Modelling Feasible Network Configurations for UMTS *

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Abstract

A model for the optimisation of the location and configuration of base stations in a UMTS network is described. The focus is primarily on modelling the configuration problem sufficiently accurate using mixed-integer variables and (essentially) linear constraints. These constraints reflect the limited downlink code capacity in each cell, the interference limitations for successful up- and downlink transmissions, the need for sufficiently strong (cell) pilot signals, and the potential gain for mobiles from being in soft(er) hand-over. It is also explained how to use the model as a basis for rating network configurations.

Keywords: UMTS, radio interface, network planning, configuration, perfect power control, mathematical model, mixed integer programming, MOMENTUM, IST-2000-28088, Key Action IV, Action Line IV.4.1

1. Introduction

The dimensioning of the radio interface between the users' mobile equipment and the network operator's infrastructure is a key step during the initial deployment of a UMTS network and its subsequent expansions. The careful configuration of this interface is of vital importance to the network operator, because the radio interface determines the capability to provide services, and it accounts for a major portion of the total network installation and maintenance costs.

Under the roof of the European IST program the project "Models and Simulations for Network Planning and Control of UMTS" or MOMENTUM, for short, aims at a long lasting impact on the development of UMTS planning tools. MOMENTUM characterises new services UMTS is going to deliver, builds usage profiles and planning scenarios to model the future demands, develops flexible models, algorithms, and new simulation as well as evaluation approaches for the optimised configuration of the new wireless telecommunication infrastructure.

In the context of the MOMENTUM project the central goal of this paper is to develop a model for the automatic planning and optimisation of the radio network interface. Our focus is on the "static" installation of radio base stations. We address the following questions: which of the candidate sites shall be used to erect base stations; what sectorization shall be used at each site; which antenna types shall serve the individual sectors; what shall the heights and the tilts of the antennas be; what shall the maximal transmission powers in each cell be; how much power shall be allocated to the pilot signals; and how much hard capacity shall be provided for each cell. These are the decisions we want to take for each site in a planning area. More dynamic, other aspects of a base station installation are not considered. Among these aspects are which scrambling codes to use, details of (soft) hand-over, and all settings related to radio resource management.

The layout decisions for the UMTS radio interface are driven by the mobile services that an operator intends to offer. The challenge of finding a suitable layout for the UMTS base stations can be phrased as follows:

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select locations for the base stations from the set of possible sites and determine the configuration of the cells hosted at each location such that the desired services can be offered and the budget restrictions are met. While this statement is rather vague and needs further clarification, it is typically the last consensus among experts.

Competing Planning Goals

It is whishful thinking to expect one general measure telling which of two given networks is better than the other. The ultimate decision on which radio network configuration to choose is and has to be taken by the radio network planners. The planning and optimisation tools should assist, however, the planner to take this decision best possible. Depending on parameter settings, the optimisation process has to produce alternative designs that particularly fit according to the operator's planning goals.

We distinguish two major viewpoints on a network configuration. The one perspective is performance centered, and a configuration is assessed according to how well it supports the expected traffic load. The other perspective is budget centered, where the focus is on issues such as how much are the installation costs, running costs and the flexibility of the configuration to adopt changing demands and services. Neither of the two perspectives does generally provide a reliable answer to the question whether this or that network configuration should be favoured. Even worse, the performance centered view typically favors expensive over-dimensioned configurations due to their superior performance, whereas the budget centered view typically favors comparably inexpensive configurations that barely can support the given traffic load. Usually these two perspectives will yield conflicting ratings.

We present a mathematical model of "feasible" radio network configurations with respect to offered traffic loads. The applicability of this model is threefold:

- The model can be used as a basis for rating the *network performance* under a given set of traffic snapshots.
- The model allows to determine the *network costs* of the configuration selected.
- The model assigns a *network score* to a given configuration. The score is used to compare network configurations during the optimisation. The score may be assembled from various details on the network's performance and its cost.

Performance Evaluation

Let us assume that we know how to estimate the deployment cost for a network configuration by examining which sites and which equipment is used. In practice the details of this cost estimation are of course quite involved. The cost for a site, for example, depends on whether it is already in use by the same or another operator, whether an outdoor or an indoor base station is needed, how the site can be connected to the access network. Equipment may be shared among operators, which reduces the cost for the individual operator.

Far more intricate is the estimation of the performance for the configuration under consideration. By performance estimation we understand the estimation of the service coverage, capacity and quality of the network. It is well-known that, due to the WCDMA technology employed in UMTS, resolving this question is much more complex for UMTS than it is for GSM. Typically simulations are used for this purpose. Such simulations should mimic the behaviour of the real system as closely as possible.

The state-of-the-art is to use so-called static system-level simulators. The attribute "system-level" indicates that the radio transmission link is not simulated in full detail, but its performance is estimated from link simulation and link measurement results for comparable radio signal propagation environments. The attribute "static" indicates that the dynamic system behaviour is mostly neglected, i. e., users are not actually moving, radio resource management algorithms are not actually executed, fast power control is not actually performed, etc. The impacts of these features are merely estimated from the statistics of "dynamic" simulations or life system observations.

A static system-level simulator generates traffic snapshots, assesses these snapshots and compiles statistics on that. A traffic snapshot is generated according to traffic estimates, which are given as input, usually in the form of space-discretised distributions, by locating users into the planning region. Each user is attributed with specific service demands. In total, the generated sequence of traffic snapshots has to comply with the prescribed traffic distributions provided as input.

Now, the performance of the given network configuration with respect to each snapshot is assessed independently. The crucial part in this assessment is to determine which user is served by which base station at which power level.

Once the power levels for the served users are determined and the rest of the users in the snapshot is put to outage, several figures are extracted, which describe how well this snapshot is handled by the network. The evaluation of many snapshots does allow to conclude how well the network serves traffic that statistically conforms to the traffic distribution used. If more than one traffic distribution is to be considered, this is usually done in distinct runs.

In summary, the network simulator can be used to asses the given network's performance under one or several given traffic distributions (or profiles). The simulator is therefore used during the planning and optimisation of the UMTS radio network to compare alternative configurations.

As we turn to automatically planning and optimising the radio network configuration, the situation changes radically. The network configuration is no longer given, and the problem is to propose network configurations that perform well under a set of estimated future traffic profiles. The resulting network configurations are then analysed thoroughly using an above mentioned simulator.

The planning objective is to select a network configuration that serves several alternative estimated future demands best on average, that is, that optimises the expected value of users' satisfaction for these demands. In mathematical terms, we are faced with a stochastic integer program.

