. Berruto, M. Gudmundson, R. Menolascino, W. Mohr and M. Pizarroso, Research activities on UMTS radio interface, network architectures, and planning, IEEE Communications Magazine (1998) 82–95.
11. P. Calégari, F. Guidec, P. Kuonen and D. Wagner, Genetic approach to radio network oprimization for mobile systems, in: *Proceedings of IEEE VTC 97* (1997) pp. 755–759.
12. M. Cappelli and L. Tarricone, A bioelectromagnetic overview of the universal mobile telecommunication system (units), in: *Proceedings of IEEE MTT-S International Microwave Symposium Digest* (2002).
13. D. Catrein, L. Imhof and R. Mathar, Power control, capacity, and duality of up- and downlink in cellular CDMA systems. Technical Report, RWTH Aachen (2003).
14. B. Chamaret, S. Josselin, P. Kuonen, M. Pizarroso, B. Salas-Manzanedo, S. Ubeda and D. Wagner, Radio network optimization with maximum independent set search, in: *Proceedings of IEEE VTC 97* (1997) pp. 770–774.
15. A. Eisenblatter, A. Fugenschuh, T. Koch, A. Koster, A. Martin, T. Pfender, O. Wegel and R. Wessaly, Modelling feasible network configurations for UMTS, in: *Telecommunications Network Design and Managment* (Kluwer, 2003) pp. 1–22.
16. M. Gallagher and W. Webb, UMTS the next generation of mobile radio, IEE Review 45(2) (1999) 59–63.
17. M. Galota, C. Glasser, S. Reith and H. Vollmer, A polynomial-time approximation scheme for base station positioning in UMTS networks, in: *Proceedings of the 5th International Workshop on Discrete Algorithms and Methods for Mobile Computing and Communications (DIAL-M)* (ACM, 2001) pp. 52–59.

18. K.S. Gilhousen, I.M. Jacobs, R. Padovani A.J. Viterbi, L.A. Weaver and C.E. Wheatley, On the capacity of a cellular CDMA system, IEEE Trans. on Vehicular Technology 40 (1991) 303–312.
19. F. Glover and M. Laguna, *Tabu Search* (Kluwer Publishers, 1997).
20. Q. Hao, B.-H. Soong, E. Gunawan, J.-T. Ong, C.-B. Soh and Z. Li, A low-cost cellular mobile communication system: A hierarchical optimization network resource planning approach. IEEE Journal on Selected Areas in Communications 15 (1997) 1315–1326.
21. M. Hata, Empirical formula for propagation loss in land mobile radio service. IEEE Trans. on Vehicular Technology 29 (1980) 317–325.
22. H. Holma and A. Toskala, *WCDMA for UMTS* (Wiley, 2000).
23. M.R. Karim, M. Sarraf and V.B. Lawrence, *W-CDMA and cdma2000 for 3G Mobile Networks* (McGraw Hill Professional, 2002).
24. C.Y. Lee and H. G. Kang, Cell planning with capacity expansion in mobile communications: A tabu search approach. IEEE Trans. on Vehicular Technology 49(5) (2000) 1678–1690.
25. R. Mathar and T. Niessen, Optimum positioning of base stations for cellular radio networks, Wireless Networks (2000) 421–428.
26. R. Mathar and M. Schmeink, Optimal base station positioning and channel assignment for 3 g mobile networks by integer programming, Annals of Operations Research 107 (2001) 225–236.
27. A. Molina, G.E. Athanasiadou and A.R. Nix, Cellular network capacity planning using the combination algorithm for total optimization, in: *Proceedings of IEEE VTC* (2000) pp. 2512–2516.
28. A. Molina, G.E. Athanasiadou and A.R. Nix, Optimized base station location algorithm for next generation microcellular networks. Electronic Letters 36(7) (2000) 668–669.
29. D. Parsons. *The Mobile Radio Propagation Channel* (Wiley and Sons, West Sussex, 1996).
30. A. Samukic, UMTS universal mobile telecommunications system: Development of standards for the third generation, IEEE Transactions on Vehicular Technology 47(4) (1998) 1099–1104.
31. H.D. Sherali, M. Pendyala and T. Rappaport, Optimal location of transmitters for micro-cellular radio communication system design. IEEE Journal on Selected Areas in Communications 14(4) (1996) 662–673.
32. K. Tutschku, Demand-based radio network planning of cellular mobile communication systems, in: *Proceedings of the IEEE INFOCOM'98,* Vol. 3 (1998) pp. 1054–1061.
33. K. Tutschku, N. Gerlich and P. Tran-Gia, An integrated approach to cellular network planning, in: *Proceedings of the 7th International Network Planning Symposium—Networks, 96* (1996).

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