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Demand-based Radio Network Planning of Cellular Mobile Communication Systems

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Abstract: This paper presents a demand-based engineering method for designing radio networks of cellular mobile communication systems. The proposed procedure is based on a forward-engineering method, the *Integrated Approach* to cellular network planning and is facilitated by the application of a new discrete population model for the traffic description, the *Demand Node Concept*. The use of the concept enables the formulation of the transmitter locating task as a *Maximal Coverage Location Problem (MCLP)*, which is well known in economics for modeling and solving facility location problems. For the network optimization task, we introduced the *Set Cover Base Station Positioning Algorithm (SCBPA)*, which is based on a greedy heuristic for solving the MCLP problem. Furthermore, we present the planning tool prototype ICEPT (Integrated Cellular network Planning Tool), which is based on these ideas and show a first result from a real world planning case.

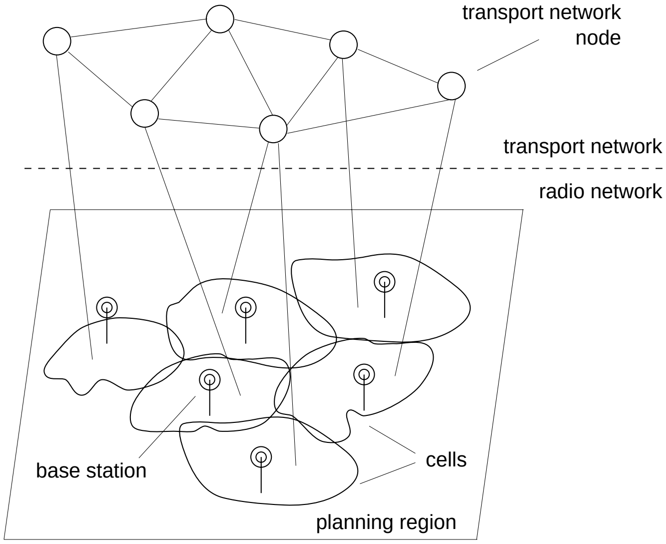


Figure 1: Abstract cellular mobile communication network model

I. Introduction

The planning of future cellular mobile radio networks faces three new major challenges. First, there is the tremendous increase in the demand for mobile communication services. Second, the new technologies of the 3^{rd} generation networks require demand based planning methods, e.g. the coverage area of a CDMA transmitter depends on both the radio wave propagation and the user density, cf. Veeravalli et al. (1997). And third, due to deregulation acts, the competition between the mobile service operators is increased. Therefore new planning methods are required which are able to *synthesize* efficient, economic and optimal network configurations.

The core task of cellular system design is to set up an optimal radio network, cf. Figure 1, which provides the best feasible *coverage* of the investigated planning region. During the design process, this aim is achieved by an optimal selection of base station sites and the perfect determination of the basic RF parameters, like the maximal base station transmitting power, the antenna height, or the number and the orientation of the sectors. In the past, the major design criteria of cellular networks was the *area coverage*. Conventional mobile engineering methods, like the analytical approach, cf. Gamst et al. (1986), however, were mainly focused on providing the best possible radio signal at *every* location of the planning region. The capacity aspects in network design were addressed only in later stages of the planning process.

Due to the transition of mobile radio into a mass-communication system, the cost of providing the service has become an important issue in system design. *Demand coverage* can be viewed as *revenue coverage*. Thus, this criterium has to be considered as a key engineering constraint.

To overcome the disadvantages of the conventional approach, a *forward-engineering*, demand-adaptive cellular network design method was introduced by Tutschku et al. (1996). The *Integrated Approach* starts the network design with the analysis of the expected teletraffic and uses this information together with other objective performance values to derive in a forward reasoning step an optimized radio network configurations. This process is mainly facilitated by the application of a new discrete population model for the traffic description, denoted as the *Demand Node Concept (DNC)*, cf. Tutschku et al. (1997). Due to this concept, the radio network design task can be formulated as a problem of the class of *Set Covering Problems (SCP)*, which are well known in economics to model and solve *facility location problems*, cf. Ghosh and McLafferty (1987). Thus, the *Integrated Approach* enables a demand-based cellular planning methodology and addresses the optimization problems emerging in future cellular radio network planning.

