A Novel View on Cell Coverage and Coupling for UMTS Radio Network Evaluation and Design*

Andreas Eisenblätter,[1,2] `eisenblaetter@atesio.de`
Hans-Florian Geerdes,[2] `geerdes@zib.de`

[1]atesio GmbH, Berlin, Germany
[2]Zuse Institute Berlin (ZIB), Germany

Abstract

UMTS radio network evaluation and design are currently important issues for telecommunication operators. We present a novel view on network evaluation. The recent dimension reduction approach is generalized to an analytical approximation of the network's general performance based on average traffic. The pivot is an average coupling matrix that captures the essential coverage and cell coupling properties of the radio network. Based on this new evaluation method, we present new optimization methods, namely a new optimization model based on designing the generalized average coupling matrix and an efficient 1-opt local search. We give preliminary computational results that show the potential of our methods on realistic data.

Keywords: Radio Network Design, WCDMA, UMTS, Integer Programming, Radio Network Performance Evaluation

1 Introduction

Telecommunication operators are currently deploying UMTS radio network across the world. How to design the network to efficiently serve the users with high quality radio services is a key question in this context. We address how to configure the base stations antennas in pursuit of an effective network design.

Radio Network Design and Tuning. Given a user distribution and potential antenna installations for each cell, we want to design a network with good coverage and appropriate capacity. If possible without compromising these two goals, cells should be eliminated to save infrastructure. There is no generally accepted definition of an "optimal" UMTS network. Many aspects are relevant, see [9]. Installation parameters for a cell include antenna height, tilt, and azimuth (horizontal direction). The differences among potential antenna installations for one cell show mainly in the signal propagation properties, that is, the radio signal's attenuation between user and antenna. We only address the downlink direction (transmissions from base station to mobile user), since it is supposed to be the limiting direction. A more detailed treatment of UMTS radio network design and the methods presented here can be found in [3].

Related Work. A survey charting the evolution of centralized planning for cellular systems is given in [18]. Optimization models for UMTS planning based on snapshots are suggested in [1, 5]. Integer programming methods for 3G network planning are presented in [11]. Some papers deal with subproblems [14, 2, 10]. A landmark monography on technical aspects of UMTS is [9]. Network design using metaheuristics is performed in [6, 7, 8].

---

*Supported by the DFG research center Matheon "Mathematics for key technologies" in Berlin within project B4.

2 Load Evaluation Based On Average Traffic

Recently, closed linear characterizations of the receive and transmit powers for UMTS cells have been presented [12, 16]. From these characterizations, individual transmit powers for the up- and downlink of all mobiles can be derived. They can be used to significantly speed up snapshot-based UMTS network evaluations (during simulations or automatic network optimization). We generalize these characterizations by basing them on average traffic intensities instead of an individual snapshot. This generalization is the basis for the new network design methods presented subsequently. The characterizations are obtained under the assumptions that *perfect power control* applies to all dedicated radio links, that no cell is in overload, and that no restrictions are imposed on the transmit powers of base stations and mobiles. Only the downlink case is of interest for our purposes here.

For cell i, let $\bar{p}_i^{\downarrow}$ denote the total transmit power in the cell, $\check{p}_i^{\downarrow}$ the cumulative power of all (not power-controlled) common channels, and $p_i^{(\eta)}$ the power the cell needs to emit for its users under the assumption that all receptions are interference free, that is, the power needed for overcoming noise only. Moreover, let $C^{\downarrow}$ denote a square matrix containing the interference coupling within cells (on the diagonal) and between cells. A linear equation system allows to derive the total cell transmit powers given the other terms:

$$\bar{p}^{\downarrow} = \left(I - C^{\downarrow}\right)^{-1} \cdot (p^{(\eta)} + \check{p}^{\downarrow}) \tag{1}$$

We give the definitions of $p_i^{(\eta)}$ and $C^{\downarrow}$ for the simple case that no soft hand-over and no interference raise (cf. [15]) is taken into account. The definitions are more involved in the general case.

