Mobile Network Planning Issues

Rodney Rambally, Yufei Wu
University of Trinidad and Tobago
John Donaldson Campus, Port of Spain, Trinidad

ABSTRACT

There are many issues that have to be considered during planning phase of 3G networks. Some of the most important factors are: quality of service (QoS), cost of implementation and provisioning, traffic coverage ratio, and resource utilization. This paper analyzes planning aspects of 3G mobile radio network deployment and proposes optimization models which explicitly take into account some important factors such as QoS and power control. It proposes a tabu search algorithm to solve the overall planning problem considered as NP-hard. Computational experiments with realistic problem sizes are conducted to describe some important aspects of efficient 3G deployment, and show both the efficiency and the practicality of the tabu search algorithm.

Keywords: Mobile network planning and optimization, NP-hard, Tabu Search

1. INTRODUCTION

This paper analyzes planning issues of mobile radio network deployment, and provides some insights into efficient network planning and optimization and choosing a good planning objective by taking into account operators' business demands.

Section II presents a mobile network planning and optimization model. Section III describes the solution structure and search strategies. Section IV demonstrates experimentally that the model and the proposed tabu search algorithm can efficiently find good solutions for realistic 3G deployment scenarios.

2. SYSTEM MODEL

In this section, we present the system model for the third generation mobile hierarchical cell planning and optimization problem. We also define the decision variables, design constraints and objective functions.

Working area and traffic

A set of sites are candidates for the positioning base stations, denoted by $S = \{1,\ldots, m\}$, where a base station (BS) can be installed and that an installation and maintenance cost C_j is associated with each candidate site j, $j \in S$. Each site is defined by its coordinates (x, y), and eventually by z (height above sea level).

A set of traffic test points (TPs) $I = \{1,\ldots, n\}$ is assumed. Each TP $i \in I$ can be considered as a centroid where a given amount of traffic d_i is requested and where a certain level of service (measured in terms of *SIR*) must be guaranteed [1]. The required number of simultaneously active connections for TP i, denoted by u_i, turns out to be a function of the traffic, i.e., $u_i = f(d_i)$. The mobile terminals are located on TPs, where the network must overcome a signal quality threshold *SIRmin*, to ensure a given quality of service (QoS). The value of the threshold depends on the service type. To check the signal quality threshold on each TP, the signal strength is computed on each point [2].

Decision variables

In general, a BS antenna can be in one out of q different configurations, denoted by set $L = \{1,\ldots,q\}$. A configuration represents a sextuplet BS = (location, type, height, tilt, azimuth, power). This accounts, for instance, for a variable tilt selected out of a set of possible angles with respect to the vertical axis, and for a variable height selected from a finite set of values with respect to the ground level. Since propagation gains depend on the BS antenna configuration, we denote by the propagation gain from TP i to potential site j if the BS antenna is in configuration w. The decision variables are needed for each configuration:

$$x_{ijw} = \begin{cases} 1 & \text{if TP } i \text{ assigned to BS } j \\ & \text{with configuration } w \\ 0 & \text{otherwise} \end{cases} \qquad (1)$$

$$y_{jw} = \begin{cases} 1 & \text{if BS } j \text{ with configuration } w \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

for $i \in I$, $j \in S$ and $w \in L$. Once these basic decisión variables have been determined, other dependent system variables, such as loading factors and SIR for each mobile terminal, etc., can be easily derived from [3].

Decision constraints

Constraints (3) make sure that each TP i is assigned to at most one BS. Note that by restricting the assignment variables x_{ijw} to take binary values, it is required that in every feasible solution all active connections must be assigned to a single BS.

$$\sum_{j \in S} \sum_{w \in L} x_{ijw} \leq 1 \tag{3}$$

If the left terms of constraints (3) were forced to be equal to one, that is, each TP must connect to a BS, the results would too demanding for network resources. In some cases, a feasible solution would not be found. Therefore, constraints (3) are relaxed and allow some TPs not to be assigned.

