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Interference minimization using automatic design of cellular communication networks

Kurt Tutschku
Institute of Computer Science, University of Würzburg
Am Hubland, D-97074 Würzburg, Germany
Tel.: +49-931-8885511, Fax: +49-931-8884601

E-mail: tutschku@@informatik.uni-wuerzburg.de

Abstract: This paper presents an automatic cellular network design algorithm which determines the location of transmitters with respect to co-channel interference (CCI). The proposed method is capable of maximizing the average CCI ratio in the planning region while optimizing the covered teletraffic demand. Additionally, we investigate how the proposed algorithm can be extended for locating micro- and macro-cells.

I. Introduction

The cellular concept introduces frequency reuse for FDMA/TDMA wireless networks to increase the traffic capacity of the radio part of these systems. Users in geographically separated areas are simultaneously employing the same carrier frequency. However, the frequency reuse introduces co- and adjacent-channel interference which limits the theoretical capacity gain of the reuse if the geographical separation of cells with the same frequency is too small.

The high capacity design of a cellular network requires that, after selecting the cell site, frequencies are allocated to the cells in such a way that the co-channel and the adjacent channel interference in the cells is minimized. Due to the inhomogeneous traffic distribution and the irregular shape of the cell boundaries, however, the frequency allocation procedure is extremely difficult. In order to decrease the complexity of this engineering task, already the selection of cell sites should be carried out with regard to interference. Especially, the worst case scenario of co-channel interference (CCI), has to be addressed in an early stage during the cellular design.

In this paper, we present an automatic cellular network design algorithm which determines the location of transmitters with respect to co-channel interference. The proposed method is capable of maximizing the average CCI ratio in the planning region while optimizing the covered teletraffic demand. Additionally, we investigate how the proposed algorithm can be extended for locating micro- and macro-cells.

The paper is organized as follows. In Section II we first discuss the interference minization objectives and introduce the Demand Node Concept (DNC), which facilitates the application of automatic cellular network design algorithms. We then formulate the base station location task as a discrete covering problem, and we then demonstrate how interference minization can be stated as a constraint in the optimization task. Additionally, we present results from two case studies. In Section III, we demonstrate how the interference minimization can be extended to micro/macro cell design. In Section IV, we summarize our presentation and give an outlook to further extensions of the proposed method.

II. Interference minimizing radio network design

Before introducing the interference minimizing design algorithm, below we outline the basic RF objectives for automatic radio network engineering and the calculation of the co-channel interference (CCI) ratio in cellular systems.

A. RF design objectives

Most automatic cellular network design algorithms consider the received signal power level $\Omega_{(dB)}$ at certain test points as their main design objective, cf. Calégari et al. (1997) and Chamaret et al. (1997). However, the consideration of this value as the sole design criterion is insufficient for real world planning cases. The provision of a usable radio link requires at least the fulfillment of two constraints:

a) the received signal level Ω_{dB} has to obey the threshold $\Omega_{th,(dB)}$, defined by the link budget, cf. Faruque (1996):

$$\Omega_{(dB)} > \Omega_{th,(dB)}, \tag{1}$$

b) the co-channel interference ratio $\Lambda_{(dB)}$ is not allowed to exceed the interference threshold $\Lambda_{th,(dB)}$:

$$\Lambda_{(dB)} < \Lambda_{th,(dB)}. \tag{2}$$

The threshold $\Lambda_{th,(dB)}$ is defined by the receiver sensitivity.

However, the usage of the interference value as a design criterion for a single base station is quite a challenge: the interference measured at a certain location depends firstly on the signal disturbance introduced by an investigated new base station, and secondly on the configuration of other interfering, already located, transmitters.

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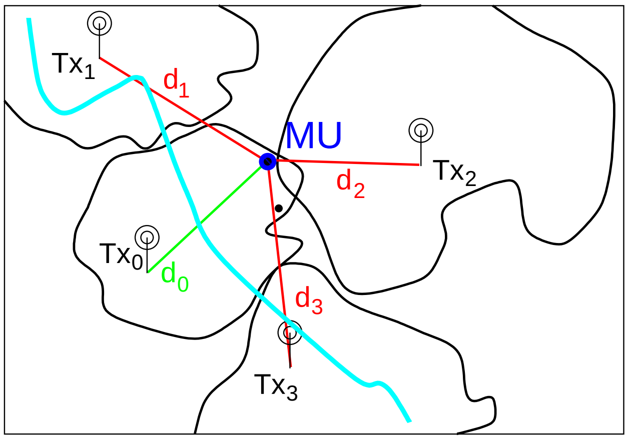