The methods to solve such a stochastic integer program strongly depends on the assumptions on the probability distribution for the alternatives between the estimated demands. We obtain what is mathematically called a nonlinear discrete optimisation problem with a lower semi-continuous objective function. For the problem sizes we are faced with, such problems are far beyond tractability using the methods and the computer power available today [33].

The way to deal with this situation is the same as that for network performance evaluation. The network planning is performed on the basis of traffic snapshots, which are generated according to one or several traffic profiles. These traffic profiles have to capture the scenarios for which the network shall be tuned for. We understand the resulting optimisation problem as follows: find network configurations that perform best possible with respect to all the given snapshots subject to the technical and monetary side constraints. At the mathematical level, this results in a huge mixed integer program.

The capability to evaluate snapshots basically requires that the model is a surrogate for the core part of a static network simulator. The evaluation of the network's performance does not have to be as accurate as that of a simulator, but it has to be much faster. In this respect the core part of the mathematical model can be understood as a (coarse) network/snapshot-evaluation routine in the sense of a static simulator.

The model also needs to assess the performance of varying network configurations under the same set of traffic requirements. This is done within the model for several snapshots simultaneously and it is augmented with the generation of different network configurations. Contrast this with the situation of a traditional static network simulator, which assess one fixed configuration's quality.

Assume we have produced a network configuration that evaluates favourably with respect to the given snapshots. This configuration is then analysed using a simulator. Should the outcome of this analysis be favourable as well, then we succeeded with generating a good radio network configuration. Should, however, the outcome of this analysis show problems, we trace the snapshots for which the proposed configuration fails. The optimisation can be started over again using an augmented set of snapshots. This procedure is repeated until a satisfactory solution is found (or until it becomes clear that the imposed constraints are too restrictive, in which case the network planning engineer has to reconsider and relax these constraints).

The model proposed in the following reflects weeks of detailed discussions with the UMTS and radio engineering experts. The primary goal in shaping the model is to capture all relevant practical side constraints. Accordingly, the focus has been on obtaining an appropriate much rather than an easily accessible model.

2. Literature Survey

Many documents are concerned with the new UMTS standard and give definitions and descriptions related to UMTS, such as the SIR target, power control, and code assignment. The book [18], edited by Holma and Toskala, gives a comprehensive introduction to WCDMA, UMTS services and applications, radio interface protocols, and radio resource management, to name just a few. One chapter [17] in this book provides a good survey about different aspects of the planning process like coverage, capacity, and quality of service.

Just recently the book [24], edited by Laiho, Wacker, and Novosad, was published and deals with planning and optimising UMTS radio networks. Among others, it sketches the network planning process, discusses the requirements of radio network planning tools, introduces a static system-level radio network simulator, addresses radio resource management, provides details concerning cell deployment, UMTS specific coverage and capacity enhancement methods as well as the technical management of radio network optimisation. This book does not, however, outdate this paper or renders it unnecessary. On the contrary, the book contains much of the information necessary to develop models and automated network planning/optimisation methods, which is otherwise hardly publicly available, but it does not itself contain such models and methods.

The literature focusing on methods and algorithms for automated UMTS radio network planning and optimisation is still rather limited.

Berruto et al. [8] include a survey on research activities of the EU-founded ACTS (Advanced Communication Technologies and Services) projects FRAMES (Future Radio Wideband Multiple Access Systems), RAINBOW (Radio Access Independent Broadband on Wireless) and STORMS (Software Tools for the Optimisation of Resource in Mobile Systems). The main areas of research are the development of a radio interface, the network subsystem, and network planning methodologies to provide a technology which fulfils the UMTS requirements.

Noblet et al. [31] present the results of their simulation of a WCDMA network in terms of coverage, QoS and capacity. They point out the difference between WCDMA to TDMA and FDMA. The interference aspect as well as the different user profile (several services and data rates, circuit switched and packet data) are stated as the main differences. They discuss an example of a network using generated data of a UMTS static system simulator, which was based on an IS-95 Motorola simulator. As a result the author states that GSM cells can be reused for planning a WCDMA network at the expense of adding new base stations.

Fallot-Josselin [14] describes a model for the base station location planning problem based on a combinatorial set covering model. WCDMA-typical constraints (like soft-capacity, power control mechanism) are not taken into account. The author suggests a genetic algorithm approach for the solution of the problem. (Genetic algorithms are a meta-heuristic which tries to copy natural evolution, i. e., survival of the fittest, mutation, and cross-over.)

Ibbetson and Lopes [21] develop an algorithm for the automatic placement of cellular base stations. The authors concentrate on the traffic, i. e., the data rate, and do not take the SIR target into account. They also allow in their model that less than 100% of the mobiles are served. Two algorithms for finding the optimal base station configuration are developed. The first one uses a recursive search for the optimal configuration by taking the traffic into account and lowering the radius of the cells which have to serve a high demand. The second one uses a grid, where in each center of the squares a base station is located. For squares carrying a high density, the square is divided into four quarters, and the whole procedure is iterated.

Tutschku et al. [34] present a mobile radio network planning tool called ICEPT, which is based on an integrated design approach. The approach analyses the spatial distribution of the expected traffic located in a cellular system. They make use of the four major design areas of cellular networks: radio transmission, mobile subscriber, resource allocation, and system architecture. The authors concentrate on the traffic and do not take into account the interference of the base stations.

Molina et al. [30] discuss the performance of three well known algorithms to find the optimal location of the base stations in a network. These algorithms are a greedy algorithm, a genetic algorithm and a combination algorithm for total optimisation. The authors test these algorithms on several scenarios which use a given set of demand nodes, a fixed set of possible locations for the base stations, and a certain demand of traffic. The SIR target is not taken into account.

Amaldi et al. [3, 4, 5, 6] study integer programming models and discrete algorithms that aim at supporting the decisions in the process of planning where to locate new base stations. The authors consider the SIR as quality measure and two different power control mechanism: either keep the received signal power or the estimated SIR at a given target value. The authors argue that the uplink (mobile to base station) direction is more stringent (compared to the downlink) in the presence of full-duplex balanced connections as voice calls. As this problem is NP-hard and general purpose MIP solver fail in solving practical instances in reasonable time, Monte-Carlo greedy-type heuristics are developed. Finally, computational results from small to large (realistic) instances are reported.

The model of Amaldi et al. is based on the well-known and well-studied classical uncapacitated facility-location problem. A set of candidate sites is given where a base station can be installed. The distribution of users is modeled by the use of test points (sometimes called demand nodes). Each test point can be considered as a centroid where a given amount of traffic (measured in Erlang) is requested and where a certain level of service (measured in terms of SIR) must be guaranteed. The propagation information is also assumed to be known. For each possible site and each test point one must compute the path loss beforehand.

