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Coverage Planning for Optimizing HSDPA Performance and Controlling R99 Soft Handover

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Abstract—Coverage planning is an important engineering task in deploying UMTS networks implementing both high speed downlink packet access (HSDPA) and Release 99 (R99) services. Coverage planning amounts to determining the cell coverage pattern by means of setting the common pilot channel (CPICH) power of the cells. A conventional strategy is to uniformly allocate a proportion of the total power to CPICH. In this paper, we develop mathematical modeling and optimization approaches to bring the benefit of power saving enabled by optimizing non-uniform CPICH to enhance HSDPA performance, while preserving a desired degree of soft handover (SHO) for R99. The study focuses on HSDPA performance at cell edges, where data throughput is typically low. An integer linear programming model is developed for the resulting optimization problem. The model admits optimal or near-optimal planning solutions for relatively small networks. Solution algorithms based on local search and repeated local search are developed. These algorithms are able to perform the optimization for large-scale networks time-efficiently. Experimental results for both synthesized networks as well as instances originating from real planning scenarios demonstrate the benefit of our optimization approach.

I. Introduction

First introduced in 3GPP Release 5 [1], High Speed Downlink Packet Access (HSDPA) is under deployment worldwide. Technical features of HSDPA include adaptive modulation and coding (AMC), hybrid automatic repeat request (HARQ) and fast scheduling at Node B. These techniques enable lower link latency and significantly higher data rates in comparison to earlier UMTS releases, making HSDPA a key step in the evolution toward mobile broadband Internet. Research on engineering HSDPA networks ranges from analysis of physical- and link-layer capacity [8, 16], resource sharing and admission control strategies [4, 21], scheduling policies [6, 10, 15, 18], to performance consideration in network dimensioning and planning [3, 20, 26, 28]. The last topic is becoming increasingly important as the HSDPA service grows rapidly in scale, and it leads to new optimization problems in view of the current literature (e.g., [2, 19]).

Because HSDPA targets Internet data, the primary performance consideration in network planning is data throughput. Factors having influence on data throughput include the amount of transmit power used by HSDPA, the number of channelization codes supported by the user equipment (UE), as well as the channel condition and interference. Among them, transmit power is a key resource parameter in network dimensioning. Unlike the Dedicated Channel (DCH) in 3GPP Release 99

(R99), HSDPA does not adopt power control on its High Speed Downlink Shared Channel (HS-DSCH); increasing downlink power gives better throughput. At present, having R99 and HSDPA services co-existing in a network is the most likely scenario, for which the output power of Node B is shared between common channels (CCH), DCH, and HS-DSCH. A commonly recommended power-sharing strategy is the fill-up approach [7], meaning that to assign the entire slack power, left from serving CCH and DCH, to HS-DSCH. By this approach, HSDPA power is dynamic, yielding better resource utilization than using a constant amount of HS-DSCH power. A result of the fill-up approach is that the cells constantly operate at full (or close-to-full) power at the downlink.

The research in this paper deals with coverage planning and optimization in UMTS networks implementing both HSDPA and R99. Here, coverage refers to presence of service, announced via the common pilot channel (CPICH). In UMTS networks, CPICH is a broadcast channel used by the cells to announce their presence. The channel carries a pre-defined bit/symbol sequence. CPICH enables UEs to perform channel estimation and facilitates cell selection. Coverage planning means to achieve a desired coverage pattern of the cells by setting their CPICH power levels. A conventional strategy is to uniformly assign a constant proportion, typically 10-15%, of the total power to CPICH [11]. Although convenient, this strategy may be inefficient in heterogeneous radio propagation environments [25]; in particular, the resulting power consumption is often unnecessarily high for coverage. It has been shown in previous research that adopting non-uniform CPICH and optimizing its power setting can save CPICH power [23, 24] and balance cell load [27, 29]. Whereas power saving on CPICH may not be a crucial aspect to the power-controlled R99 traffic, it is of great significance to HSDPA – Any power saving on channels other than HS-DSCH immediately makes additional power available to HS-DSCH and consequently higher data throughput. Moreover, reducing the CPICH power enables additional power saving on some of the other common control channels, of which the power is typically set in proportion to that of CPICH.

Soft handover (SHO) is a feature in the UMTS R99 standards. While in the SHO state, a UE is connected to two or more cells at the same time. At the downlink, the UE can simultaneously receive the same bit stream from these cells. This allows the UE to decode the steam more reliably

by combining the received signals, as well as to explore the diversity gain. Whether or not a UE can be in SHO and the SHO performance gain depend on the relative strengths of the received cell CPICH signals. Under uniform CPICH, potential SHO regions can be easily determined in network planning, because the absolute value of the uniform power does not affect the relative signal strengths. This is not the case for non-uniform CPICH. Pursuing CPICH power saving for HSDPA performance optimization should, therefore, take into account the impact on the SHO degree.

In this paper, we develop mathematical modeling and optimization approaches for planning non-uniform CPICH with preserved SHO control. We focus on data throughput at cell edge for a couple reasons. First, users located at cell edges have low throughput, and consequently improvement in service quality is more perceived and appreciated at cell edges. Second, emphasizing on cell edge reduces HSDPA service holes, and thus decreases the likelihood that HSDPA users have to transit via R99 DCH while moving between cells. Within the service area of a cell, we define the edge as the location that requires the highest HSDPA transmit power for reaching a minimum data rate. For SHO, the performance consideration is modeled by a desired size of SHO region over the entire network service area.