Figure 1: Interferer scenario

B. Co-channel interference

Figure 1 depicts a typical cellular scenario. A mobile unit MU in distance d_0 receives the strongest signal from base station Tx$_0$, which is denoted as the *best server*. The reception of this signal is disturbed by three surrounding *interferers* Tx$_{k,k=1\ldots3}$. Additionally, it is assumed that the interferers are transmitting on the same frequency as the best server. The average downlink CCI ratio at the location of the mobile unit is, cf. Stüber (1996):

$$\Lambda_{(dB)} = \Omega_{(dB)}(d_0) - 10\log_{10}\{\sum_{k=1}^{N_I} 10^{\Omega_{(dB)}(d_k)/10}\}, \quad (3)$$

where $\Omega_{(dB)}(d_k)$ is the received signal power level from transmitter Tx$_k$, d_k is the distance of the mobile unit to the transmitter and N_I is the number of interferers.

C. Automatic cellular network design algorithms

Automatic cell site selection algorithms facilitate the deployment of mobile systems in two significant ways. First, they are capable of optimizing the network configuration. An automatic method can verify a huge number of different sites until the optimal set of sites is selected under the given constraints. Second, automatic selection algorithms accelerate the engineering process. A preliminary network configuration is synthesized by the algorithm. It serves as a starting point for the actual design. Hence, the network designer does not have to deal with invalid sites. The engineer can immediately start with the detailed determination of the system parameters.

A demand-based automatic network design algorithm was introduced by Tutschku (1998). This algorithm will be extended in this section so that it also accounts for interference. The application of the proposed algorithm is enabled by the employment of a discrete population model for the traffic description, the *Demand Node Concept (DNC)*, cf. Tutschku et al. (1996) and Tutschku et al. (1997). The application of the concept enables the formulation of the transmitter location task as a *Maximal Coverage Location Problem (MCLP)*, which is well known in economics for modeling and solving facility location problems.

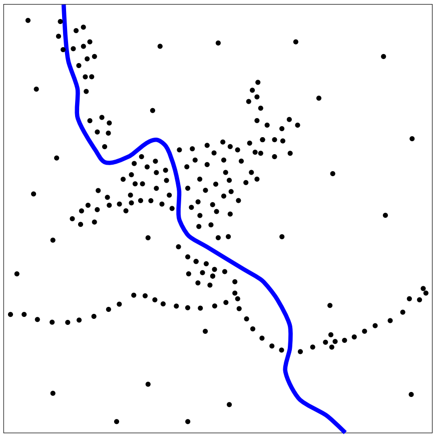


Figure 2: Demand node concept: node distribution

1) Demand Node Concept

The core technique of the concept is to represent the spatial distribution of the demand for teletraffic by discrete points:

Definition 1: A *demand node* represents the center of an area that contains a quantum of demand from teletraffic viewpoint, accounted in a fixed number of call requests per time unit.

The DNC leads to a discretization of the traffic demand in both space and demand. An example of an demand node distribution is shown in Figure 2. It depicts an area of size $15km \times 15km$ around the city of Würzburg, Germany, also showing the Main river. The DNC is not only useful for the mobile subscriber characterization, it also enables a new definition of the term coverage area:

Definition 2: The *coverage area* of a transmitter is the set of demand nodes which are provided with a usable radio link according to Eqn.(1) and Eqn.(2).

An appealing feature of the DNC, together with Definition 2, is the fact, that the validation of the RF performance of a new base station requires only the calculation of field strength values at positions where it is highly probable to locate a mobile subscriber. It is not necessary anymore to compute the performance values at every location within the service area. Thus, the DNC leads to a significant speed up of the design of cellular systems.

2) Network optimization

Problem definition: Due to Definition 2, supplying users with a mobile radio service is equivalent to *covering* demand nodes. An optimization algorithm has to determine the location of transmitters such that the proportion of demand nodes within the permitted service range is maximized. The service range is restricted by Eqn.(1) and Eqn.(2). Hence, the base station locating task is reduced to a *Maximal Covering Location Problem (MCLP)*, which is mathematically defined as:

$$\text{Maximize} \quad Y = \sum_{i \in I} a_i y_i \tag{4}$$

subject to:

$$\sum_{j \in N_i} x_j \geq y_i \;\; \forall i \in I \;\; \wedge \;\; \sum_{j \in J} x_j = p \;\; \forall i \in I, \forall j \in J. \tag{5}$$

Here J is the set of potential facility sites (indexed by j), I is the set of demand nodes (indexed by i), Y is the objective function (i.e. the weighted coverage), x_j indicates if there is a facility at location with index j, y_i is the decision variable denoting whether demand node i is covered or not, a_i is the population represented by demand node i (i.e. the teletraffic demand), N_i is the set of base stations which are providing sufficient signal strength at demand node i, and p is the maximum number of transmitters to be deployed.