We start out in the "traditional" setting of a snapshot. For mobile m, let $\alpha_m^{\downarrow} \in (0, 1]$ denote the service-specific transmit activity, $\mu_m^{\downarrow}$ the service-specific CIR target, and $\bar{\omega}_m \in [0, 1]$ the fraction of own-cell signals that is received as interference due to loss of code orthogonality in the radio propagation environment. Moreover, let $\gamma_{im}^{\downarrow}$ denote the end-to-end attenuation between cell i and mobile m, and let M_i be the set of users served by cell i. Mobile m can be associated with a server independent *downlink user load* $l_m^{\downarrow}$ defined as:

$$l_m^{\downarrow} := (\alpha_m^{\downarrow}\, \mu_m^{\downarrow})/(1 + \bar{\omega}_m\, \alpha_m^{\downarrow}\, \mu_m^{\downarrow}) \tag{2}$$

This quantity is the key to defining the *traffic noise power* $p^{(\eta)}$ and the *downlink coupling matrix* $C^{\downarrow}$:

$$p_j^{(\eta)} := \sum_{m \in M_j} \frac{\eta_m}{\gamma_{jm}^{\downarrow}}\, l_m^{\downarrow}\,, \qquad C_{ii}^{\downarrow} := \sum_{m \in M_i} \bar{\omega}_m\, l_m^{\downarrow}\,, \qquad C_{ij}^{\downarrow} := \sum_{m \in M_i} \frac{\gamma_{jm}^{\downarrow}}{\gamma_{im}^{\downarrow}}\, l_m^{\downarrow} \quad (i \neq j) \tag{3}$$

Under the above assumptions, equation (1) can be obtained as follows. The starting point is the CIR equation (!) that determines the transmit power $p_{im}^{\downarrow}$ of the radio link between a cell i and mobile m in the presense of intra-/inter-cell interference and noise: $(\gamma_{im}^{\downarrow}\, p_{im}^{\downarrow})/(\gamma_{im}^{\downarrow}\, \bar{\omega}_m\, (\check{p}_i^{\downarrow} + \sum_{n \in M_i, n \neq m} p_{in}^{\downarrow}) + \sum_{j \neq i} \gamma_{jm}^{\downarrow}\, (\check{p}_j^{\downarrow} + \sum_{n \in M_j} p_{jn}^{\downarrow}) + \eta_m) = \mu_m^{\downarrow}$. The equations for all cells and mobiles define a linear system for the dedicated link powers. The total transmit power of cell i is defined as $\bar{p}_i^{\downarrow} = \sum_{m \in M_i} \alpha_m^{\downarrow}\, p_{im}^{\downarrow} + \check{p}_i^{\downarrow}$. Substituting the $p_{im}^{\downarrow}$ terms and solving for the total cell powers completes the argument.

We now generalize the definitions (2) and (3) beyond snapshots by extending them to spatial (average) traffic intensity. This allows to apply the transmit power equation (1) directly based on (average) traffic intensities. Let S be the set of all services offered and let T_s, $s \in S$ be the service-specific average traffic distribution, and let $T_s(p)$ denote the average traffic intensity of service s at location p. The definition of user load is generalized to the average traffic at $p \in A$:

$$l_p^{\downarrow} := \sum_{s \in S} \frac{\alpha_s^{\downarrow}\, \mu_s^{\downarrow}}{1 + \bar{\omega}_p\, \alpha_s^{\downarrow}\, \mu_s^{\downarrow}}\, T_s(p) \tag{4}$$

The average (downlink) coupling matrix and traffic noise power are now defined by substituting the sum over all users in the cell by the integral over the average load in the cell's area A_i:

$$p_i^{(\eta)} := \int_{p \in A_i} \frac{\eta_p}{\gamma_{ip}^{\uparrow}}\, l_p^{\downarrow}\, dp\,, \qquad C_{ii}^{\downarrow} := \int_{p \in A_i} \bar{\omega}_p\, l_p^{\downarrow}\, dp\,, \qquad C_{ij}^{\downarrow} := \int_{p \in A_i} \frac{\gamma_{jp}^{\downarrow}}{\gamma_{ip}^{\downarrow}}\, l_p^{\downarrow}\, dp \tag{5}$$

3 The Matrix Design Model of Cell Coverage and Coupling

The performance properties of a network design on a snapshot can be largely described by the coupling matrices $C^{\uparrow}$ and $C^{\downarrow}$ derived in Section 2. The generalized average coupling matrices provide an estimation of the network properties that is independent of single snapshots. This is central to our new perspective on radio network design, namely, as a problem of designing a "good" average coupling matrix.