Constraints (4) are called minimum service requirements, which ensure that service is available in the working area that have at least a proportion β of all traffic demand nodes.

$$\sum_{j \in S} \sum_{w \in L} \sum_{i \in I} \mu_i x_{ijw} \geq \beta . \sum_{i \in I} \mu_i \tag{4}$$

In our model, the cost of a BS involves the cost of site installation and cost of the configuration:

$$C_j(y_{jw}) = C_j^S + C_j^L \tag{5}$$

The overall cost of a radio access network in the predefined working area, C(**y**), is the sum of the non-configuration cost of each BS antenna C_j^S , and its associated configuration cost , i.e., $C(\mathbf{y}) = \sum_{w \in L} \sum_{j \in S} y_{jw} . C_j(y_{jw})$. Cost is an extremely important factor for choosing an adequate network configuration. Denote C_{max} an externally given ceiling cost, or a budgetary limit in total monetary investment. In most cases, it is practical to consider the budget constraints (6).

$$\sum_{w \in L} \sum_{j \in S} y_{jw} . C_j(y_{jw}) \leq C_{max} \tag{6}$$

$$x_{ijw} \leq \min\left\{1, \frac{g_{ij}^w P_{\max}}{P_{tar}}\right\} y_{jw} \tag{7}$$

Constraints (7) correspond to the most stringent constraints among the coherence constraint $x_{ijw} \leq y_{jw}$, which ensures that TP i is only assigned to site j if a BS with configuration w is installed in j, and the power limit on a single connection from BS j to TP i:

$$\frac{P_{tar}}{g_{ij}^w} x_{ijw} \leq P_{\max} y_{jw} \tag{8}$$

where P_{max} is the maximum emission power for the connection from site j to TP i and P_{tar} / g_{ij}^w corresponds to the emission power required by BS j to guarantee the target received power P_{tar} at TP i.

$$\sum_{i \in I} \frac{P_{tar}}{g_{ij}^w} x_{ijw} \leq P_{tot} y_{jw} \tag{9}$$

For each pair of site $j \in S$ and TP $i \in I$, constraints (8), which are active only if TP i is assigned to BS j (i.e., $x_{ijw} = 1$), correspond to the signal quality requirement. Finally, constraints (9) impose an upper limit P_{tot} on the total emission power of every BS.

In addition to the constraints (8) and (9), the quality of service constraints should be emphasized. Since in a power-based power control mechanism P_{tar} / g_{ij}^w is the power that needs to be emitted from a BS with configuration w in site j to guarantee a received power of P_{tar} at TP i. For each connection between a BS installed in j and a TP i falling in a sector of this BS, the *SIR* constraints can be expressed as follows [4]:

$$\frac{P_{tar} x_{ijw}}{I_{inter} + I_{intra}} \geq SIR_{\min} x_{ijw} \tag{10}$$

Equation (11) represents the total interference incurred in the same cell, whereas Equation (12) describes the interference from all the other BSs, measured at mobile unit i in the service area.

$$I_{intra} = \alpha \left(\sum_{\substack{k \in I_j^{\sigma_{ijw}} \\ x_{kjw}=1}} u_k \frac{g_{ij}^{w} P_{tar}}{g_{kj}^{w}} x_{kjw} - P_{tar} \right) \qquad (11)$$

$$I_{inter} = \sum_{v \in L} \sum_{\substack{l \in S \\ l \neq j}} \sum_{\substack{k \in I_l^{\sigma_{ilv}} \\ x_{kl}=1}} u_k \frac{g_{il}^{v} P_{tar}}{g_{kl}^{v}} x_{klv} \qquad (12)$$

where for any site $l \in S$, $w \in L$, the index set $I_l^{\sigma_{ilw}}$ denotes the set of all TPs in I that fall within the sector σ_{ilw} of the BS with configuration w and location l, which contains TP i.

Problem formulation

Our aim is to formulate the mobile downlink planning problem as an example planning problem. The available cell sites (S), the traffic demand nodes (I) with capacity requirements (μ), configuration set (L) are fixed input parameters. We will introduce three formulations of the cell planning problem. In all cases, the following variables are the basic decision variables. Based on these basic decision variables, most of radio access network parameters can be derived from[4].

1) The number of selected base stations and their configuration, denoted by multi-dimensional vector ***y***.
2) The capacity assignment matrix, ***x***.
3) The power assignment vector (mobile transmitter participation), ***p***.