Objective function for interference minimization: An interference minimizing design of a cellular network requires that the decision variable y_i, which indicates whether a demand node is covered or not, obeys the two constraints given by Eqn.(1) and Eqn.(2). Hence, we define mathematically the covering criteria as:

$$y_i = \begin{cases} 1 & \exists j \in N_i : \quad (\Omega_{(dB)}(i,j) > \Omega_{th,(dB)}) \\ & \qquad \wedge (\Lambda_{(dB)}(i) < \Lambda_{th,(dB)}(i)) \,, \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where $\Omega_{(dB)}(i,j)$ is the received signal strength at demand node i from transmitter j, and $\Lambda_{(dB)}(i)$ is the co-channel interference according to Eqn.(3).

Heuristic solution: Due to its flexibility, a greedy algorithm based on the proposal by Vohra and Hall (1993) was chosen as a method for solving the MCLP. The algorithm imposes no restriction on the maximum number of potential base station locations. The heuristic is based on the assumption that the desirability of using configuration j in an optimal solution increases with the number of covered demand nodes. The complete algorithm is shown in Algorithm 1 and the function for calculating the number of covered demand nodes is depicted in Function 1.

3) Results

To prove the capability of the proposed interference minimizing design method, Algorithm 1 and Function 1 were integrated into the ICEPT planning tool prototype of the University of Würzburg, cf. Tutschku et al. (1997), and tested on a real world planning case. The task was to find the optimal locations of seven transmitters in the region around the city center of Würzburg, cf. Figure 2(a). The value seven for the number of transmitters is the real number of base stations deployed in the Würzburg region by a cellular network operator.

Algorithm 1 (Optimize configuration)

variables:

S_i	*configuration of a transmitter at location with index i*
$\mathcal{S}$	*set of all potential transmitter configurations*
$\mathcal{C}$	*set of selected transmitter configurations*
DN	*set of all demand nodes*

algorithm:

```
1  proc optimize_net() ≡
2    begin
3      $\mathcal{S} \leftarrow$ all configurations $S_i$;
4      $\mathcal{C} \leftarrow \emptyset$;
5      find $S_i \in \mathcal{S}$ : if_cover($\mathcal{C} + S_i, DN$) is max;
6      $\mathcal{C} \leftarrow \mathcal{C} + S_i$;
7      $\mathcal{S} \leftarrow \mathcal{S} - S_i$;
8      if $\|\mathcal{C}\| = p \vee$ if_cover($\mathcal{C}$) $>$ required %
9        then return $\mathcal{C}$;
10        else goto 5;
11     fi
12   end
```

Algorithm 1: Optimize Configuration

Two case studies were performed. In the first experiment, the coverage criterion was only defined by Eqn.(1), i.e. a demand node was considered as covered if, and only if, it measures a sufficient signal strength. In the second experiment, the coverage criterion was defined by Eqn.(1) and Eqn.(2), i.e. the interference constraints were considered. Figure 3(a) depicts the transmitter locations computed in experiment 1 and Figure 3(b) shows the locations obtained by experiment 2. The positions of the transmitters are marked by the ◇ symbol. The lines indicate the convex hull around the set of demand nodes which are supplied by the base station.

Table 1 displays coverage as well as average CCI ratios. In experiment 1, the algorithm obtains a very high area and demand coverage according to constraint Eqn.(1). However, the average CCI ratio at covered demand nodes is extremely poor. This behavior is a result of the objective function. Demand nodes are counted as supplied even when a signal reception is impossible due to interference. Large cells cover many demand nodes and have a high coverage gain. Thus, they are preferred to smaller cells. Figure 3(a) reveals this behavior. The algorithm deploys mostly cells with a large geographical extension. We would like to state at this point that in all experiments, the algorithm is allowed to deploy transmitters with two different

	Exp. 1	Exp. 2
area coverage	94.8%	86.2%
demand coverage (Eqn.(1) only)	89.5%	80.4%
demand coverage (Eqn.(1) and Eqn.(2))	45.8%	69.3%
average CCI ratio at covered demand nodes	5.61 dB	12.7dB