We develop an integer linear programming model for the resulting optimization problem. The model links the CPICH power setting to coverage, the best-server pattern, cell-edge HSDPA service availability, and degree of SHO. The optimum point to the model is a CPICH power setting maximizing cell-edge HSDPA performance, while ensuring CPICH coverage as well as an adequate level of SHO. Using a standard solver, the model admits optimal or near-optimal solutions to relatively small networks. To tackle the planning problem for large-scale networks, we present solution algorithms based on local search and repeated local search. These algorithms aim at finding high-quality solutions effectively and time-efficiently. We report performance evaluation for synthesized networks as well as instances originating from real planning scenarios of various sizes. The results made available by the integer programming model indicate that the two heuristic algorithms, local search and repeated local search, perform close to optimality. The optimized CPICH power leads to significant improvement over the uniform power setting in data throughput at cell edges, showing the importance and benefit of optimization in HSDPA coverage planning.

The remainder of the paper is organized as follows. In Section II, the system model is presented. Details of the integer linear optimization model are given in Section III. In Section IV, we present solution algorithms adopting local search and repeated local search. Performance evaluation is presented Section V. Section VI concludes the paper and outlines lines of further research.

II. THE SYSTEM MODEL

A. Preliminaries

We use $\mathcal{C} = \{1, \ldots, C\}$ to denote the set of cells in a UMTS network implementing HSDPA and R99. The total power available in cell i is denoted by P_i^{tot}. Similar to many previous work on UMTS optimization [2], the network service area is modeled by a regular grid of pixels $\mathcal{J} = \{1, \ldots, J\}$. A pixel $j \in \mathcal{J}$ is a small square area within which radio propagation is considered uniform in the network planning context. High pixel resolution increases the accuracy of planning but also the problem size in optimization. Denote by $g_{ij}, i \in \mathcal{C}, j \in \mathcal{J}$, the total power gain between the base station antenna of cell i and pixel j. The parameter can be obtained by measurements or signal propagation prediction models.

Candidate CPICH power levels are modeled by a discrete set $\{p^1, p^2, \ldots, p^l, \ldots, p^L\}$. Similar to the power gain parameter, the spacing between the power levels has impact on accuracy and problem size. The R99 SHO consideration is specified by parameter μ, denoting the minimum required percentage of pixels in SHO. Whether or not a pixel is expected to be in SHO depends on the cell coverage pattern, which, in its turn, is determined by the CPICH power allocation (see Section II-D). A necessary condition for being in the SHO state is CPICH coverage of two or more cells.

B. CPICH Coverage

Every pixel must be covered by the CPICH of at least one cell. We model coverage by E_c/I_o, i.e., the ratio between the received chip energy and the total received power spectral density at the UE's antenna connector. Cell i covers pixel j if and only if the CPICH E_c/I_o meets a threshold γ_c (typically between -20 dB and -18 dB). Denoting the CPICH power level of cell i by $p_i^{l_i}$, the coverage condition of cell i at pixel j reads

$$E_c/I_o = \frac{p_i^{l_i} g_{ij}}{\sum_{k \in C} p_k^{tot} g_{kj} + \nu_0} \geq \gamma_c. \qquad (1)$$

In (1), the calculation of the amount of interference assumes that the cells operate at full power, i.e., the fill-up approach discussed in Section I. Parameter ν_0 is the noise effect in j. Note that cell i is included in the denominator, as E_c/I_o is measured before signal decoding. By (1), whether or not a cell covers a pixel is determined by the CPICH power level of this cell. If j is covered by more than one cell, we assume that the one giving the highest E_c/I_o is the serving cell, referred to as the best server. It is straightforward to derive the minimum power required in cell i to cover pixel j from (1). Denote this power by $p_i^{l_{ij}}$, defined by the equation below.

$$p_i^{l_{ij}} = \min_{l \in 1, \ldots, L} \{p^l : p^l \geq \frac{\gamma_c(\sum_{k \in C} p_k^{tot} g_{kj} + \nu_0)}{g_{ij}}\} \qquad (2)$$

Since the CPICH power levels are bounded by p^L, a cell can potentially cover a subset of the pixels. We use $\mathcal{J}_i$ to denote

this set for cell i. For later use, we denote the potential covering cells of pixel j by $\mathcal{C}_j$.

There are usually pixels that can be covered by one cell only. Typically, such a pixel is very near to the base station antenna of one cell but far away from the others. Suppose that cell i is the only possible covering cell at pixel j. Obviously i has to be the covering cell of j, and the CPICH power index of i must be at least l_{ij}. Thus we can perform a pre-processing and derive a lower bound on the minimum power level of each cell $i \in \mathcal{C}$; all CPICH power levels below this lower bound can be discarded from further consideration in coverage planning.

If we opt for a uniform CPICH power setting, we are interested in knowing a scalar power value, which, if used by all cells, will secure the coverage of the entire service area. Let p^U denote the minimum possible uniform CPICH power for full coverage. This value will be used as a reference in our performance evaluation. Clearly, to cover j, $p^U \geq \min_{i \in \mathcal{C}} p_i^{l_{ij}}$. To cover the entire service area, the minimum uniform power is

$$p^U = \max_{j \in \mathcal{J}} \min_{i \in \mathcal{C}} p_i^{l_{ij}}. \qquad (3)$$

If we are able to find a non-uniform CPICH power allocation which consume less power than p^U, then the difference is re-allocated to HSDPA. This will be reflected by the definition of the cost function of optimization in Section III-B.