The optimisation algorithm has two contradicting goals. On one hand it tries to minimize the overall installation cost of used sites. On the other hand it favours assignments of test points to base stations with smaller total power (and therefore tries to open many base stations). A trade-off parameter is used to weight between these two goals. Side constraints in this model guarantee coverage and QoS.

Mathar and Schmeink [28] make use of discrete mathematical programming approaches in order to solve the frequency allocation and cell site selection problem in an integrated setup. They consider both CDMA and FD/TDMA technologies to be important for 3rd generation mobile systems. If all users share the same bandwidth, their objective is to place base transmitter stations such that a maximum of traffic can be carried at low interference rates. The expected traffic is represented by spatially scattered weighted nodes.

The problem to select an optimal set of base station locations from a given pool of configurations is formulated as an integer linear program and solved by standard MIP solvers. For systems that employ FD/TDMA schemes, the cell site optimisation process depends on the assignment of channels. The authors suggest a linear programming approach to solve both objectives in a single planning step.

The used model is based on a set covering model together with Markov chains (Jackson networks) modelling the stochastic behaviour of users. Traffic is considered to be discrete by introducing demand nodes. Because of the complexity of the problem, special branch-and-bound procedures are developed as exact and approximate solution methods. An example is given for a typical urban scenario with base transmitters below rooftops.

Mathar gives in [26] some MIP (mixed integer programming) models and computational studies for the cell site selection problem, which are more or less set covering based models with the budget as an additional knapsack constraint. Constraints due to the quality of service (such as SIR targets or power control mechanisms) are not included into the model but studied afterwards with stochastical methods.

Mathar and Niessen [27] model various aspects of the base station problem as integer linear programs. They start with an integer programming formulation for the problem of maximizing the number of covered demand nodes by at most K base stations. This model is extended in several ways, for instance, by penalizing multiple coverage, by minimizing interference between base stations or by the number of blocked channels. For the solution of the problem the authors suggest simulated annealing. They exhaustively discuss their computational results for one real-world example.

Howitt et al. [19] model the base station location problem as a nonlinear optimisation problem. For the solution of this problem they apply a global optimisation strategy based on modelling the objective function with a stochastic process. They compare their algorithm for an indoor scenario with one and two base stations with local optimisation techniques and derive an improvement of up to 90% for this instance.

Akl et al. [2] discuss the problem of determining the maximal network capacity by optimising simultaneously the transmitted pilot-signal powers and the base station locations, whereas the locations can be moved continuously. This results in a constrained nonlinear optimisation problem, which is solved by gradient methods. They have tested their algorithms on an example with 36 base stations and conclude that for uniform user distribution a uniform network layout is best possible, whereas for non-uniform distributations the base stations need to be relocated inside the hot spots. The results also show that for congested base stations it is better to increase the pilot power than decreasing it in order to improve the network capacity.

Galota et al. [16] focus in on theoretical algorithmic aspects of the base station location problem. The authors prove that a simplified planning problem using rather weak constraints is $\mathcal{NP}$-hard. From this paper we conclude that our problem is also $\mathcal{NP}$-hard and is thus at least theoretical difficult.

Galota et al. [15] discuss a simplified model of the UMTS base station planning problem, where they assume the base stations and mobiles in the plane and where the fact whether a mobile is covered by some base station just depends on the distance. The authors give a profit function which linearly depends on the distances and model the handover by counting the number of base stations covering each mobile. For the solution of the problem the authors give a polynomial approximation scheme and show that in terms of complexity this is the best one can achieve (that is there exists no fully polynomial approximation scheme unless $\mathcal{P} = \mathcal{NP}$).

At first sight GSM is closely related to UMTS in terms of planning radio networks, that is the same basic questions where to locate and how to configure base stations come up as well, see for instance [1, 10, 13, 20, 23, 35, 22, 32]. Some of the basic constraints discussed there are contained in our models as well, but in GSM radio coverage and system capacity can basically be planned separately. Thus, the models for UMTS are far more complex and a comparison of the models and results for GSM and UMTS is hardly possible.

From the base station planning point of view, the commercial cdma-One system, formerly called IS-95, is much more alike UMTS than GSM. cdma-One uses code division multiple access just like UMTS, but in terms of service (essentially) only radio telephony is provided, see for instance [12, 25, 37].

3. Planning Parameters

To plan a UMTS network and its environment a complex setup is needed, which is described by a vast number of physical, system and simulation parameters like propagation, maximum transmission power and number of snapshots to take. We first describe the input data for the planning process. A compilation of all parameters can be found in the appendix, see page 20. These are the *parameters* for which the values are known in advance, prior to the planning. The unit of all noise and power parameters is Watt. For a discussion on the technical details of these parameters see [18].

Sites

One main objective of modelling the UMTS base station configuration is to decide the locations of the base stations.

We are given a set of potential *sites*, denoted by $\mathcal{S}$. For each site selected from the set $\mathcal{S}$, we have to configure the site with antennas. Each antenna has settings to be specified when installed at a site. These parameters are the same as those that influence the propagation model [9, Chapter 2.2]. In particular, there are the coordinates, direction, tilt and the chosen type of the antenna.

We denote by $\mathcal{I}(k)$ all potential installations of antennas that are allowed at site $k \in \mathcal{S}$ and set $\mathcal{I} = \bigcup_{k\in\mathcal{S}} \mathcal{I}(k)$.

It is often possible to select several installations per site. Each installation corresponds to an antenna or a sector of a cell. Note that these does not need to be co-located at the identical position. This does not matter in the model, since the only influence that the position of an installation has, is through the attenuation values. It is even possible to have different sites at the same position. One problem, however, may be our assumption that all possible installations at a site are compatible and that all possible combinations of installations are allowed.

The number of installed channel elements at a site limits the maximum transmission data rate at that site. Since the air interface is ultimately limiting the data rate, to our knowledge the number of channel elements needed to accommodate the utilised bandwidth is of minor importance. An operator will have no problem to make sure that the number of channel elements is not the limiting factor in the network. Even though it could easily be modelled as a resource in the same way as the code consumption if necessary.

Mobiles

In order to assess a configuration of the base stations, we need to test alternative communication demand patterns. We call a specific distribution of mobiles with specific service demands a *snapshot*.

To model mobility, varying traffic activity, and the effects due to packet services we are given a set of *snapshots* $\mathcal{D}$. For each snapshot $d \in \mathcal{D}$ we denote by $\mathcal{M}_d$ the set of mobiles that need to be served simultaneously and set $\mathcal{M} = \bigcup_{d\in\mathcal{D}} \mathcal{M}_d$.