Let $\mathcal{I}$ denote the set of all potential installations. We describe a network design by an incidence vector $z \in \{0,1\}^{|\mathcal{I}|}$. For a feasible network design, we have to choose exactly one installation for each cell. We call the set of network designs that fulfill this condition $\mathcal{F} \subset \{0,1\}^{|\mathcal{I}|}$. All entries in row i of the coupling matrix are computed by integrating over the area A_i served by cell i. For determining the elements of the coupling matrix, it is therefore crucial to determine these best server areas.

Server of Single Points. Consider a point p in the planning area. We introduce a decision variable $c_i^{(p)}$ that expresses whether p is served by installation i. This is the case if and only if a) installation i is selected and b) no installation with a stronger signal at p is selected. In the example in Fig.1, p is served by i if and only if installation j (and not k) is selected for the right-hand cell. Assuming that the pilot powers of all antennas are set to the same value, this depends only on the attenuation values $\gamma^{\downarrow}$. We denote by $D_i^{(p)}$ the set of all installations that *dominate* i at p:

$$D_i^{(p)} := \left\{ j \in \mathcal{I} \, : \, \gamma_{jp}^{\downarrow} > \gamma_{ip}^{\downarrow} \right\}$$

In the example, only k dominates i at p, hence $D_i^{(p)} = \{k\}$. We have the relation $c_i^{(p)} = 1 \Leftrightarrow z_i = 1 \wedge z_j = 0 \; \forall \, j \in D_i^{(p)}$. This relation can be expressed by linear inequalities as follows:

$$c_i^{(p)} \geq z_i - \sum_{g \in D_i^{(p)}} z_g \, , \qquad c_i^{(p)} \leq z_i \, , \qquad c_i^{(p)} \leq 1 - z_g \quad \forall \, g \in D_i^{(p)} \tag{6}$$

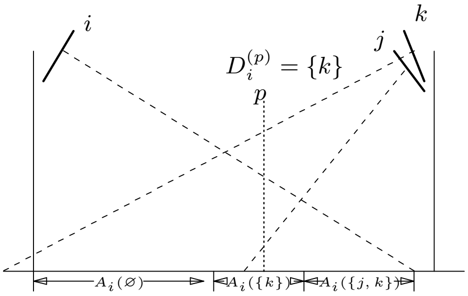


Figure 1: Example

Partitioning the Planning Area. The above construction can be carried out for all points in the planning area. The area served by installation i is then the set of all points $p \in A$ with $c_i^{(p)} = 1$. However, this linear description of the area served by i may be very large. On the other hand, the description for a single point p depends only on the set $D_i^{(p)}$ of installations that dominate i at p: all points with the same set of installations dominating i will lead to the same inequalities (6). We aggregate these points into one set. This yields a partition of the planning area A according to the installations that dominate i. For a given set $D \subset \mathcal{I}$, $i \notin D$ of installations, we define $A_i(D)$ as the set of points in which exactly the installations in D dominate i:

$$A_i(D) \quad := \quad \left\{ p \in A \, : D_i^{(p)} = D \right\}$$

These sets do not actually form a partitioning of the area, since there might be many points receiving the same signal strength from different installations. This can be resolved by breaking ties arbitrarily (which is on all accounts valid if the set of such points is very small). However, a more refined version of this model should include soft handover and thereby deal with regions of similar signal strength from several installations in a different way. Assuming that there are no "ties", we have

$$A = \biguplus_{D \subset \mathcal{I}} A_i(D)\,.$$

The example partitioning generated by installation i is shown in Fig.1. Either all points in $A_i(D)$ are served by i or none, depending on whether any installation in D is selected. We thus define a binary variable $c_i^{(D)} \in \{0, 1\}$ stating whether this is the case, and couple it to the decision variables z in analogy to (6). For a given network design $z \in \mathcal{F}$ we then know that

$$A_i(z) = \biguplus_{D \subset \mathcal{I}\,:\, c_i^{(D)}=1} A_i(D)\,. \tag{7}$$