The paper is organized as follows. In Section II we discuss the advantages of the integrative, demand-based cellular network design approach. Therefore, we first define the new objectives of cellular network engineering and we outline the conventional mobile radio design methodology. We then introduce the *Integrated Approach* for cellular mobile network planning and explain its core idea, the Demand Node Concept. In Section III we briefly present the various other approaches to automatic transmitter locating. Section IV is devoted to the formulation of the transmitter locating task as a discrete Set Covering Problem. In Section V we present a planning tool prototype based on the ideas of the Integrated Approach and we show a first result from a real world planning case. In Section VI, we summarize our presentation and give an outlook to further extensions of the proposed method.

II. Demand-based Cellular Network Planning

A. New cellular network design objectives

Due to the radical changes in technology and usage of mobile radio systems, the design criteria of next generation cellular networks have altered substantially. Beside the primary RF objective of providing a reliable radio link at every location in the planning region, state-of-the-art network design has to ensure a high quality-of-service as well as considering the aspects of cutting the cost of deploying a cellular radio system. Hence, the new design objectives of mobile networks can be organized in three areas: *a)* RF objectives, *b)* capacity and teletraffic engineering objectives, and *c)* network deployment objectives.

The *RF design objectives* are usually expressed in terms of radio link quality measures. In first place, a good link design has to ensure a sufficient radio signal level throughout the planning region. Additionally, it has to minimize the signal disturbance by co-channel and adjacent-channel interference. Related to that is the provision of a high margin between the signal level and the interference power level in order to support, for example, a high user mobility. Advanced RF performance values, like a low bit error rate (BER), or a low call blocking probability due to insufficient signal strength can be derived from the basic RF performance values.

The *capacity and teletraffic engineering objectives* comprise mainly three criteria: the resource requirements, the network capacity, and the capacity related quality-of-service values seen by the user. Since the available frequency spectrum for mobile radio systems is extremely limited, the network design has to minimize the number of frequencies required in a cell as well as it has to reduce the overall number of carriers used in the network. To increase the total system capacity, the design has to enforce a large frequency reuse factor.

The *network deployment objectives* mainly address the economic aspects of operating and engineering a cellular system. Deploying a complete new network or installing additional hardware in an operating system is highly risky. There are significant costs associated with setting up a new facility. Therefore an efficient network design has to minimize the hardware cost, for example by using as few base stations as possible or by deploying cost-efficient facilities, like low-power transmitters. In addition, the cost-efficiency of the network can be increased if the deployment of new network equipment is based on the analysis of the demand for the offered service.