Table 1: Interference minimization for single-stage-design

```
Function 1 (Coverage under interference constr.)

variables:
  $\mathcal{T}$     set of investigated configurations
  $DN$    set of all demand nodes
  $dn_i$   demand node with index i
  $c$     weighted coverage

algorithm:
funct if_cover($\mathcal{T}, DN$) ≡
  begin
    $c \leftarrow 0$;
    for all $dn_i \in DN$ do
      best_server ← 0
      find $T_j \in \mathcal{T} : \Omega_{(dB)}(i,j) > \Omega_{th,(dB)}$
          $\wedge\, \Omega_{(dB)}(i,j)$ is max; /* Eqn.(1) */
      best_server ← $j$;
      if best_server > 0
        then $\Lambda_{(dB)} \leftarrow$ inter($dn_i$, best_server, $\mathcal{T}$);
                    /* Eqn.(3) */
          if $\Lambda_{(dB)} > \Lambda_{th,(dB)}$ /* Eqn.(2) */
            then $c \leftarrow c + a_i$;
          fi
      fi
    od
    return $c$;
  end
```

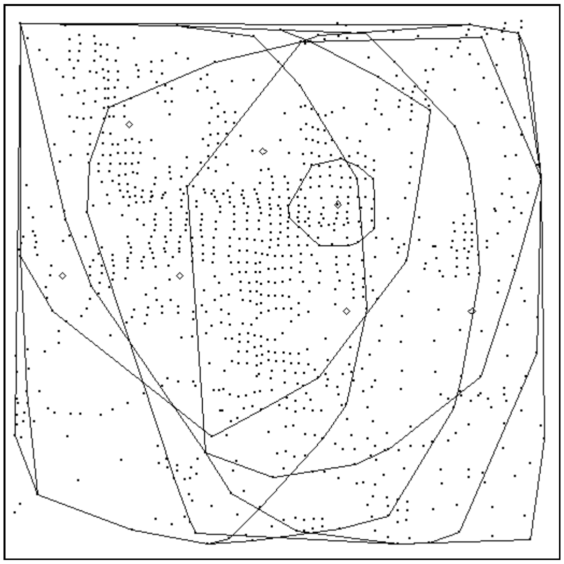
Function 1: Compute coverage under interference constraints

power levels: 40dBm or 55dBm.

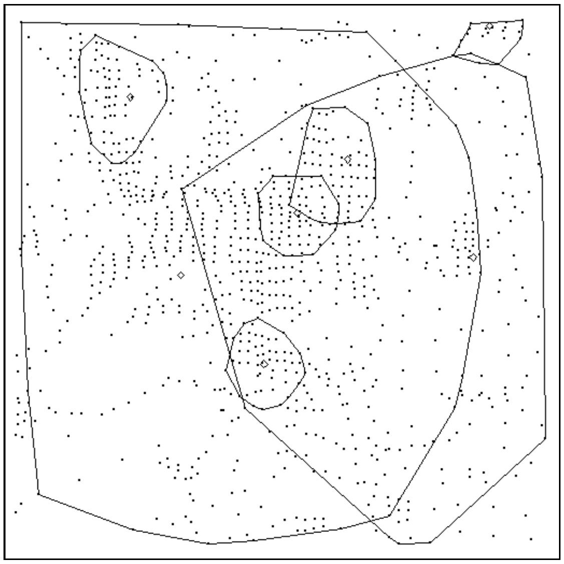
In experiment 2, the coverage criterion also includes the interference constraint of Eqn.(2). The obtained area coverage is smaller than in experiment 1. However, the demand coverage under the stricter constraints of Eqn. (1) and Eqn. (2) is significantly larger. Moreover, the average CCI ratio at covered demand nodes has increased tremendously. Due to the interference criterion, the algorithm selects only the transmitter configuration which add the least signal disturbance. The heuristic chooses five "small" and two "large" cells to cover the region, cf. Figure 3(b). Although the selected cells are transmitting with the same low power level of 40dBm, the solution resembles a micro/macro cell design.

III. Micro/Macro Cell Design

A common method to increase the teletraffic capacity of cellular networks while reducing interference is the application of micro- and macro-cells. In areas of high teletraffic, micro-cells should be deployed to reduce interference and to obtain a higher spatial frequency reuse, whereas macro-cells should be employed for the provision of area coverage. Motivated by the results obtained in the previous section, it is of interest how the interference minimizing technique proposed above can be extended to micro/macro cell design.