Note that the chosen base station installations do not need to be able to serve all mobiles that ever come up. It suffices if they can serve all mobiles for each snapshot.

For our purpose the *spreading* codes, whose function is to spread the signal up to 3.84 Mcps which fits in a bandwidth of 5 MHz, are of interest. The algorithm to generate orthogonal spreading codes may be roughly described as follows, for details see [18, Chapters 3 and 6] or [36].

The way to generate codes is recursive. One starts with the codes 1 and 0, respectively. Let a be a bit pattern and $\bar{a}$ the bit pattern of a where every bit is inverted. Then a has two distinct successors. The first one is obtained by doubling a to aa while the second one by concatenating a and $\bar{a}$ to $a\bar{a}$.

Obviously, one may describe the pattern just by the steps one uses to generate the code. If one sets a 0 for doubling a to aa and 1 for the concatenation a to $\bar{a}$, a code of length 2^n may be described by just n bits. Furthermore, two codes are orthogonal if and only if the longer one does not start with the pattern of the shorter one. This is equivalent to the fact that for orthogonal codes the bit sequence to generate the shorter code is not a prefix of the bit sequence defining the longer code.

In information theory the so-called *Kraft's inequality*, see Minn and Siu in [29], gives a necessary condition for a set of codes such that no code is prefix of another. The codes in this context correspond to the bit patterns which describe the generation of the spreading codes as explained above and must not be mixed up with the spreading codes themselves. For a set C of codes, Kraft's inequality says that $1 \geq \sum_{c \in C} 2^{-n_c}$, where n_c denotes the length of code $c \in C$.

To avoid fractional values one may rescale Kraft's inequality by multiplying with $2^{n_{max}}$ where n_{max} is the maximal code length (in the sense of a bit pattern describing the generation of the code) which may occur and we obtain $2^{n_{max}} \geq \sum_{c \in C} 2^{n_{max}-n_c}$.

In the following we refer to the *code consumption* assigned to mobile $m \in \mathcal{M}$ as λ_m. A large λ_m stands for a high data rate and must be at least $2^{n_{max}-n(\lambda_m)}$ with $n(\lambda_m)$ beeing the code length corresponding to λ_m according to our explanations above.

By the RRM an installation may not assign all possible codes but just a subset to the mobiles. Let Λ_i be the resource *budget* available for installation $i \in \mathcal{I}$.

Note that we do not model the use of secondary code trees or code fragmentation in detail. Mobiles just consume kind of an "average" number of codes from the preset budget of an installation.

The Radio Path

A number of parameters concern the transmission, the radio path, and the reception. These parameters are explained next.

For every pair $(m \in \mathcal{M}, i \in \mathcal{I})$ of mobiles m and installations i the *attenuation* is defined as the ratio of energy received by the receiver to the energy emitted by the transmitter. Due to, e. g. mast head amplifiers, this does not need to be symmetric, so we have attenuation $\gamma^{\uparrow}_{mi}$ for the uplink and $\gamma^{\downarrow}_{im}$ for the downlink.

The value can be computed with data from the propagation model together with the characteristics of the antennas. It depends on:

- The path loss for the reference height and the height gain for the physical location of the transmitter and receiver.
- The properties of an installation such as the antenna gains for transmission and reception, antenna pattern, direction and tilt, cable and combiner loss and use of amplifiers. Especially the angle of radiation is important here.
- The properties of the mobile, like antenna gain and pattern, and cable and connector losses.
- The service specific body loss for the mobile's side of the transmission link.

Noise includes thermal noise and other noise sources, such as receive noise and interference from distant antennas. We will use two sets of parameters, one for the installations (uplink) η_i for $i \in \mathcal{I}$, the other for the mobiles (downlink) η_m for $m \in \mathcal{M}$.

For $m \in \mathcal{M}$ we denote the minimal and maximal uplink transmission power by $\Pi^{\min\uparrow}_m$ and $\Pi^{\max\uparrow}_m$, respectively.

In the downlink we have the maximal total transmission power of an installation $i \in \mathcal{I}$ as $\Pi^{\max\downarrow}_i$, the minimal and maximal transmission power per link as $\dot{\Pi}^{\min\downarrow}_i$ and $\dot{\Pi}^{\max\downarrow}_i$, and the minimal and maximal pilot transmission power as $\hat{\Pi}_i^{\min\downarrow}$ and $\hat{\Pi}_i^{\max\downarrow}$, respectively.

We use service specific *activity factors* $\alpha_m^\uparrow$ and $\alpha_m^\downarrow$ for each mobile $m \in \mathcal{M}$ in the up- and downlink. The activity factor indicates how *active* a mobile is engaged in a circuit-switched connection. For example, the activity factor for speech service is often taken as 67% or 0.67. The activity factor for circuit-switched data services is typically 1.0, meaning it is active all the time. For packet-switched services there is usually no activity factor defined, so we use 1.0. If the mobile is using a service mix, the activity factor is a mixture of the corresponding factors. Depending on the service (e. g. video-stream) the factor may be different in up- and downlink. For more information related to service activity see [24, Chapter 3].

The *orthogonality* factor ω_{im} in the downlink between an installation $i \in \mathcal{I}$ and a mobile $m \in \mathcal{M}$ depends on the environment, see also [18, Chapter 8]. Ideally, the CDMA signals for two distinct downlink connections in one cell are orthogonal, that is, they are mutually not perceived as interfering. Multi-path propagation and diffraction weaken this property. The orthogonality factor states how much of a signal may be considered orthogonal, a factor of 1.0 means total orthogonality. The remainder has to be treated as interference at the receiving mobile. We also use $\bar{\omega}_{im} = 1 - \omega_{im}$ to simplify some of the inequalities below.

If, due to heavy code consumption codes from a secondary code-tree have to be used, the orthogonality of the signals is reduced. This is not reflected in the model, but might be incorporated in a threshold setting, see also the treatment on "Code Consumption".

We denote the *signal to interference ratio* (SIR) *targets* for mobile $m \in \mathcal{M}$ by $\mu_m^\uparrow$ for the uplink and by $\mu_m^\downarrow$ for the downlink. The parameter $\mu_m^\uparrow$ is the ratio between the signal strength of the connection from mobile m to the base station and the sum of all signals received at the base station. There are also SIR requirements for the (downlink) pilot channel. They are denoted by $\hat{\mu}_m^\downarrow$ for $m \in \mathcal{M}$.