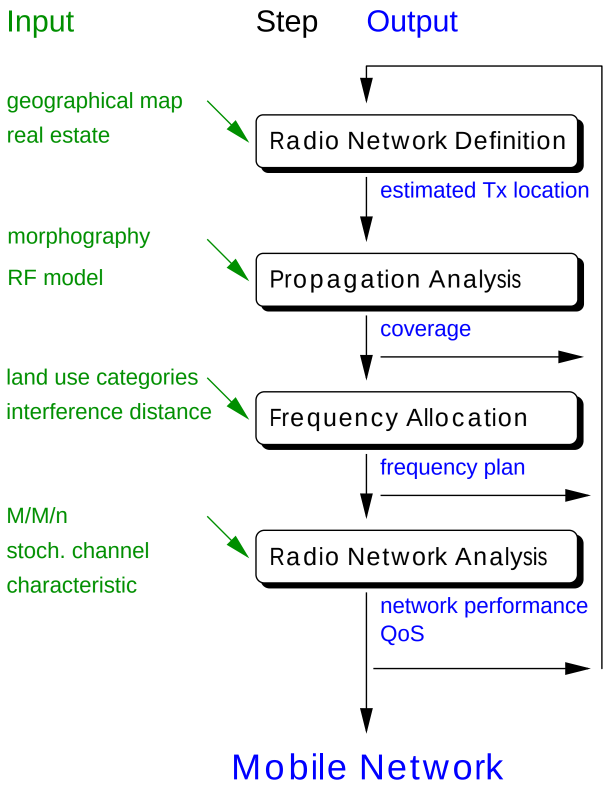


Figure 2: Conventional approach of cellular network planning

B. Conventional Cellular Network Planning

The conventional planning approach which is widely used in today's commercial cellular network planning tools like *PEGASOS*, cf. T-Mobil (1996), or *PLANET*, cf. MSI Plc. (1996), is based on the so-called *analytical approach* to cellular network planning, cf. Gamst et al. (1986). This approach is focused on the determination of the transmitter parameters, like transmitter location, antenna type, or transmitting power. It obeys the above described RF objectives but neglects the capacity and the network design objectives during the engineering process.

In principle, the analytical approach consists of four phases, *Radio Network Definition*, *Propagation Analysis*, *Frequency Allocation*, and *Radio Network Analysis*, that are passed in several turns iteratively, cf. Figure 2.

During the *Radio Network Definition* phase, a human expert chooses the cell sites. In order to obtain a regular structure, usually the popular concept of distributing the transmitters on a hexagonal grid is used in this step.

Using these transmitter configurations, the *Propagation Analysis* of the area evaluates the radio coverage by field strength prediction methods. Here, stochastic channel models are applied. Usually, several field strength pre-

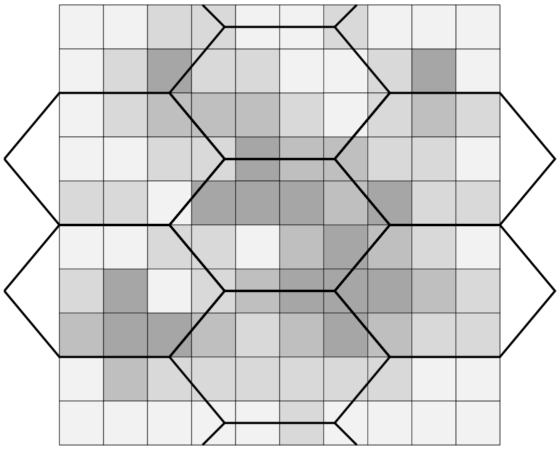


Figure 3: Conventional hexagonal traffic count

diction methods are implemented but the tools offer little if any support in choosing the appropriate propagation model. If the planning expert decides that the coverage is not sufficient enough, new transmitter positions have to be chosen and the propagation again has to be analyzed.

The radio network capacity issues are addressed in the next step, the *Frequency Allocation*. At first, the teletraffic distribution within the planning region is derived based on rough estimates on the land use of the area. The distribution is then stored in a traffic matrix. In the next step, a hexagonal grid representing the cells, is superimposed on the planing region, cf. Figure 3. The different grey values in Figure 3 are representing the different entries in the teletraffic matrix. The traffic per hexagonal cell is determined by tallying the entries of the traffic matrix in each cell, cf. Faruque (1996). The required number of traffic channels and frequencies of a cell is computed by using land-line capacity planning techniques like the common Erlang-B-formulae, cf. Mouly and Pautet (1992). If, for a given frequency reuse pattern and for given interference distance constraints, all the cells of the area can be supplied with the required number of channels, the algorithm proceeds to Radio Network Analysis. Otherwise the algorithm starts all over again.

The *Radio Network Analysis* calculates the quality-of-service values of the area with regard to blocking and hand-over dropping probabilities. Again, stochastic channel characteristics as well as user demand estimates from the traffic data-base are used to calculate the network performance. If grade-of-service specifications are met, the task is accomplished, otherwise the algorithm has to be restarted.

The major disadvantage of the analytical approach is its restriction to the RF design objectives. Network and capacity issues are more or less neglected by the approach. In addition, the design steps are treated in isolation and trade-offs between the design objectives are hard to obtain. An overall optimization is not feasible. Moreover, the conventional approach is a *reverse-engineering* process, cf. Cheung et al. (1994). The network configuration is only changed after performance measurements are calculated. The reverse reasoning technique prohibits the application of algorithmic optimization methods.