C. HSDPA Power Consideration at Cell Edge

To model HSDPA performance, a suitable metric is the narrowband SINR ratio after de-spreading the HS-PDSCH [7]. For cell i and a pixel j served by i, this SINR value takes the following form.

$$SINR_{ij} = SF^{HS} \times \frac{P_i^{HS}}{P_i^{tot}(1 - \alpha_j + \frac{I_{oc}}{T_{or}})}. \qquad (4)$$

In (4), the spreading factor SF^{HS} equals 16. The two terms I_{oc} and I_{or} are defined as $I_{oc} = \sum_{k \in \mathcal{C}: k \neq i} P_k^{tot} g_{kj} + \nu_0$ and $I_{or} = P_i^{tot} g_{ij}$, representing the inter-cell interference plus noise, and the received power of cell i, respectively. Parameter α_j is the orthogonality factor at pixel j. The numerator P_i^{HS} is the transmit power used by HSDPA. Note that, except for P_i^{HS}, the values of the entities in (4) are known.

HSDPA targets data traffic. Given a mobility profile and the number of channelization codes, the single-user HSDPA data throughput, including the effects of AMC and HARQ, can be modeled as a function of the SINR. In our system model, HSDPA service is considered available if the data throughput meets a minimum target value, which, in turn, translates into SINR. For example, a data throughput of 100 Kbps with 5 channelization codes corresponds to a minimum SINR of about 2.5 dB [7].

Let γ_{HS} denote the SINR threshold defining service availability. Suppose cell i is the best server at pixel j. From (4), we can derive the minimum power necessary to make HSDPA

service available at j, leading to the following formula. This power value is denoted by p_{ij}^{HS}.

$$p_{ij}^{HS} = \frac{P_i^{tot}(1 - \alpha_j + \frac{I_{oc}}{I_{or}})\gamma_{HS}}{SF_{HS}} \qquad (5)$$

Within the service area of cell i, the cell edge refers to the pixel demanding the highest power for service availability. Note that the best-server pattern and thus the edge of every cell are induced by the CPICH power setting (see Section II-B). Because power allocation between HSDPA and R99 is dynamic, P_i^{HS} varies over time. Reserving an amount of power sufficient to ensure HSDPA service at cell edges to P_i^{HS} will likely impose a severe limitation on R99 capacity. Instead, we optimize the coverage and best-server patterns such that the power required for providing HSDPA service to the cell edges is as low as possible.

D. Condition for SHO

A UE may be in SHO if it is covered by at least two cells, and the relative strengths of the received CPICH signals are close to each other. In this paper, we consider two-way SHO, i.e., SHO enabled by the the best server and second best server.

Consider any pixel j and suppose its best and second best servers are i and k, respectively. Pixel j is considered in two-way SHO if the relative difference in the received power of the two cells' CPICH does not exceed a threshold γ_s. The condition is formulated in the following inequality. A graphical illustration is given in Figure 1. It is clear that the SHO region is, similar to the coverage pattern and cell-edge HSDPA power requirement, a result of the CPICH power setting.

$$p_i^{l_i} g_{ij} / p_k^{l_k} g_{kj} \leq \gamma_s \qquad (6)$$

Fig. 1. An illustration of the SHO condition.

E. The Optimization Problem

Having discussed the components of the system model, we can now formalize the optimization problem of HSDPA coverage planning.

Find a CPICH power vector such that the total power required for HSDPA service availability at cell edges, taking into account the power saving over the uniform CPICH, is minimized, and such that the following side constraints are satisfied:

- *all pixels are covered by at least one cell, and*

- *the proportion of the SHO region in the service area is at least μ.*

From a computational complexity standpoint, finding the optimum to the problem is NP-hard in general. The result originates from the NP-hardness of its special case, in which no SHO is required [23].

III. INTEGER LINEAR PROGRAMMING

A. Variables

We develop an integer linear programming model for the HSDPA coverage planning problem. The model uses four sets of binary variables to represent CPICH power selection, best-server pattern, cell-edge definition, and SHO region, respectively.

$$x_{il} = \begin{cases} 1 & \text{if cell } i \text{ uses CPICH power } p^l, \\ 0 & \text{otherwise.} \end{cases}$$

$$s_{ij} = \begin{cases} 1 & \text{if cell } i \text{ is the best server at pixel } j, \\ 0 & \text{otherwise.} \end{cases}$$

$$y_{ij} = \begin{cases} 1 & \text{if pixel } j \text{ defines the edge of cell } i, \\ 0 & \text{otherwise.} \end{cases}$$

$$h_j = \begin{cases} 1 & \text{if pixel } j \text{ is in SHO,} \\ 0 & \text{otherwise.} \end{cases}$$

B. The Cost Function

The cost function represents the HSDPA power required by service availability at cell edges, taking into consideration the CPICH power saving over the uniform power value p^U. For cell i, the cell-edge HSDPA power requirement equals $\sum_{j \in \mathcal{J}_i} p_{ij}^{HS} y_{ij}$. Note that exactly one of these y-variables may equal one. The power saving on CPICH in respect of the uniform power is $p^U - \sum_{l=1}^{L} p^l x_{il}$, where the second term is the cell CPICH power. Putting the two pieces together, the overall cost function becomes the following expression.

$$\min \sum_{i \in \mathcal{C}} (\sum_{j \in \mathcal{J}_i} p_{ij}^{HS} y_{ij} - (p^U - \sum_{l=1}^{L} p^l x_{il})) \quad (7)$$

Because p^U is a constant, it can be discarded in the optimization process. Removing p^U, the equivalent form of (7) is $\min \sum_{i \in \mathcal{C}} (\sum_{j \in \mathcal{J}_i} p_{ij}^{HS} y_{ij} + \sum_{l=1}^{L} p^l x_{il})$.

C. Constraints

The optimization model uses several sets of constraints to link the CPICH power vector to the coverage pattern and SHO. We start with some constraints that are straightforward in mathematical modeling.