The SIR target S/I for a radio link depends on three factors. If R is the data rate of the carried service, W is the UMTS specific chip rate of 3.84 MHz, and E_b/N_0 is the required ratio between signal bit energy and interference spectral density (including noise spectral density), then

$$\frac{S}{I} = \frac{E_b}{N_0} \cdot \frac{R}{W} \quad .$$

The quotient E_b/N_0 depends on the service and on the speed of the mobile, among others. So far the E_b/N_0 values have typically been obtained from radio link simulations, see [24, Table 2.9], for example, but more and more real measurements become available.

4. Modeling Feasibility

In this section, we build a mathematical model that describes what we consider a *feasible network configuration*. This model is a mixed integer linear program or MIP, for short. Each feasible solution for the MIP identifies a selection of sites to open, installations to use at each site, assignments of mobiles to installations and the power levels of each installation and mobile for each snapshot from $\mathcal{D}$.

Our model is driven by the service dependent SIR targets. With the parameters from the previous section, we can compute the generated interference and the power at the transmitters that is needed to meet the SIR targets. Notice the underlying assumptions on the power control mechanism. The following formulas are designed with perfect power control in mind. It is currently not yet clear if and to which extent realistic power control mechanisms can be taken into account by systematically modifying the SIR targets [11, p. 37].

Since we are kind of statically evaluating the powerlevels an adjustment for power control headroom and fading may be included in the SIR target.

In the model we present, each mobile is connected to at most one antenna. A discussion on how to incoorporate soft(er) hand-over follows at the end of this section. Figure 1 illustrates the parameters and constraints that are described in this section. Again, a compilation of all variables used in the model can be found in the appendix, see page 20.

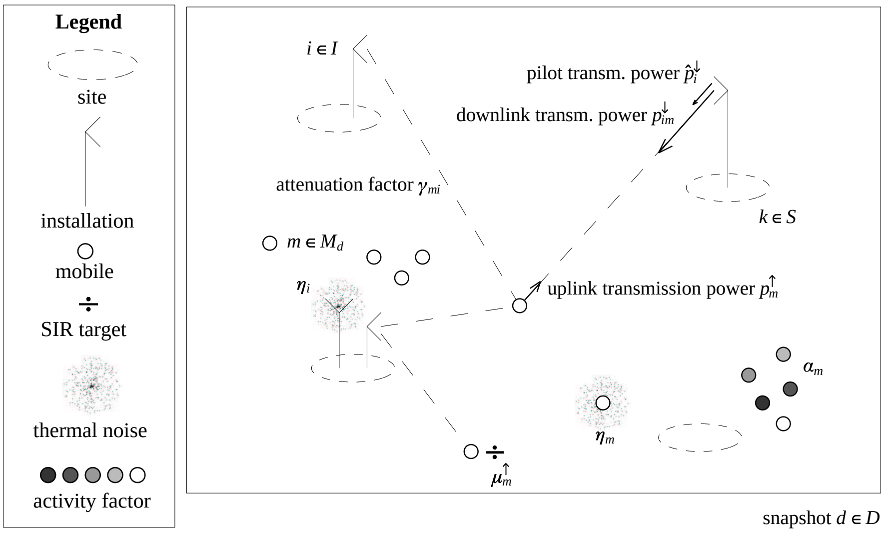

Figure 1: *Simplified Model Diagram*

Site Selection

Our first set of variables and constraints governs the selection of base station installations and the "assignment" of served mobiles to the selected installations.

For the sites we introduce binary variables s_k, $k \in \mathcal{S}$ with the interpretation $s_k = 1$ if and only if, or *iff*, for short, site k is used.

Furthermore, we have binary variables z_i, $i \in \mathcal{I}$, where $z_i = 1$ iff installation i is used.

For the assignment of the mobiles we have two types of binary variables. First w_m where $w_m = 1$ iff mobile $m \in \mathcal{M}$ is served at all and secondly x_{mi} with $x_{mi} = 1$ iff mobile $m \in \mathcal{M}$ is served by installation $i \in \mathcal{I}$.

The following constraints are associated with the selection of the sites.

An installation i is only available if its site $\sigma(i)$ is selected:

$$z_i \leq s_{\sigma(i)} \qquad \forall i \in \mathcal{I} \tag{1}$$

An upper limit $\Upsilon_k^{\max}$ on the number of installations at site k can be specified:

$$\sum_{i \in \mathcal{I}(k)} z_i \leq \Upsilon_k^{\max} \qquad \forall k \in \mathcal{S} \tag{2}$$

Only a selected installation may serve mobiles:[†]

$$x_{mi} \leq z_i \qquad \forall m \in \mathcal{M}, i \in \mathcal{I} \tag{3}$$

[†]From a mathematical point of view, this constraint is redundant if inequality (5) is used.

Each mobile is served by exactly one installation if it is served at all:

$$\sum_{i \in \mathcal{I}} x_{mi} = w_m \qquad \forall m \in \mathcal{M} \tag{4}$$

The serving of a mobile consumes codes at the installation:

$$\sum_{m \in \mathcal{M}_d} \lambda_m x_{mi} \leq \Lambda_i z_i \qquad \forall i \in \mathcal{I}, d \in \mathcal{D} \tag{5}$$

Notice: Since each mobile is served by at most one installation in our model, we cannot easily account for multiple code consumption of mobiles in soft(er) hand-over, an issue that will be discussed at the end of this section.

Uplink

The uplink transmission powers are under fast power control in a UMTS network. The objective is to emit the necessary power to reach the base station with the appropriate SIR value.

For the uplink power level of mobile m we use a continuous variable $p_m^{\uparrow}$. To model uplink the following constraints are necessary.

Each mobile has minimum and maximum transmission power level that is active iff the mobile is served. We regard the transmissions of unserved mobiles as not relevant.

$$\Pi_m^{\min\uparrow} w_m \leq p_m^{\uparrow} \leq \Pi_m^{\max\uparrow} w_m \qquad \forall m \in \mathcal{M} \tag{6}$$

The idea of the SIR target is to relate the signal power received from a specific mobile at a base station to the total energy received at that base station.

We assume in the model that *perfect power control* is employed. This means the transmission power is set to the minimum level necessary to fulfil the SIR target (see e. g. [7]). It is currently not yet settled if and to which extent realistic power control mechanisms can be taken into account by systematically modifying the SIR targets, compare with the note on "Realistic Power Control" in [11, p. 37].

$$\frac{\gamma_{mi}^{\uparrow}\, p_m^{\uparrow}}{\sum\limits_{\substack{n \in \mathcal{M}_d \\ n \neq m}} \gamma_{ni}^{\uparrow}\, \alpha_n^{\uparrow}\, p_n^{\uparrow} + \eta_i} \geq \mu_m^{\uparrow} x_{mi} \qquad \forall m \in \mathcal{M}_d, d \in \mathcal{D}, i \in \mathcal{I} \tag{7}$$

Downlink

Similar to the uplink case, the downlink transmission powers (for dedicated channels) are also under fast power control in order to meet the desired SIR value at the mobiles.