We obtain a mathematical programming model that describes the best server area of any network design. This can be used to calculate both the main diagonal entries of the downlink coupling matrix and the (interference dependent) off-diagonal entries.

Calculating Main Diagonal Entries and Noise Load. Using the partitioning (7) of A_i, we can calculate the main diagonal entries of $C^{\uparrow}$ and the corresponding noise load $p^{(\eta)}$ for any network design $z \in \mathcal{F}$ by subdividing the computation of the integrals in (5) accordingly:

$$C^{\downarrow}_{ii}(z) = \sum_{D \subset \mathcal{I}} \left(\int_{p \in A_i(D)} \bar{\omega}_p \, l^{\downarrow}_p \, dp \right) c_i^{(D)}\,, \qquad p_i^{(\eta)}(z) = \sum_{D \subset \mathcal{I}} \left(\int_{p \in A_i(D)} \frac{\eta_p}{\gamma^{\downarrow}_{ip}} \, l^{\downarrow}_p \, dp \right) c_i^{(D)} \tag{8}$$

Calculating Off-Diagonal Entries. The same principle can be used to determine the off-diagonal elements of $C^{\downarrow}$. The element $C^{\downarrow}_{ij}$ is influenced by the settings for installation i and j. We thus introduce another dependent binary variable $c_{ij}^{(D)}$ that specifies whether any contribution to $C^{\downarrow}_{ij}$ is generated on $A_i(D)$. This is the case if $A_i(D)$ belongs to the service area of installation i and installation j is selected, that is $c_{ij}^{(D)} = c_i^{(D)} \cdot z_j$. This product of binary variables can be transformed to three linear inequalities in the canonical way:

$$c_{ij}^{(D)} \le z_j\,, \qquad c_{ij}^{(D)} \le c_i^{(D)}\,, \qquad c_{ij}^{(D)} \ge c_i^{(D)} + z_j - 1$$

The entry $C^{\downarrow}_{ij}$ is now determined for any network design $z \in \mathcal{F}$ in analogy to (8):

$$C^{\downarrow}_{ij}(z) = \sum_{D \subset \mathcal{I}} \left(\int_{p \in A_i(D)} \frac{\gamma^{\downarrow}_{jp}}{\gamma^{\downarrow}_{ip}} \, l^{\downarrow}_p \, dp \right) c_{ij}^{(D)}$$

Coverage. There is another condition for a point to be served by installation i: the pilot signal has to be received with sufficient absolute strength ($\mathrm{E_c}$ coverage) and signal quality ($\mathrm{E_c/I_0}$ coverage) for the user to register with the network. We only treat the first point here. Assuming a fixed pilot power level, this means that the attenuation $\gamma^{\downarrow}_{ip}$ to any point p served by in question must not fall below a threshold value $\bar{\gamma}$. This condition can easily be added to the definition of $A_i(D)$. For imposing additional coverage constraints (e. g. that 99% of the area A must be covered by the network), we can then use the area covered by the cell of installation i:

$$|A_i(z)| = \sum_{D \subset \mathcal{I}} |A_i(D)|\; c_i^{(D)}$$

4 Computational Results

We apply the methodology presented in the previous sections to realistic radio planning scenarios from the EU project MOMENTUM [13, 4], which are publicly available.