CPICH Power Selection. Every cell has to use exactly one of the possible power levels, thus

$$\sum_{l=1}^{L} x_{il} = 1, \quad i \in \mathcal{C}. \quad (8)$$

Single Best Server. At each $j \in \mathcal{J}$, one of its potentially-covering cells is the best server, therefore

$$\sum_{i \in \mathcal{C}_j} s_{ij} = 1, \quad j \in \mathcal{J}. \quad (9)$$

Relation between Coverage and Best Server. The following constraints model a necessary condition for being best server: Cell i may be the best server of j only if CPICH coverage is provided; in other words, the cell must use a power level of at least l_{ij}.

$$s_{ij} \le \sum_{l=l_{ij}}^{L} x_{il}, \quad j \in \mathcal{J}, i \in \mathcal{C}_j. \quad (10)$$

Cell-edge HSDPA Power Requirement. The HSDPA power requirement of the edge of cell i equals the maximum value among the pixels having i as the best server, hence

$$s_{ij} \le \sum_{n: p_{in}^{HS} \ge p_{ij}^{HS}} y_{in}, \quad j \in \mathcal{J}, i \in \mathcal{C}_j. \quad (11)$$

If $s_{ij} = 1$ (i.e., i is the best server of j), constraint (11) requires that a y_{in} variable, for which $p_{in}^{HS} \ge p_{ij}^{HS}$, must be chosen. Thus $s_{ij} = 1$ implies that the HSDPA power of cell i will be at least that necessary for providing service availability at j. For any cell, (11) will hold as equality for the pixel defining cell edge. For the other pixels served by the cell, (11) will hold as strict inequality.

Remark 1: In every cell, exactly one pixel defines the edge, thus constraints $\sum_{j \in \mathcal{J}_i} y_{ij} = 1, i \in \mathcal{C}$, are valid. It is not difficult to show, however, that these constraints are redundant, i.e., at optimum they are induced by the other constraints together.

The following two constraint sets model best-server selection and SHO condition. They form the crucial part of the model. We give a detailed treatment of these constrains as they are less straightforward than the other ones.

Best-server Selection: If a pixel is covered by multiple cells, the one with the highest CPICH strength is the best server. Modeling this fact necessitates some additional notation. Consider pixel $j \in \mathcal{J}$ and two cells $i, k \in \mathcal{C}_j$. For each possible CPICH level p^m ($m = 1, \ldots, L$) at cell i, the minimum CPICH level, for which cell k gives *better* signal than cell i at j, is denoted by $l(j, i, k, m)$. Equivalently speaking, $p^m g_{ij} < p^l g_{kj}$, for all $l \ge l(j, i, k, m)$, as illustrated in Figure 2.

Fig. 2. An illustration of the best-server condition.

For the scenario in Figure 2, obviously cell i is not the best server, if the CPICH power level of k is l or above. This observation leads to the following constraints.

$$s_{ij} \leq 2 - (\sum_{l=1}^{m} x_{il} + \sum_{l=l(j,i,k,m)}^{L} x_{kl}), \quad j \in \mathcal{J} : |\mathcal{C}_j| \geq 2, i, k \in \mathcal{C}_j,$$

$$l_{ij} \leq m \leq L. \tag{12}$$

There is one group of (12) for every pixel j and each pair of its potentially covering cells $i, k \in \mathcal{C}_j$. A constraint in the group has the following effect. If cell i uses a CPICH level less than or equal to m, then $\sum_{l=1}^{m} x_{il} = 1$. Moreover, $\sum_{l=l(j,i,k,m)}^{L} x_{kl} = 1$ if cell k uses a level of at least $l(j,i,k,m)$. If both are true, then the right-hand side of (12) is zero, and hence s_{ij} is forced to be zero. Otherwise (12) does not pose any restriction on s_{ij}.

Note that constraint (12) does not explicitly define best server. Its effect is to forbid all scenarios in which a cell is *not* the best server of a pixel. This construction, together with the single-server constraint (9), ensure that $s_{ij} = 1$ *if and only if* cell i is the best server at j.

SHO Region. Our notion of modeling SHO mathematically follows the spirit of (12). For every pixel, we consider covering scenarios in which SHO does *not* take place. Suppose that cell i with CPICH power p^m is the best server at j. Then another cell k will not yield SHO at j with respect to cell i, if the power p^l used by k does not cover j at all, or the difference in the received CPICH strengths $p^m g_{ij} - p^l g_{kj}$ exceeds the SHO threshold. Among such power levels of k, denote by $c(j,i,k,m)$ the *highest* one. That is, $c(j,i,k,m)$ is the highest CPICH level, for which the received CPICH of k at j does *not* give SHO together with cell i, provided that the best server is i and its power level is p^m. See Figure 3 for an illustration. Note that $c(j,i,k,m)$ may be null.

Fig. 3.   An illustration of the SHO condition.

Assume again cell i is the best server at j. If for all $k \neq i$, the power used by k is below $c(j,i,k,m)$, then SHO does not occur at j. This relation gives the following constraints.

$$h_j \leq 1 - (x_{im} + \sum_{k \in \mathcal{C}_j \setminus \{i\}} \sum_{l \leq c(j,i,k,m)} x_{kl} - |\mathcal{C}_j| + 1),$$

$$j \in \mathcal{J} : |\mathcal{C}_j| > 1, i \in \mathcal{C}_j, m = l_{ij}, \ldots, L \tag{13}$$

There is one constraint of (13) for a combination of pixel, each of its potentially covering cells, and each of the power levels of the cells. Suppose $x_{im} = 1$. If a cell $k \in \mathcal{C}_j \setminus \{i\}$ does not give SHO together with i at pixel j, $\sum_{l \leq c(j,i,k,m)} x_{kl} = 1$. And if this happens to all cells in $\mathcal{C}_j \setminus \{i\}$, the value in the

parentheses of (13) is one, and the right-hand side becomes zero, forcing h_j to be zero. Otherwise the constraint does not impose any restriction on the value of h_j. To summarize, for every $j \in \mathcal{J}$, (13) defines all scenarios that would prohibit this pixel from being in SHO.