1) Minimal Cost Planning: A practical objective deals with the price of the solution in terms of installation and provision costs. In this formulation, the goal of the planning is to achieve as low cost as possible.

Instead of optimizing the technical performance, such as coverage outage, which would potentially lead to a network with unnecessary high resource usage, we choose the objective for minimizing the network cost. The planning objective is defined as follows:

$$\text{Minimize} \quad \sum_{w \in L} \sum_{j \in S} y_{jw} . C_j(y_{jw}) \qquad (13)$$

2) Maximum Capacity Planning: A more real-life formulation of the cell planning problem is to aim for maximizing the satisfied capacity demands. The optimization problem can be written as:

$$\text{Maximize} \quad \sum_{w \in L} \sum_{j \in S} \sum_{i \in I} \mu_i x_{ijw} \qquad (14)$$

The objective function is the sum of the served capacity demands. The constraints for this optimization scenario are the same as in the previous formulation.

3) Maximum Profit Planning: This model explicitly considers the trade-off between the revenue potential of each BS site with its cost of installation and configuration. This trade-off is subject to QoS constraints in terms of sufficient SIR ratios (constraints (10)). The objective of the model is to maximize the total annual profit generated by the cellular network operator, which is equal to the total annual revenue minus the annual costs. Mathematically we have:

$$\text{Maximize} \quad \Big[\theta \sum_{w \in L} \sum_{j \in S} \sum_{i \in I} \varepsilon \mu_i x_{ijw} - \sum_{w \in L} \sum_{j \in S} y_{jw} . C_j(y_{jw}) \Big] \qquad (15)$$

ε denotes the annual revenue ($) generated by each channel utilized in the working area. θ is a weighting factor. Relation (15) represents the maximum profit optimization when $\theta = 1$.

All three formulations (13), (14) and (15) are subject to constraints (3) – (12).

3. SOLUTION PROCEDURE

In order to apply tabu search to solve the planning problem, we need to define [5]:

1) An initial feasible solution.
2) Representations for feasible solutions.
3) Neighborhoods for feasible solutions.
4) Search techniques for neighborhoods, and
5) Evaluation methods for gains in objective values.

Solution structure and neighborhood

Decision variables are the BS locations, their powers, their antenna heights, etc. Given these decision variables, a radio access network configuration can be defined as a set of vectors $[(p_1, h_1, \ldots), \ldots, (p_m, h_m, \ldots)]$, which can be represented abstractly by the network configuration vector ***y***. In practice, configuration parameters can take values from a certain range.

After y is decided, every traffic demand node TP $i \in I$

is assigned to a serving BS using a capacity assignment algorithm, described later in this section, that is, to determine the capacity assignment pattern, denoted by vector $\boldsymbol{x}$.

Each feasible search space point, denoted by $\boldsymbol{J}(x, y)$, is a particular set of locations, powers, heights, and other configurations for each BS, and a particular assignment pattern of traffic demand nodes to each selected BS satisfying the various constraints. To generate a new neighbor, two sets of neighborhood generating operators are required, one that moves the locations and configurations of BSs and another that changes the capacity assignment pattern for each BS. The first set of operators is defined as follows:

1) *On-Off:* a BS site is chosen randomly. If there is a BS at the site, it is removed. If there is no BS at the site yet, a new BS is placed at the site.
2) *Local Move:* one of the decision variables (power, height, or other configuration parameters) of a randomly chosen BS is appointed randomly, and the new neighbor is generated by taking its value one size above or below its current value.

Capacity assignment algorithm

The second set of operators is the capacity assignment algorithm. Given the locations of BSs, their powers, heights and other configurations, demand nodes I should be assigned first to the available BS that has the largest signal attenuation factor before establishing connections to other BSs [3]. The algorithm works like this:

1) *Step 0:* Start with a given radio access network configuration $\boldsymbol{y}$.
2) *Step 1:* For each $i \in I$, calculate minimum power P_{tar}/g_{ij}^{w} according to propagation matrix G = [g_{ij}^{w}]; assign demand node i to its closest BS j, requiring the minimal transmit power; calculate $\boldsymbol{x}$. Constraints (7) are automatically satisfied.
3) *Step 2:* If $\boldsymbol{x}$ from Step 1 and $\boldsymbol{y}$ satisfy constraints (9), go to Step 3; otherwise repeat the process: randomly select and disconnect a demand node i belonging to the overcrowded BS j, which will reduce its transmit power accordingly, until constraints (9) are satisfied.
4) *Step 3:* If $\boldsymbol{x}$ from Step 2 and y satisfy constraints (10), go to Step 4; randomly select and disconnect a demand node i belonging to the overcrowded BS j, which reduces its transmit power, until constraints (10) are satisfied.
5) *Step 4:* Output final capacity assignment vector $\boldsymbol{x}$.

4. EXPERIMENTAL RESULTS

In pure capacity maximization planning, the network cost is not included in the optimization process, which may result in network configurations with unnecessarily high cost. In pure cost minimization planning, the capacity is not included in the optimization process, which may result in network configurations with unacceptable low capacity. Our purpose with the following quantitative examples is to illustrate the tradeoff between capacity and cost. Table 1 contains important planning input data.

TABLE 1: 3G MOBILE PLANNING DATA

Parameters	Values
Mobile antenna height	1.8 m
Frequency	2 GHz
Mobile antenna gain	0 db
BS antenna gain	14 db
SIR_{min}	0.009789
E_b/I_o	7 db
Processing gain	512
Mobile receiver sensitivity	-110 dBm
WCDMA orthogonality	0.7
Thermal noise density	-130 dBm/Hz
Annual revenue per channel	$10,000

From Table 2, intuitively, BS antenna height configuration costs are not significant when compared to other cost components. This means that the antenna heights are not important in cost optimization, but important in capacity optimization, because antenna heights are a dominating factor in determining coverage area and received power strengths at traffic demand node points. We apply tabu search to solve the above planning problem, but using alternative objective functions, according to the following three scenarios:
1) *Capacity Optimization (CO):* Cost is completely disregarded during the optimization, the objective function is formulated in relation (14) to maximize the served traffic in the working area (or minimize the number of unserved traffic points where some constraints are not satisfied (outage). For simplicity, we call this scenario pure capacity optimization.

TABLE 2: ANTENNA PARAMETERS

Max transmit power		BS antenna height	
Permitted values (watts)	Cost (unit $K)	Permitted values (m)	Cost (unit $K)
20	100	10	10
40	150	20	20
80	200	30	30

2) Cost Optimization (COST): Capacity factor is completely ignored during the optimization, the objective function is formulated in relation (13) to minimize the total cost and hopefully find the cheapest feasible network configuration during the optimization process.

3) Combined Cost and Capacity Optimization (COM): Cost is part of the objective function, according to relation (15). The weighing factor θ allows us to give priority to either minimizing cost or maximizing capacity. To find an appropriate value for θ, a number of alternative values have been applied, and the results are subject to comparisons based on a large number of independent tabu search executions. Fig. 1 summaries the results of four representative values, $\theta = 0.1$, 1.0 and 10.

Low θ value results in low success in terms of finding high capacity feasible network configurations, which can be attributed to the possibility to sacrifice one or more traffic demand nodes to obtain a cheaper network configuration. This phenomenon is demonstrated by the low traffic service ratio (capacity) as well as by the apparently low total cost figures, as it is exemplified by the $\theta = 0.1$ case in Fig. 1. The $\theta = 1$ case already represents a situation where network configurations have on average a higher capacity and cost than feasible configurations with low network cost. The $\theta = 10$ case makes solutions cluster than $\theta = 1$. Increasing θ further does not lead to additional capacity improvement (not shown here).

Fig. 2 summaries the results of the three optimization cases *CO*, *COST*, *COM* in terms of the total cost of the obtained network configurations. The histograms are generated from the results of 100 independent tabu search runs for each of the three cases.

We use the same parameters and test cases as above for *CO*, *COST*, and *COM*, and apply $\theta = 1$ for *COM*. It can be seen that pure cost optimization case yields considerable cost reduction when at least 40% traffic demand must be satisfied. It is believed that pure cost optimization case would not select any BS if we did not specify a minimum traffic satisfaction requirement.