Optimization Methods. The first method we are using for network optimization is a simple but efficient local search scheme. In a 1-opt procedure, all variations to single cells are tested for improvement of the overall network quality. This can be implemented in various ways, using different objective functions, etc. It is not obvious how to use the model developed in Section 3 for finding radio networks with a “good” load distribution, We sketch a basic proposal. The first idea is that networks with unequally distributed load among neighboring cells are undesirable. If cell coupling/interference is ignored, the load distribution can be read off the main diagonal of the coupling matrix. For achieving a good *load balancing*, we propose to reduce the gap between load in neighboring cells. We currently experiment with different notions of neighborhoods. Interference, on the other hand, is reflected by the off-diagonal entries. We thus propose to use a sum of the load differences and all off-diagonal elements as objective function for network design:

$$\min \quad \sum_{\substack{i,j \\ \text{Neighbors}}} |C^{\downarrow}_{ii}(z) - C^{\downarrow}_{jj}(z)| + \sum_{i \neq j} C^{\downarrow}_{ij}(z) \tag{9}$$

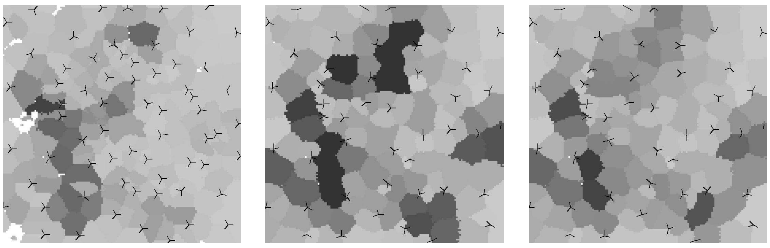
$$\text{s.t.} \quad \sum_{i \in \mathcal{I}} |A_i(z)| = |A| \tag{10}$$

$$z \in \mathcal{F}$$

In addition, we impose through (10) that the entire planning area is covered by the network (If this is not possible, the right-hand side of (10) can be reduced accordingly.) For radio networks of practice-relevant size (say, hundreds of cells) the complete optimization model is no longer tractable with reasonable resources. We therefore apply the optimization model to obtain optimal solutions for small parts of the network and then move the optimization focus. For a given input radio network z^0, an area with high load is identified. As potential installation changes, we only admit local variations (increasing or decreasing tilt or azimuth by one unit) in the overloaded area. We thus reduce the set $\mathcal{I}$ of all potential antenna installations to a much smaller subset $\mathcal{I}^0$.

Preliminary Results. We start from the reference radio network included in the scenario, apply the 1-opt procedure, which is allowed to suspend cells and sites, to vary azimuth within ±30°, and to choose a tilt (combination of electrical and mechanical tilt) in the range of $2 - 13°$. We then apply the matrix design approach repeatedly to the result with the same set of available modifications as before, except for suspending cells. We assess the quality of the resulting networks only with the average based method. However, these methods have empirically proved to provide a good estimation of the network's performance [17] and to correctly identify the areas with high outage probability and/or coverage problems.

Table 2(d) shows that the first optimization step could greatly reduce the number of cells (which translates into saved cost for infrastructure) and by the same token close coverage holes. The average downlink load in the network is increased, but to a reasonable level given the smaller number of cells. Applying the matrix-design approach could then significantly reduce the average load, the reduced average of 1.73 percentage points corresponds to a 8 % saving in total output power. Coverage was not compromised in this step. The load distribution maps show a reduced total load, mainly due to a better load balancing.



	No. of cells	Avg.Ld. DL (%)	E$_c$ Cov. (%)
Ref.	193	17.45	99.32
1-opt	123	23.71	99.99
Matrix	123	22.00	99.99

(a) Reference (b) 1-opt (c) Matrix design (d) Performance indicators

Figure 2: Load distribution and computational results for an example UMTS radio network

5 Conclusion

In this paper, we introduced a new analytical characterization to estimate cell load in UMTS radio networks. This characterization is based directly on average traffic intensity maps and, thus, generalizes previous characterizations based on traffic snapshots. We employed this characterization in two ways.