Remark 2: We do not need to explicitly state that i is the best server in (13) – The constraint does not impose value restriction on h_j if a cell other than i, say cell k, is the best server. If k gives better CPICH than i at j, then the power level used by k must be higher than $c(j,i,k,m)$, and hence the corresponding x-variable does not appear in the right-hand side of the constraint.

SHO performance. The SHO degree over the service area has to meet parameter μ. This is defined by one single constraint.

$$\sum_{j \in \mathcal{J}} h_j \geq \mu J \tag{14}$$

Explicitly requiring that some regions are in SHO may be of relevance in network planning. In this case (14) can be complemented by $h_j = 1$ for all pixels of regions with explicit SHO requirement.

IV. SEARCH ALGORITHMS

The integer linear programming model can be used for finding the optimal or a near-optimal solution for relatively small networks. For large-scale planning scenarios, however, obtaining solutions from the model is out the reach of state-of-the-art optimization solvers. For this reason, we develop heuristic algorithms using local search and repeated local search to reach high-quality solutions time-efficiently.

A. Local Search (LS)

The basic idea of local search (LS) is to iteratively improve the overall performance metric defined by (7), by successively adjusting CPICH power levels. The key operation is to reduce the CPICH power of one cell by one step. If this leads to an improvement of (7) and does not violate the SHO degree requirement, the new solution is accepted and an update is made. The algorithm keeps two lists of cells: forbidden list and eligible list. A cell is in the forbidden list if any further decrease of its CPICH power will cause a coverage hole. The main loop in the algorithm is formed by making trial reductions of CPICH power of the cells in the eligible list. Every time the loop starts, the eligible list is composed by all cells other than those in the forbidden list. In each iteration, a cell in the eligible list is randomly chosen, and a trial of CPICH power reduction is performed. If power reduction can not be done because of coverage, the cell is permanently moved to the forbidden list. If CPICH reduction does not improve the objective function, or it causes a violation of the SHO requirement, the cell is deleted from the eligible list, but not added to the forbidden list. The algorithm terminates if no improvement is found when the eligible list becomes empty, otherwise the list is re-initialized, and the main loop is repeated.

A more formal description of LS is given in Algorithm 1. In the algorithm, $\mathcal{F}$ and $\mathcal{G}$ denote the forbidden and eligible lists, respectively. Vector $\mathbf{p} = (p_1^{l_1}, \ldots, p_i^{l_i}, \ldots, p_C^{l_C})$ represents the best solution found by the algorithm, whereas $\hat{\mathbf{p}}$ and $\bar{\mathbf{p}}$ denote, respectively, the initial CPICH power and a trial power allocation. The objective function values of these solutions are denoted by f, $\hat{f}$, and $\bar{f}$, respectively. For any of the power vectors, for example $\mathbf{p}$, we use $c(\mathbf{p}, j)$ to denote a function returning the number of cells covering pixel j, and $b(\mathbf{p}, j)$ the best server of j. If $c(\mathbf{p}, j) \geq 2$, $d(\mathbf{p}, j)$ denotes the second best server of j.

Algorithm 1 Local_Search

1: $\hat{f} \leftarrow \sum_{i \in \mathcal{C}} (\max_{j \in \mathcal{J} : b(\hat{\mathbf{p}}, j) = i} p_{ij}^{HS} + \hat{p}_i^{l_i})$

2: $\mathbf{p} \leftarrow \hat{\mathbf{p}}$, $f \leftarrow \hat{f}$

3: $\mathcal{F} \leftarrow \emptyset$

4: **for** $i \in \mathcal{C}$ **do**

5:     **if** $\exists j \in \mathcal{J} : c(\mathbf{p}, j) = 1 \wedge b(\mathbf{p}, j) = i$ **then**

6:         $\mathcal{F} \leftarrow \mathcal{F} \cup \{i\}$

7:     **end if**

8: **end for**

9: **repeat**

10:     $f' \leftarrow f$

11:     $\mathcal{G} \leftarrow \mathcal{C} \setminus \mathcal{F}$

12:     **while** $\mathcal{G} \neq \emptyset$ **do**

13:         $\bar{\mathbf{p}} \leftarrow \mathbf{p}$

14:         Choose randomly $i \in \mathcal{G}$

15:         $\bar{p}_i^{l_i} \leftarrow p^{l_i - 1}$

16:         $h \leftarrow 0$

17:         **for** $j \in \mathcal{J} : c(\bar{\mathbf{p}}, j) \geq 2$ **do**

18:             **if** $p_{b(\bar{\mathbf{p}}, j)}^{l_{b(\bar{\mathbf{p}}, j)}} g_{b(\bar{\mathbf{p}}, j), j} / p_{d(\bar{\mathbf{p}}, j)}^{l_{d(\bar{\mathbf{p}}, j)}} g_{d(\bar{\mathbf{p}}, j), j} \leq \gamma_s$ **then**

19:                 $h \leftarrow h + 1$

20:             **end if**

21:         **end for**

22:         **if** $h < \mu J$ **then**

23:             $\mathcal{G} \leftarrow \mathcal{G} \setminus \{i\}$

24:         **else**

25:             $\bar{f} \leftarrow \sum_{i \in \mathcal{C}} (\max_{j \in \mathcal{J} : b(\bar{\mathbf{p}}, j) = i} p_{ij}^{HS} + \bar{p}_i^{l_i})$