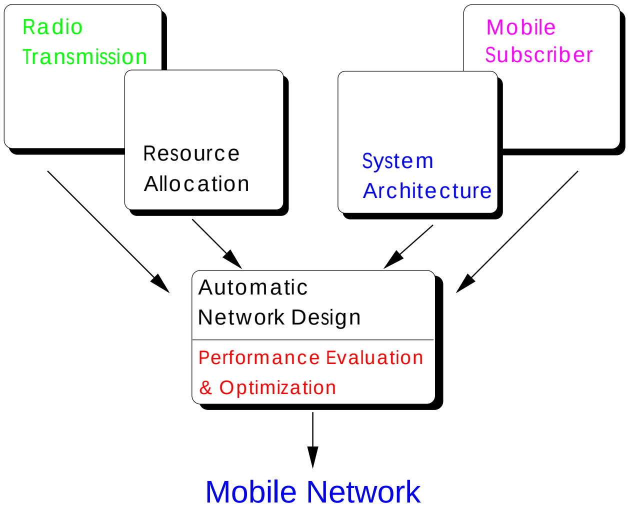


Figure 4: Integrated planning approach

C. Integrated Approach to Cellular Network Planning

The *Integrated Approach* to cellular network planning overcomes the shortcomings of the the conventional approach by organizing the cellular design constraints and quality objectives in four basic modules, cf. Tutschku et al. (1996). The new concept is depicted in Figure 4. The four basic design aspects of the integrated approach are: *Radio Transmission*, *Mobile Subscriber*, *System Architecture*, and *Resource Management*. This structured set of input parameters is used by the concept for the synthesis of a cellular configuration. The network configuration is generated by the *Automatic Network Design* module.

Due to the equal and parallel contribution of all the basic modules to the network design, the integrated concept is able to obey the interactions and dependencies between the objectives. Especially, the capacity and network design objectives can be addressed early and in an appropriate way. Due to this characteristic, the integrated approach is therefore able to find trade-offs between contrary objectives and achieves optimized network configurations. Moreover, the integrated approach constitutes a forward-engineering technique. Its methodology facilitates the application of automatic network design algorithms, cf. Section IV.

D. Mobile User Characterization

In contrast to the conventional design method, where emphasis is mainly laid on RF issues, the new integrated approach considers the expected teletraffic of the service area as an equally contributing factor to the network planning. Moreover, the integrated method starts its network design sequence with an analysis of the expected teletraffic demand within the considered supplying area.

Demand Node Concept

The core technique of the Integrated Approach is the representation of the spatial distribution of the demand for teletraffic by discrete points, called *demand nodes*. Demand nodes are widely used in economics for solving facility location problems, cf. Ghosh and McLafferty (1987).

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.

These demand nodes form the common basis of all components of the integrated approach. The application of the demand nodes, denoted as the *Demand Node Concept (DNC)* leads to a discretization of the traffic demand in both space and demand. It constitutes a *static population model* for the description of the mobile subscriber behavior. An illustration for the Demand Node Concept is shown in Figure 5. Figure 5(a) depicts publicly available map data from an area of size $15km \times 15km$ around the city of Würzburg, Germany. The spatial traffic distribution of the area is derived from this data by the application of sophisticated estimation methods. It is stored in the traffic matrix, cf. Figure 5(b). Figure 5(c) shows a simplified result of the demand discretization. The demand nodes are generated by a *partitional clustering method*, cf. Tutschku et al. (1997). Hence, demand nodes are dense in areas of high demand and sparse in regions of low demand.