Likewise, pure capacity optimization yields considerable cost increase. Here we assume that the budgetary constraint allows no more than 20 BS sites installed. The combined cost and capacity optimization case lies somewhere between two extreme cases, striking a meaningful tradeoff. For explanation we can look at Table 3, which contains that statistical results of 100 resulted network configurations found by tabu search for each objective (*CO*, *COST*, *COM*). The resource utilization of the networks is measured by the average number of BS transmitters in the networks, average total power, average height of antennas in the networks and by the average cost. Besides the average values over the 100 runs, we indicate the parameters of the best found network in terms of cost.

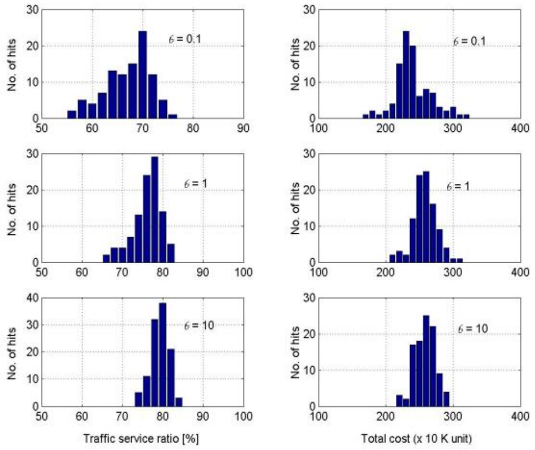

Fig. 1: Resulting overall traffic coverage ratios and total cost histograms for three different capacity weighting factors, $\theta = 0.1$, 1 and 10.

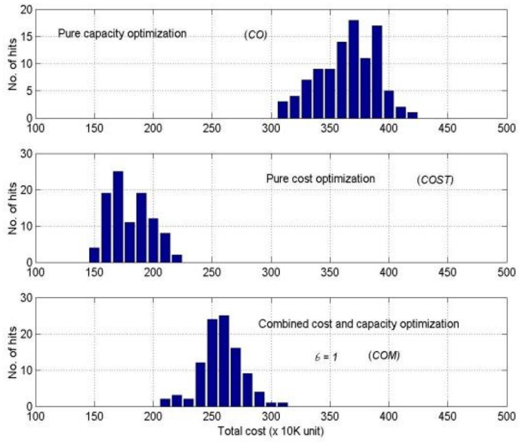

Fig. 2: Resulting total cost values for pure capacity optimization, pure cost optimization, combined cost and capacity optimization ($\theta = 1$).

Comparing the statistical values, the total power usage of these three cases are very similar. In pure capacity optimization, the results favor networks with a larger number of lower BSs. In contrast to that, networks of the pure cost optimization contain fewer BSs with higher structural antenna.

Comparing the best achievable results of *CO* and *COM*, the total power usage (i.e., *CO*, 56.81 dBm and *COM*, 55.05 dBm) and the average antenna height (*CO*, 17.05 m and *COM*, 17.50 m) are approximately the same for both objectives, but the number of BSs is decreased from 12 (*CO*) to 8 (*COM*).

TABLE 3: SUMMARY OF ALLOCATED RESOURCES FOR SCENARIOS *CO, COST, COM*

Optimization case	*CO*		*COST*		*COM* (θ = 1)	
	best	mean	best	mean	best	mean
No. of BS	12	14.78	5	6.60	8	10.71
Total power	56.81	57.29	53.98	55.46	55.05	56.17
Average power	46.02	45.59	46.99	47.27	46.23	45.87
Average height	17.05	16.08	22.00	22.12	17.50	17.48
Total cost	3060	3745	1410	1866	2040	2727

Measurement Unit: power [dBm], height [m] and cost[$K]

This result indicates that the network remains "over-provisioned" under *CO*, that is, the optimization does not attempt to remove unnecessary BSs, neither to cut back

5. CONCLUSION

This paper analyzes planning aspects of mobile radio network deployment and proposes optimization models which explicitly take into account some important factors such as QoS and power control. It also proposes a tabu search algorithm to solve the overall planning problem considered as NP-hard. Future work should focus on developing better algorithms and models which incorporate multi-traffic scenarios, existing network expansion, and time factors.

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