26:             **if** $\bar{f} < f$ **then**

27:                 $f \leftarrow \bar{f}$, $\mathbf{p} \leftarrow \bar{\mathbf{p}}$

28:                 **if** $\exists j \in \mathcal{J} : c(\mathbf{p}, j) = 1 \wedge b(\mathbf{p}, j) = i$ **then**

29:                     $\mathcal{F} \leftarrow \mathcal{F} \cup \{i\}$

30:                 **end if**

31:             **else**

32:                 $\mathcal{G} \leftarrow \mathcal{G} \setminus \{i\}$

33:             **end if**

34:         **end if**

35:     **end while**

36: **until** $f = f'$

37: Return($\mathbf{p}$, f)

In Algorithm 1, the list of forbidden cells is initialized in lines 4–8. The main loop starts at line 9. As long as the eligible list $\mathcal{G}$ is non-empty, a cell in the list is randomly chosen, and a trial of reducing the CPICH power by one step is performed (lines 14–15). The resulting SHO degree is computed at lines 17–21. The cell is deleted from the eligible list if the SHO constraint is not satisfied. Otherwise, the objective function value is computed (line 25). Depending on whether or not the value gives an improvement, either an update of the solution is made (lines 27–30), or the cell is excluded from the eligible list (line 23). In the former case, a check is carried out to determine if any further reduction of the CPICH power of the cell will violate coverage. Eventually, the eligible list becomes empty. At this point, the algorithm checks if any improvement has been obtained within the while-loop. If so, the eligible list is re-initialized and the procedure repeats.

B. Repeated Local Search (RLS)

Running the LS algorithm gives one single solution to the coverage planning problem. We can obtain improvements by applying the LS algorithm repeatedly. Note that selecting a cell from the eligible list is performed randomly. Thus running the algorithm multiple times will likely result in different solutions, without changing the initial CPICH power vector $\hat{\mathbf{p}}$. However, this simple strategy of repeating the algorithm is not effective, since the initial solution $\hat{\mathbf{p}}$ may be rather poor in terms of optimality, and always starting from the same solution imposes a rather hard limitation on the solution space that the algorithm will explore.

We develop a repeated local search (RLS) algorithm, in which the initial solution is derived from the one currently best known. Denote the latter by $\mathbf{p}^*$. This power vector satisfies both coverage and SHO constraints. Recall that the SHO condition (Section II-D) is defined in the relative difference of the strongest and second strongest CPICH signals. Hence if all elements of $\mathbf{p}^*$ are scaled up by a common factor, denoted by β, the SHO degree requirement, and obviously coverage as well, will remain satisfied. The number of pixels in SHO will likely grow for $\beta \mathbf{p}^*$, as cell overlap increases. In our RLS algorithm, the value of β is randomly chosen each time to introduce diversity in searching the solution space. Note that the values in $\beta \mathbf{p}^*$ may no longer be in the candidate set of power levels $\{p^1, \ldots, p^L\}$. Therefore a rounding operation is needed, followed by examining the SHO degree. If the SHO constraint remains satisfied, LS is run using the rounded values of $\beta \mathbf{p}^*$ as the initial solution.

RLS is described in Algorithm 2. The first line refers to the initial run of the LS algorithm. LS is then repeated T times using initial solutions derived from the best known power vector $\mathbf{p}^*$. The scaling of the vector is done in lines 3–4, where β^U denotes the upper limit of the scaling factor. Next, rounding is performed. SHO degree is examined in lines 7–11. If the solution passes the SHO check, LS is invoked (line 13), and a solution update is carried out if improvement is found.

V. EXPERIMENTAL RESULTS

In this section, we present the numerical results of the integer programming model and the two search algorithms on six test

Algorithm 2 Repeated_Local_Search

1: $(\mathbf{p}^*, f^*) \leftarrow$ Local_Search$(\hat{\mathbf{p}})$
2: **for** $i = 1$ to T **do**
3:     Select randomly $\beta \in (1.0, \beta^U]$
4:     $\hat{\mathbf{p}} \leftarrow \beta\mathbf{p}^*$
5:     Round the elements of $\hat{\mathbf{p}}$ to values in $\{p^1, \ldots, p^L\}$
6:     $h \leftarrow 0$
7:     **for** $j \in \mathcal{J} : c(\hat{\mathbf{p}}, j) \geq 2$ **do**
8:         **if** $p^{l_{b(\hat{\mathbf{p}}, j)}}_{b(\hat{\mathbf{p}}, j), j} g_{b(\hat{\mathbf{p}}, j), j} / p^{l_{d(\hat{\mathbf{p}}, j)}}_{d(\hat{\mathbf{p}}, j), j} g_{d(\hat{\mathbf{p}}, j), j} \leq \gamma_s$ **then**
9:             $h \leftarrow h + 1$
10:        **end if**
11:    **end for**
12:    **if** $h \geq \mu J$ **then**
13:        $(\mathbf{p}, f) \leftarrow$ Local_Search$(\hat{\mathbf{p}})$
14:        **if** $f < f^*$ **then**
15:            $f^* \leftarrow f, \mathbf{p}^* \leftarrow \mathbf{p}$
16:        **end if**
17:    **end if**
18: **end for**
19: Return$(\mathbf{p}^*, f^*)$

networks. The optimization model is solved by ILOG CPLEX [13]. The two search algorithms are written in C++, and run on an HP Compaq 8510p mobile workstation with Intel Core2 Duo Processor (2.4 GHz and 2G RAM).