The demand node concept is very useful for the mobile subscriber characterization. Its additional feature is the transformation of the continuous transmitter location problem into an equivalent discrete optimization task. The application of optimization methods is facilitated by a new definition of the term supplying area:

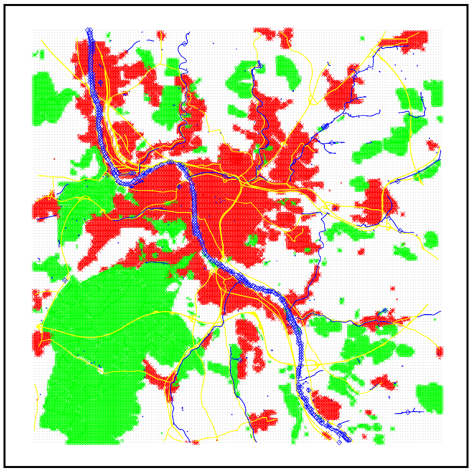
Definition 2:

The *supplying area* of a transmitter is the set of demand nodes which measure a path loss on the forward link and on the reverse link that is above the threshold defined by the link budget.

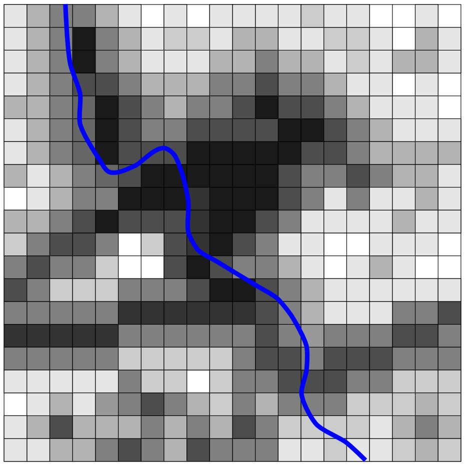
Due to this definition supplying users with a mobile radio service is equivalent to *covering* demand nodes. An optimization algorithm has to determine the location of the transmitters such that the proportion of demand nodes within the permitted service range is maximized. Hence, the base station locating task is reduced to a *Maximal Covering Location Problem (MCLP)*, cf. Section IV.

E. Resource allocation and network design

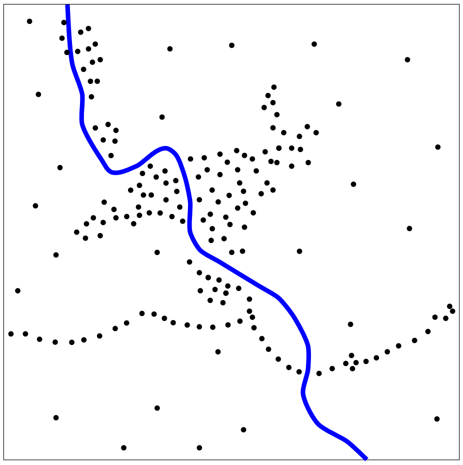
The Demand Node Concept simplifies also the resource allocation task. Since the demand nodes are distributed according to the expected service demand and due to the new definition of the term supplying area, cf. Definition 2, the expected traffic in a specific cell can be immediately obtained from the number of nodes in a cell. A potential base station site can be verified before it is selected, whether it obeys the traffic and hardware constraints or not. Thus, it is possible to check if a certain cell configuration is able to carry the expected traffic. Otherwise, the configuration is discarded and not considered for optimization. This verification can enforce, for example, the deployment of small and cheap transmitters over using large and heavily loaded macro-cells. Additionally, this leads directly to a higher frequency reuse and can result in a much easier frequency allocation task.



(a) Land use



(b) Traffic matrix



(c) Node distribution

Figure 5: Demand node concept

III. Automatic transmitter location algorithms

Since the design complexity of mobile cellular networks has drastically increased in the past, automatic network design algorithms came into the focus of various research groups. In the following section, we review the major approaches to this problem.

A. The Adaptive Base Station Positition-ing Algorithm

The *Adaptive Base station Positioning Algorithm (ABPA)* was introduced by Fritsch et al. (1995). It uses already an early version of the Demand Node Concept. It was one of the first methods that considers, parallel to the RF objectives, the expected traffic as a direct constraint for the cell location. ABPA is based on the idea of *competing base stations* which try to cover as many demand nodes as possible. The algorithm determines two parameters of transmitters, the position and the transmitting power. For locating the base stations, ABPA shifts the transmitters around in the virtual scenario. The movement of the base station is conducted by the attraction of base stations to not covered demand nodes and by the repellation of base stations from multiply supplied nodes. In a similar way, the algorithm adapts the power level of the transmitters. To prevent ABPA from getting stuck in locally optimal configurations, the algorithm performs transitions to a worse configuration with a predefined probability as in Simulated Annealing, cf. Aarts and Korst (1990). The major drawback of ABPA is its speed. The shifting of the transmitters requires that after every transition, the coverage has to be recalculated.