Here we use continuous variables $p_{im}^{\downarrow}$ for the power level between installation i and mobile m. In addition, we have a continuous variable $\hat{p}_i^{\downarrow}$ for the pilot power of installation i.

The following constraints describe the downlink case. The transmission power in the downlink is limited per link.

$$\dot{\Pi}_i^{\min\downarrow} x_{mi} \leq p_{im}^{\downarrow} \leq \dot{\Pi}_i^{\max\downarrow} x_{mi} \qquad \forall i \in \mathcal{I}, m \in \mathcal{M} \tag{8}$$

Also the pilot is limited:

$$\hat{\Pi}_i^{\min\downarrow} z_i \leq \hat{p}_i^{\downarrow} \leq \hat{\Pi}_i^{\max\downarrow} z_i \qquad \forall i \in \mathcal{I} \tag{9}$$

And per installation:

$$\hat{p}_i^{\downarrow} + \sum_{m \in \mathcal{M}_d} p_{im}^{\downarrow} \leq \Pi_i^{\max\downarrow} z_i \qquad \forall i \in \mathcal{I}, d \in \mathcal{D} \tag{10}$$

The SIR formula for the downlink reads:

$$\frac{\gamma_{im}^{\downarrow}\, p_{im}^{\downarrow}}{\phi(m,i) + \underbrace{\bar{\omega}_{im}\gamma_{im}^{\downarrow}\hat{p}_i^{\downarrow}}_{\text{own pilot signal}} + \hat{\phi}(m,i) + \eta_m} \geq \mu_m^{\downarrow} x_{mi} \qquad \forall m \in \mathcal{M}_d, d \in \mathcal{D}, i \in \mathcal{I} \tag{11}$$

We also have to meet the SIR requirement for the pilot signal:

$$\frac{\gamma_{im}^{\downarrow}\hat{p}_i^{\downarrow}}{\phi(m,i) + \underbrace{\bar{\omega}_{im}\gamma_{im}^{\downarrow}\alpha_m^{\downarrow}p_{im}^{\downarrow}}_{\text{own data signal}} + \hat{\phi}(m,i) + \eta_m} \geq \hat{\mu}_m^{\downarrow} x_{mi} \qquad \forall m \in \mathcal{M}_d, d \in \mathcal{D}, i \in \mathcal{I} \tag{12}$$

In the above constraints, $\phi(m,i)$ denotes the interference from other transmissions

$$\phi(m,i) = \sum_{\substack{n \in \mathcal{M}_d \\ n \neq m}} \Bigg(\overbrace{\bar{\omega}_{im}\gamma_{im}^{\downarrow}\,\alpha_n^{\downarrow}\,p_{in}^{\downarrow}}^{\text{from same cell}} + \overbrace{\sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \gamma_{jm}^{\downarrow}\,\alpha_n^{\downarrow}\,p_{jn}^{\downarrow}}^{\text{from other cells}} \Bigg) \tag{13}$$

and $\hat{\phi}(m,i)$ denotes the interference from other pilot signals

$$\hat{\phi}(m,i) = \sum_{\substack{j \in \mathcal{I} \\ j \neq i}} \gamma_{jm}^{\downarrow}\hat{p}_j^{\downarrow} \tag{14}$$

Currently, we only model the maximum of all occurring ratios. In other approaches the sum of the SIR targets seemed to be preferred. In linear optimisation the evaluation of the sum cannot be handled very well. Therefore one has to ask either for just *one* target strong enough or for a *given number*.

Notice: Again, inequality (11) does not account for mobiles in soft(er) hand-over. The next section contains a proposal on how to incorporate this aspect into (11).

Soft Hand-over Gain

The model as described above does not reflect the possibility that a mobile is in soft(er) hand-over, that is, it is simultaneously linked to two or more cells. In the model, a mobile is always served by at most one installation.

We discuss next how to incorporate the effects of soft(er) hand-over into our model. An accurate modelling of soft(er) hand-over currently appears to be prohibitive. We see the following reasons for this:

- In the downlink direction, the base stations' signals are maximum ratio combined at the mobile station. The desired effect is that the required service-dependent SIR target is often reduced and, hence, the required downlink transmission powers at the base stations are decreased. An accompanying negative effect is that this downlink connection consumes code and transmission power resources at all involved installations. Accounting for these effects properly requires to trace all these installations. This drastically increases the combinatorial complexity of the model.
- In the uplink direction, maximum ratio combining or selective combining is used for the mobile's signal, depending on whether softer or soft hand-over is in effect, even combinations of soft and softer hand-over are possible. The SIR target reduction for soft hand-over is usually smaller than that for softer hand-over. Recall that in the former case, a RNC selectively combines decoded digital frames, picking the frame with less errors. In the latter case, the base station combines the signal coming from different Rake fingers prior to decoding. We do not see how to model this using (essentially) linear constraints.
- Another result of soft(er) hand-over is that fading effects are "averaged" out. Since we do not model fading explicitly we can not incorporate this effect other than by changing the SIR target.

For these reasons, we stick to our decision that each mobile is linked to at most one cell. Consequently, we can account for soft(er) hand-over in the inequalities (5), (7), and (11) only in a heuristic fashion.

There are several possibilities: It is often assumed that about 30% of the mobiles will be in soft(er) hand-over. Since we plan for mature networks, we could assume that for all cells, in each direction, there will be another cell adjacent to it. The crudest way to account for soft(er) hand-over is to claim a general gain on the signals and adjust all SIR targets accordingly. It must be evaluated, if this is better than doing nothing.

The next possibility would be to do soft(er) hand-over calculations as post-processing. This seems questionable, because the difference in interference between using and not-using soft(er) hand-over could shift the point of optimal performance for a network by a wide margin. If, however, the soft(er) hand-over computation could not be incorporated into the main model directly, this might be better than nothing.

Clearly superior to the first two options is to incorporate a notion of soft(er) hand-over in the model itself. We explain how to do this for the uplink below. The changes for the downlink are similar.

The gain that a mobile has from being in soft hand-over depends on the size of the active set (AS) and the actual difference in attenuation. Figure 2 gives an idea of the relation.