A. Test Networks and Experimental Design

A summary of some statistics of the test networks is given in Table I. Among the test networks, four originate from real planning cases, and the other two are synthesized planning. Net1 is a realistic planning scenario provided by Ericsson Research. It is a small network, which is useful for benchmarking. Net2 and Net3 are synthesized planning scenarios obtained by randomly placing a number of sites over an area. Net4, Net5 and Net6 are realistic cases originating from European project MOMENTUM [14]. Net4 is a planning case for the city of Berlin. Net5 and Net6 are two network scenarios for the city of Lisbon. The last column of the table shows the SHO ratio achievable under the uniform CPICH power setting. For each network, experiments have been carried out for various degrees of the SHO requirement, up to the a level close to that with uniform CPICH. For HSDPA service availability, the SINR requirement is set to 2.5 dB.

TABLE I
NETWORK STATISTICS.

Network	Sites	Cells	Service Area		Achievable
			Pixels	Pixel size (m^2)	SHO rate (%)
Net1	22	60	1375	40*40	19.42
Net2	42	42	2708	40*40	24.82
Net3	140	140	9409	40*40	29.99
Net4	50	148	22500	50*50	37.28
Net5	52	140	62500	20*20	31.61
Net6	60	164	52500	20*20	35.33

Table II presents some problem parameters. Column "Noise" shows values of the thermal noise parameter μ_0. The third column displays the CPICH coverage threshold γ_c. The uniform CPICH power p^U and the average HSDPA power required for service availability at cell edge under the uniform CPICH setting are shown, respectively, in the next two columns. Net1–Net3 have a uniform orthogonality factor α_j all over the area. For Net4–Net6, orthogonality varies by pixel, depending pixel type (urban, mixed or rural area). The last column gives the total downlink transmit power.

TABLE II
PROBLEM PARAMETERS.

Network	Noise	Coverage threshold	Uniform CPICH	Average HSDPA	Orthogonality	Total power
	(W)	(dB)	(W)	(W)		(W)
Net1	1e-13	-18	1.5	3.56	0.6	15
Net2	1e-13	-18	1.4	5.16	0.6	15
Net3	1e-13	-18	1.4	5.33	0.6	15
Net4	1.5488e-14	-20	2.5	10.65	0.327,0.633,0.938	19.95
Net5	1.5488e-14	-20	2.1	10.56	0.327,0.633,0.938	19.95
Net6	1.5488e-14	-20	1.9	10.76	0.327,0.633,0.938	19.95

The integer linear programming model is applicable to the two small-sized networks Net1 and Net2. For the other networks, solving the model requires excessive computing time. The two search algorithms runs very fast for all test networks. For RLS, we enforce a limit of maximum 500 main iterations. In the coming sections, we first present the results of both optimization model and search algorithm for the two small networks. A closer look on the result is provided for Net1. Next, results of the search algorithm for the other, large networks are presented.

B. Results for Small Networks

Table III shows the computational results for Net1 and Net2. For each network and a SHO degree, the table reports the solutions obtained by solving the integer model and RLS. We use a time limit of 10 hours in solving the integer model. If this time limit is reached, the best solution reported by the solver is represented. For each solution, the table shows the average CPICH power and the HSDPA power needed to provide service at cell edge. The latter takes into account the power saving over uniform CPICH. The sum of these two values times the number of cells is the cost function defined in (7). The last column of the table displays the relative difference between the solution found by the integer model and that obtained by RLS.

As can be seen from Table III, the computing time for solving the integer model grows rapidly in the required level of SHO. The RLS algorithm is a heuristic, but runs very fast. In addition, the algorithm performs close to optimality, as shown by the gap values.

Comparing the results in Table III to that of uniform CPICH (part of Table II), a significant improvement in the CPICH power consumption can be observed. This holds even under a high level of SHO requirement. For the highest SHO degrees considered in the experiments, the power savings are 40% and

Network	SHO ratio %	Integer Model			RLS			Gap
		Average CPICH (W)	Average HSDPA (W)	Time (sec)	Average CPICH (W)	Average HSDPA (W)	Time (sec)	%
Net1	11	0.69	2.33	61	0.70	2.43	1	4.25
	13	0.73	2.37	518	0.75	2.48	1	4.63
	15	0.77	2.42	2529	0.83	2.56	2	6.03
	17	0.83	2.49	limit	0.91	2.66	2	7.00
	19	0.90	2.60	limit	1.00	2.78	2	6.83
Net2	16	0.81	3.80	3040	0.83	4.00	2	5.26
	18	0.83	3.82	limit	0.85	4.04	2	5.78
	20	0.85	3.86	limit	0.93	4.08	2	5.57
	22	0.88	3.92	limit	1.02	4.23	2	7.73
	24	1.00	4.10	limit	1.08	4.33	2	5.82

24% for Net1 and Net2, respectively. One can also observe from the table that the CPICH power has to grow by the SHO requirement. This is reasonable as higher SHO necessitates larger cell overlap, thus, a higher CPICH power.

Our system model is designed specifically to bring the benefit of CPICH power saving to HSDPA performance. This can be observed in the average power required to provide HSDPA service at cell edge. The value is improved by 27% and 21%, respectively, for the two networks, under the highest SHO requirements. The improvement becomes larger for lower SHO degree values.

In Figure 4, we give a detailed view of the required cell-edge HSDPA power for Net1 with SHO parameter $\mu = 17\%$. In total, 53 cells have their cell-edge HSDPA power requirement decreased, while the value has increases for 7 cells. The latter is due to the fact that the cost function (7) target the overall performance. For many cells, the power improvement is very significant.

C. Results for Large Networks

We have applied LS as well as RLS to networks Net3–Net6. The computational results are presented in Table IV. For each algorithm and planning scenario, Table IV reports the CPICH and HSDPA power values, and the solution time.