First, a novel matrix design model of cell coverage and coupling was introduced in the form of a mixed integer program. This MIP together with a preliminary objective function was used to iteratively optimize small regions of a realistic UMTS network and proved its effectiveness. Not surprisingly, standard MIP solvers required long computations times even on small regions. In view of the good optimization results, the development of a specialized solution method is considered a worthy option. Second, we implemented an efficient version of the average-based cell load estimator that is capable of sequentially analyzing thousands of alternative network configurations per hour. This formed the basis of simple local search method that is capable of optimizing networks with a few hundred cells.

Still pending is a detailed analysis of the accuracy of our cell load characterization. We aim for analytical results as well as for empirical studies by means of Monte-Carlo simulations using traffic snapshots.

References

[1] 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):939–952, Sept. 2003.

[2] 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.

[3] A. Eisenblätter, H.-F. Geerdes, T. Koch, A. Martin, and R. Wessäly. UMTS radio network evaluation and optimization beyond snapshots. Technical Report ZR-04-15, ZIB, Berlin, Germany, 2004.

[4] A. Eisenblätter, H.-F. Geerdes, U. Türke, and T. Koch. MOMENTUM data scenarios for radio network planning and simulation (extended abstract). In *Proc. of WiOpt'04*, Cambridge, UK, 2004.

[5] A. Eisenblätter, T. Koch, A. Martin, T. Achterberg, A. Fügenschuh, A. Koster, O. Wegel, and R. Wessäly. Modelling feasible network configurations for UMTS. In G. Anandalingam and S. Raghavan, editors, *Telecommunications Network Design and Management*. Kluwer, 2002.

[6] A. Gerdenitsch, S. Jakl, M. Toeltsch, and T. Neubauer. Intelligent algorithms for system capacity optimization of UMTS FDD networks. In *Proc. IEEE 4th International Conference on 3G Mobile Communication Technology*, pages 222–226, London, 2002.

[7] S. B. Jamaa, Z. Altman, J. Picard, B. Fourestie, and J. Mourlon. Manual and automatic design for UMTS networks. In *Proc. of WiOpt'03*, Sophia Antipolis, France, Mar. 2003. INRIA Press.

[8] A. Jedidi, A. Caminada, and G. Finke. 2-objective optimization of cells overlap and geometry with evolutionary algorithms. In *Proc. of EvoWorkshops 2004*, volume 3005 of *Lecture Notes in Computer Science*, pages 130–139, Coimbra, Portugal, Apr. 2004. Springer.

[9] J. Laiho, A. Wacker, and T. Novosad, editors. *Radio Network Planning and Optimization for UMTS*. Wiley, 2001.

[10] K. Leibnitz. *Analytical Modeling of Power Control and its Impact on Wideband CDMA Capacity and Planning*. PhD thesis, University of Würzburg, 2003.

[11] R. Mathar and M. Schmeink. Optimal base station positioning and channel assignment for 3G mobile networks by integer programming. *Ann. of Operations Research*, (107):225–236, 2001.

[12] L. Mendo and J. M. Hernando. On dimension reduction for the power control problem. *IEEE Transactions on Communications*, 49(2):243–248, Feb. 2001.

[13] MOMENTUM Project, IST-2000-28088. MOMENTUM public UMTS planning scenarios. Avaliable online at `http://momentum.zib.de/data.php`, 2003.

[14] I. Siomina and D. Yuan. Pilot power optimization in WCDMA networks. In *Proc. of WiOpt'04*, Cambridge, UK, 2004.

[15] K. Sipilä, J. Laiho-Steffens, A. Wacker, and M. Jäsberg. Modeling the impact of fast power control on the WCDM uplink. In *Proc. of IEEE VTC 1999 spring*, Houston, Texas, May 1999.

[16] U. Türke, R. Perera, E. Lamers, T. Winter, and C. Görg. An advanced approach for QoS analysis in UMTS radio network planning. In *Proc. of the 18th International Teletraffic Congress*, pages 91–100. VDE, 2003.

[17] Ulrich Türke. Personal communication, 2004. Siemens ICM, Berlin.

[18] R. M. Whitaker and S. Hurley. Evolution of planning for wireless communication systems. In *Proc. of HICSS'03*, Big Island, Hawaii, Jan. 2003. IEEE.