(a) Experiment 1



(b) Experiment 2

Figure 3: Transmitter locations in single-stage-design

A. Two-stage cellular design

The micro/macro cell engineering principle was transformed into a two-stage-design algorithm and integrated into the ICEPT tool prototype:

- **Stage 1: place micro-cells.**

  A certain number of micro-cells should be placed in such a way that the demand coverage under constraints of Eqn.(1) and Eqn.(2) is maximized. Micro-cells are defined by the transmitting power and should operate at a low power level.

- **Stage 2: place macro-cells.**

  A given number of "macro" cells should be deployed in such a way that the remaining unsupplied traffic is covered. For the experiments, two version of Stage 2 were implemented in the ICEPT prototype:

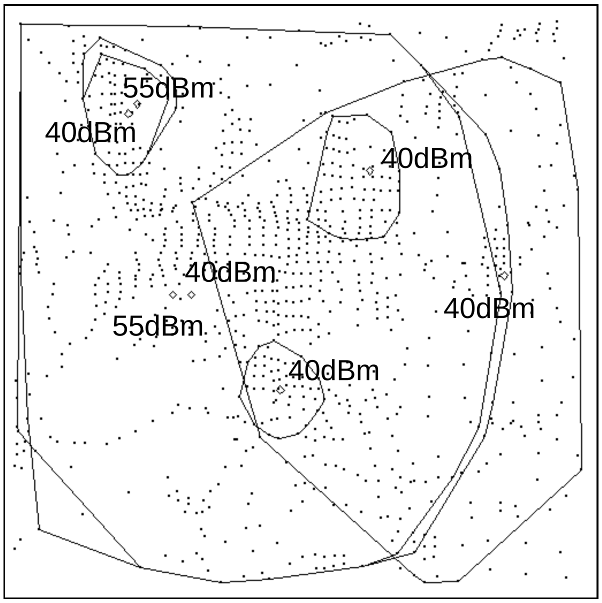


Figure 4: Transmitter locations in a two-stage-design (experiment 3)

a) only “macro” cells (i.e. cells with a high transmitting power) were allowed to be deployed.

b) those “macro” and “micro” cells, which were not selected in Stage 1, were allowed to compete.

B. Results

Again, two case studies were carried out for the Würzburg planning scenario. In experiment 3, a micro/macro cell design was performed with version *a)* of Stage 2. At the first stage, five transmitters were allowed, using a power level of 40dBm. At the second stage two transmitters were deployed, with a power level of 55dBm. The computed transmitter locations are shown in Figure 4. The power levels of the transmitters are given next to the ◇ symbol. The algorithm selects two macro-cells whose coverage area is very similar to that of the two selected micro-cells, cf. Figure 4. Table 2 shows that the deployment of the additional high power “macro” cells does not improve the solution. This behavior results from our definition of the term “macro” cell which is based on the distinction of cell types according to their power level. However, a low power cell can also have a large area extension. Thus, using a sophisticated placement, it is possible to obtain the same performance with low power cells as it is possible with high power ones. To prove this statement, we performed experiment 4 using version *b)* of Stage 2. Now the high power macro-cells had to compete with the low power micro-cells. The algorithm obtained the same solution as in experiment 2. Instead of deploying high power cells, it uses low power ones.

	Exp. 3	Exp. 4
area coverage	84.5%	86.2%
demand coverage (Eqn.(1) only)	76.0%	80.4%
demand coverage (Eqn.(1) and Eqn.(2))	68.4%	69.3%
average CCI ratio at covered demand nodes	11.3 dB	12.7dB

Table 2: Interference minimization in two stage design

IV. Conclusion

This paper presented an automatic cellular network design algorithm which determines the locations of transmitters with respect to co-channel interference (CCI). The proposed method is capable of maximizing the average CCI ratio in the planning region while optimizing the covered teletraffic demand. Additionally, we investigated how the proposed algorithm can be extended for locating micro- and macro-cells. The proposed interference minimizing method is able to obtain a network configuration with an inherent micro/macro cellular structure. It selects the best combination of “micro” and “macro” cells. A two-stage-design does not perform better under the given constraints. However, it is expected that for a different definition of the term “micro cell” - i.e. a restriction of the area extension or the covered traffic in conjunction with the low power constraint - the two-stage-sequence will perform better than the single-stage-algorithm. This is an open issue and will be investigated in the next future.

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