Network	SHO ratio %	LS			RLS		
		Average CPICH (W)	Average HSDPA (W)	Time (sec)	Average CPICH (W)	Average HSDPA (W)	Time (sec)
Net3	0.24	0.92	4.42	0.0	0.91	4.24	14
	0.26	0.97	4.46	0.0	0.93	4.26	15
	0.28	1.00	4.56	0.0	0.97	4.29	16
	0.30	1.07	4.65	0.0	1.06	4.39	16
Net4	0.30	1.23	7.88	0.3	1.20	7.56	95
	0.32	1.34	8.23	0.4	1.25	7.74	117
	0.34	1.72	8.93	0.4	1.47	8.09	130
	0.36	2.22	9.94	0.4	1.93	8.93	147
Net5	0.24	0.99	7.94	0.7	0.96	7.54	227
	0.26	1.08	8.03	0.7	1.03	7.63	224
	0.28	1.24	8.41	0.7	1.10	7.86	244
	0.30	1.82	9.65	0.5	1.27	8.22	340
Net6	0.31	1.20	8.66	0.7	1.06	8.21	219
	0.33	1.22	8.66	0.7	1.12	8.30	231
	0.35	1.41	9.23	0.4	1.20	8.51	183

Running LS requires virtually no time at all. The RLS algorithm repeats LS from various starting solutions, and thus the solution time grows linearly in the number of iterations. For 500 iterations used for our experiments, the solution time of RLS is moderate (up to a few minutes). Examining the power values in the table, it is clear that RLS is able to further improve the solution of LS, and the amount of improvement lies between 4 and 8 percent. In the remainder of this section, the analysis is based on the results of RLS.

Comparing Tables II and IV, significant power saving on CPICH is observed. For the Berlin network (Net4), for example, optimized non-uniform CPICH enables a power reduction of up to 52%. A similar amount of power saving is achieved for the other networks. As expected, tighter SHO requirement makes the CPICH consumption increase.

Fig. 5.   Cell-edge HSDPA Power Decrease.

The solution found by RLS outperforms the uniform CPICH setting in terms of a much lower power consumption needed to deliver HSDPA service to cell edge. Taking again the Berlin network as an example, the reduction in the amount of required HSDPA power is 16% with a comparable SHO degree. If lower SHO degree is required, the power reduction grow up to 29%. Figure 5 illustrates in more detail the HSDPA power reduction for all four networks and various SHO degrees. A general trend of the curves is that the amount of reduction decreases in the SHO degree. This is because increasing SHO has two impacts. The first is less power saving on CPICH. The impact is that the cells grow in size, and hence cell edge tends to be further away from the base station antenna. Even for SHO degrees close to those under uniform CPICH, however, the figure shows a clear improvement in terms of cell-edge HSDPA power.

Thus far, performance evaluation has been made under one value of SINR (2.5 dB), which is considered to be the minimum necessary for HSDPA service availability. The fill-up resource allocation approach (Section II) means that the power available to HSDPA is dynamic in network operation. It is hence of interest to examine the relation between the power available to HSDPA and the resulting SINR. For the Berlin network (Net4) and SHO $\mu = 30\%$, Figure 6 shows how the average cell-edge HSDPA SINR, calculated for uniform and optimized CPICH solutions, varies over power. For optimized CPICH, the calculation includes the power saving. We see that optimization leads to a clearly better SINR at cell edge. For instance, if

Fig. 4. Cell-edge HSDPA Power Requirement.

the transmit power of HSDPA is 7 W, cell-edge SINR under uniform CPICH is around 0 dB, hardly providing any data throughput. With optimized CPICH allocation, approximately 2.5 dB is gained, supporting a data throughput of 100 Kbps [7].

Fig. 6. Average cell edge SINR.

Fig. 7. HSDPA SINR improvement (dB).

Although our focus is on cell-edge HSDPA performance, it is also interesting to examine how much benefit can be brought to areas other than cell edge. In Figure 7, we show the SINR difference in dB scale for the uniform CPICH and optimized CPICH, over the entire service of the Berlin network, assuming 5 W allocation of HSDPA power and requiring $\mu = 30\%$ of SHO. The figure shows that, with optimized CPICH power allocation, most parts of the service area obtain improved SINR. The improvement is significant for a fairly large portion of the area – Approximately 25% of the pixels gain an SINR improvement of 2 dB or more. In average, the SINR increases by 1.3 dB over all pixels.

VI. CONCLUSIONS

We have presented an optimization approach for coverage planning in UMTS networks providing mixed HSDPA and R99 services. The approach targets optimizing non-uniform CPICH power allocation for enhancing HSDPA performance at cell edge, without losing control of SHO in the R99 service. Our system model is well-suited for planning networks in heterogeneous environments, because its does not make any assumption on cell layout or radio propagation characteristics.

We have developed an integer linear programming model for the power optimization problem. Applying a solver to the model, optimal solutions of small networks are within reach. In addition, we have developed algorithms utilizing local search and repeated local search. These algorithms allow for tackling the planning problem in large-scale networks using short computing time. Performance benchmarking of local search and repeated local search on networks, for which optimum is known, indicates that the algorithms' performance is close to optimality.

The numerical results show that, in comparison to the uniform CPICH setting, optimized non-uniform CPICH offers significant power saving and thereby higher HSDPA service availability, while keeping SHO at an acceptable level for R99. The performance improvement is particularly apparent in large networks. These results demonstrate the potential of coverage optimization in engineering HSDPA networks.

One extension of the current work is to perform coverage optimization not only for cell-edge service availability, but also for achieving other performance goals, such as cell load balancing. Another line of further research is to incorporate uplink aspects, e.g., modeling and integrating the performance of high speed uplink packet access (HSUPA) into the optimization framework.

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