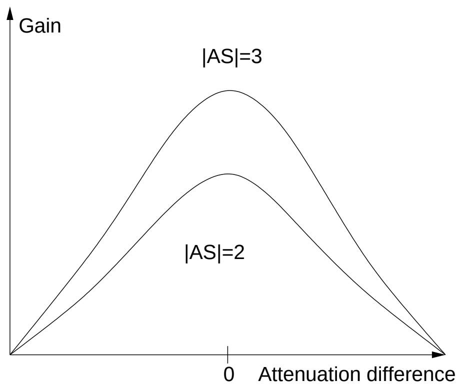

Figure 2: *Soft-handover gain depending on the attenuation difference*

For a mobile to be in soft(er) hand-over with two or more cells, the attenuation between the mobile and each of the involved cells has to be approximately the same. A maximal difference between 3 and 6 dB is expected.

For every mobile m and every installation i we define the *candidate set* as

$$\mathcal{K}_{mi}(\delta) = \left\{ j \in \mathcal{I} \setminus \{i\} \mid \frac{1}{\delta} \leq \frac{\gamma^{\uparrow}_{mi}}{\gamma^{\uparrow}_{mj}} \leq \delta \right\} \tag{15}$$

with maximum *soft hand-over attenuation threshold* δ typically between 2 and 4. Note that due to different attenuation values in up- and downlink the formula for $\mathcal{K}_{mi}(\delta)$ has to be adapted accordingly when both cases are treated simultaneously.

The installations contained in $\mathcal{K}_{mi}(\delta)$ are possible candidates for supporting installation i in serving mobile m, i. e., we do not yet know which of the installations in the set will be chosen to be used. Additional restrictions may apply and can be added to the definition (15).

The changes to inequalities (5) and (7) needed in order to incorporate soft hand-over gain based on the this possible active/candidate-set are described in the following.

Site Selection

From a global perspective, we could change the resource consumption parameters to accommodate for the anticipated soft hand-over rate. In inequality (5) the terms on both sides of the inequality sign can be changed.

Increasing λ_m indicates a generally higher resource consumption due to soft(er) hand-over connections. From a local perspective, decreasing Λ_i, possibly in dependence of the $\mathcal{K}_{mj}(\delta)$ sets containing i, reflects code resource reduction at installation i due to potential hand-over connections.

Phantom Powers in Up- and Downlink

The effect of soft(er) hand-over on a SIR target is modelled using what we call *phantom power*. Instead of explicitly lowering the required SIR target, a phantom power virtually increases the transmission power, but not the interference. Note that the new constraints have to be valid in general, independent of which potential installation serves the mobile in the end.

The parameter $\rho^{\uparrow}_m$ expresses the maximum possible (power) gain from being in soft(er) hand-over, and the *phantom power* $v^{\uparrow}_m$ is a continous variable controlling how much of this best possible gain is achieved. The actual gain depends on the precise conditions for mobile m, i. e., whether it is in soft(er) hand-over at all and, if so, which base station installations are processing its signal.

The benefit for mobile m from being in soft(er) hand-over between base station installations i and j is denoted by $\epsilon^{\uparrow}_{mij}$. Recall that according to our model, m is served by at most one installation, namely, the one with $x_{mi} = 1$. We call this the *primary* server and all co-serving installations *secondary* servers. We allow multiple secondary servers in the following construction. We assume, however, that their combined gain can be approximated sufficiently well by adding up the gain of having each one of them as a secondary server alone (see inequality (17)).

We replace inequality (7) by

$$\frac{\gamma^{\uparrow}_{mi}\left(p^{\uparrow}_m + v^{\uparrow}_m\right)}{\sum\limits_{\substack{n \in \mathcal{M}_d \\ n \neq m}} \gamma^{\uparrow}_{ni}\, \alpha^{\uparrow}_n\, p^{\uparrow}_n + \eta_i} \geq \mu^{\uparrow}_m x_{mi} \qquad \forall m \in \mathcal{M}_d, d \in \mathcal{D}, i \in \mathcal{I} \tag{7'}$$

and add two new constraints governing the behaviour of $v_m^{\uparrow}$:

$$0 \leq v_m^{\uparrow} \leq \rho_m^{\uparrow} \qquad \forall m \in \mathcal{M} \tag{16}$$

$$v_m^{\uparrow} \leq \rho_m^{\uparrow} - \rho_m^{\uparrow} x_{mi} + \sum_{j \in \mathcal{K}_{mi}(\delta)} \epsilon_{mij}^{\uparrow} z_j \qquad \forall m \in \mathcal{M}, i \in \mathcal{I} \tag{17}$$

Obviously, even with the changes just mentioned our model does not fully take soft(er) hand-over into account, but we expect that our heuristic approach is a viable one. Computational experiments will be made to assess our model extension.

5. Objectives

We now come back to the point of rating configurations. As already pointed out in the introduction, this is delicate and the following exposition describes some proposals on how to handle it.

The best developed theory for solving an integer linear model such as ours is based on linear programming. In order to apply the corresponding tool box of algorithms we have to have a linear objective function. In some cases, a more general quadratic or convex objective function might be acceptable, but from the current point of view, our model is too complex to allow for a non-linear objective function.

Without loss of generality, the objective function will be minimised. Our possibilities within the presented model are basically the association of cost coefficients with variables. Since the word “cost” is used here also in the sense of capital expenditure, we use the word “merit” for the cost coefficients.

As mentioned in the introduction, the antipodal planning goals are

- to define a minimum acceptable SIR target and look for the “cheapest” network configuration that would meet that target.
- to define a maximum acceptable network configuration cost and look for the network configuration that would give minimum outage and maximum power-headroom, whilst meeting that cost.

We introduced the notion of scoring a network configuration together with the cost and the performance centered view. This is elaborated in the following.

Costs

There are two types of variables that naturally can be assigned costs to. The site decision variables s together with the site cost parameter c_k^s, $k \in \mathcal{S}$, reflect the cost for opening a new site, and the installation variables z are assigned the cost c_i^z, $i \in \mathcal{I}$ for deploying this particular installation.

Hence, within our model the expression

$$\sum_{k \in \mathcal{S}} c_k^s s_k \tag{18}$$

captures the costs for opening the sites, and

$$\sum_{i \in \mathcal{I}} c_i^z z_i \tag{19}$$

captures the costs for deploying the selected installations. The two expressions together represent the cost of a given network configuration.

Performance

For a fixed traffic snapshot $d \in \mathcal{D}$, the expression

$$\sum_{m \in \mathcal{M}_d} (1 - w_m) \tag{20}$$

counts all the unserved mobiles in this snapshot.

In addition to outage, one possibility to rate the performance of a network is to look at the *power headroom* available at each transmitter (mobiles and base stations). While it is questionable how accurate perfect power control resembles reality, the amount of headroom left is always an indication for the capacity left in the network. The expression

$$\sum_{m \in \mathcal{M}_d} (\Pi_m^{\max\uparrow} w_m - p_m^{\uparrow}) \tag{21}$$

sums the power headroom for all served mobiles from the snapshot in the uplink, and

$$\sum_{i \in \mathcal{I}} (\hat{\Pi}_i^{\max\downarrow} z_i - \hat{p}_i^{\downarrow}) \tag{22}$$

sums the power headroom for the pilot signal as

$$\sum_{i \in \mathcal{I}} \sum_{m \in \mathcal{M}_d} (\dot{\Pi}_i^{\max\downarrow} x_{mi} - p_{im}^{\downarrow}) \tag{23}$$

sums the headroom for the downlink—although this is usually considered less important. More important is the following expression

$$\sum_{i \in \mathcal{I}} (\Pi_i^{\max\downarrow} z_i - \sum_{m \in \mathcal{M}_d} p_{im}^{\downarrow}), \tag{24}$$

which measures the downlink "power headroom" for each base station installation with respect to all served mobiles taken together. We therefore have to make sure that always the least possible power level is selected.

Notice that we have not associated merits to serving certain mobiles. If we would like to express a preference for serving one mobile in comparison to serving some other, this could easily be added.

Scoring

In our context, the scoring of a network configuration will be done on the basis of the two sections above. Ultimately, these expressions have to be arranged to a linear objective function in which each term may have its individual scaling factor. For example, it is likely that the expressions (20) to (24) are scaled according to the significance of the corresponding snapshot. If the snapshot is generated using a less important traffic profile, then the network's performance with respect to this snapshot weighs less.

Perspective

Except for a detailed objective function, we developed a complete integer programming model for planning and optimising the radio network part of a UMTS network. Although this model is already fairly complex, we consider this to be the "basic" model.

Significant efforts are spent within the MOMENTUM project itself but also outside of the project in order to derive heuristic rules for dimensioning the UMTS radio network. Such rules are the essence of closely investigating the interdependencies among base stations in the UMTS radio network. It would be foolish not to take these developments into account, and these developments will be used to simplifiy/modify/extend the model in the future.

The model proposed is the result of many detailed discussions with the UMTS and radio engineering experts. The primary goal is to capture most relevant side constraints. This naturaly evolved into a rather complex model. The next steps to come have to address how this complex model can be handled with methods from Operations Research. Two approaches will be taken. One line of research will be the heuristic simplification of the model, hoping that it becomes accessible to established techniques. In contrast to the situation in which a simplified model is used right from the start, we are now in the position to assess precisely the compromised embodied in a simplified model. Another line of research will develop new methods especially tailored to solving the complex model directly. Both lines of development involve extensive computational testing on real-world instances available within the MOMENTUM project.

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Appendix

The Model Parameters and Variables

Parameters		
$\mathcal{S}$		set of (potential) sites
$\mathcal{I}(k)$		set of (potential) installations at site $k \in \mathcal{S}$
$\mathcal{I}$		$\bigcup_{k\in\mathcal{S}} \mathcal{I}(k)$ union of all possible installations
$\sigma(i)$		site of installation $i \in \mathcal{I}$, $\sigma(i) = k \Leftrightarrow i \in \mathcal{I}(k)$
$\mathcal{D}$		set of snapshots
$\mathcal{M}_d$		set of mobiles of snapshot d
$\mathcal{M}$		$\bigcup_{d\in\mathcal{D}} \mathcal{M}_d$ (disjunctive) union of mobiles in all snapshots
k	$k \in \mathcal{S}$	site
i	$i \in \mathcal{I}$	installation
m	$m \in \mathcal{M}$	mobile
d	$d \in \mathcal{D}$	snapshot
$\Upsilon_k^{\max}$	≥ 1	maximum number of parallel installations at site k
$\gamma_{mi}^{\uparrow}$	$[0, 1]$	uplink attenuation factor between mobile m and installation i.
$\gamma_{im}^{\downarrow}$	$[0, 1]$	downlink attenuation factor between installation i and mobile m.
η_i	≥ 0	noise at installation i
η_m	≥ 0	noise at mobile m
$\Pi_m^{\min\uparrow}$	≥ 0	minimal uplink transmission power of mobile m
$\Pi_m^{\max\uparrow}$	≥ 0	maximal uplink transmission power of mobile m
$\Pi_i^{\max\downarrow}$	≥ 0	maximal total downlink transmission power at installation i
$\dot{\Pi}_i^{\min\downarrow}$	≥ 0	minimal downlink transmission power per link at installation i
$\dot{\Pi}_i^{\max\downarrow}$	≥ 0	maximal downlink transmission power per link at installation i
$\hat{\Pi}_i^{\min\downarrow}$	≥ 0	minimal (downlink) pilot transmission power at installation i
$\hat{\Pi}_i^{\max\downarrow}$	≥ 0	maximal (downlink) pilot transmission power at installation i
$\alpha_m^{\uparrow}$	$[0, 1]$	uplink activity factor of mobile m
$\alpha_m^{\downarrow}$	$[0, 1]$	downlink activity factor of mobile m
ω_{im}	$[0, 1]$	orthogonality factor, $\bar{\omega}_{im} = 1 - \omega_{im}$
λ_m	≥ 0	code consumption for mobile m
Λ_i	≥ 0	code budget for installation i
$\mu_m^{\uparrow}$	≥ 0	uplink SIR target for mobile m
$\mu_m^{\downarrow}$	≥ 0	downlink SIR target for mobile m
$\hat{\mu}_m^{\downarrow}$	≥ 0	pilot SIR requirement for mobile m
δ	> 1	soft hand-over attenuation threshold
$\mathcal{K}_{mi}(\delta)$		candidate-set for mobile m connected to installation i
$\rho_m^{\uparrow}$	≥ 0	maximal gain from being in soft(er) hand-over in uplink
$\epsilon_{mij}^{\uparrow}$	≥ 0	soft(er) hand-over gain in uplink if mobile m is served by i and supported by j

Variables		
s_k	$\in \{0, 1\}$	is 1 iff site k is used
z_i	$\in \{0, 1\}$	is 1 iff installation i is used
w_m	$\in \{0, 1\}$	is 1 iff mobile m is served at all
x_{mi}	$\in \{0, 1\}$	is 1 iff mobile m is served by installation i
$p_m^{\uparrow}$	$\in \mathbb{R}_+$	uplink transmission power from mobile m
$p_{im}^{\downarrow}$	$\in \mathbb{R}_+$	downlink transmission power from installation i to mobile m
$\hat{p}_i^{\downarrow}$	$\in \mathbb{R}_+$	(downlink) pilot transmission power from installation i
$v_m^{\uparrow}$	$\in \mathbb{R}_+$	uplink phantom power for mobile m