B. Other Approaches

A promising approach to automatic network design was presented by Chamaret et al. (1997). The radio network design task is modeled as *maximum independent set* search problem. However, the approach addresses only RF design aspects. It uses the *area coverage per base station* as the objective function of the optimization. Other design constraints are not considered.

In contrast to this, an algorithm which considers only the traffic distribution as a constraint for cell site locations was proposed by Ibbetson and Lopes (1997). The algorithm uses an computational geometry approach and constructs a tessellation of the planning region with a k-D-tree like search algorithm.

Another method was proposed for the design of micro-cellular radio communication systems, cf. Sherali et al. (1996). Again, this approach concentrates on RF constraints since in the considered micro-cellular environment, so far, network capacity is not of major importance.

IV. Coverage Models in Cellular Mobile Network Planning

The assumption underlying all coverage models for the facility location problem is that the accessibility to a service network within some critical range is an essential criterion of the service use. Customers beyond the access range are not adequately served by the service facilities and are therefore not likely to utilize the offered service. In planning a network of *service centers*, a crucial objective is to maximize the proportion of the demand within the specified range of the service facilities, cf. Ghosh and McLafferty (1987). In contrast to the usual facility location problems, the term *range* is in the context of wireless network planning not the physical distance between the demand node and the transmitter. Here, the term *range* denotes the path loss PL of the radio signal strength between the base station and the receiving node, cf. Parsons (1992).

A. The Set Covering Model

The objective of the set covering model is to determine the number of required service centers, i.e. base stations, and their location such that *all* users of the wireless network are served with an adequate service level, i.e. field strength level. In mathematical terms, the *Set Covering Problem (SCP)* is defined as follows, cf. Ghosh and McLafferty (1987):

$$\text{Minimize} \quad Z = \sum_{j \in J} x_j \tag{1}$$

subject to:

$$\sum_{j \in N_i} x_j \geq 1 \quad \forall j \in J, \forall i \in I \tag{2}$$

where

Z	number of facilities;
J	set of potential facility sites (indexed by j);
I	set of demand nodes (indexed by i);
x_j	$= \begin{cases} 1 & \text{if facility at} \quad j \\ 0 & \text{otherwise} \end{cases}$;
N_i	$\{j \mid f_{ij} \leq PL\}$; the set of base stations j located within the standard range PL of demand node i;
f_{ij}	the path loss between demand node i and potential base station location j;

The objective in Eqn. (1) minimizes the number of required facilities and the constraint in Eqn. (2) enforces that, in a valid solution, each demand node is covered at least once within the standard range PL. In the considered set covering model, the potential facility locations are equivalent with the location of demand nodes. In mobile network planning this is not necessarily true. Transmitters can be located only at positions where real estate can be purchased or leased. However, it can easily be shown that this constraint can be obeyed by the SCP. Furthermore, as introduced in Section II., the objective function should not only comprise the demand coverage as the sole objective. The cost-effectiveness has to be addressed also in an appropriate way. Therefore, a more detailed discussion on the objective cost function is presented further below.

B. The Maximal Covering Location Problem

A valid solution of the SCP requires coverage of all demand nodes, no matter how cost-effective the solution is. However, for an economic design of wireless communication networks a trade off between the cost of coverage and the benefit resulting from covering this area is desired. This objective leads to the definition of the transmitter location problem as a locating problem that does not require the coverage of *all* demand nodes. Church and ReVelle (1974) define this problem as the *Maximal Coverage Location Problem (MCLP)*. The MCLP assumes a limited budget and includes this as a constraint on the number of facilities to be located. Thus, the optimization tries to place a fixed number of base stations p so that the proportion of demand nodes covered by the cells within the permitted range is maximized. The mathematical definition of the MLCP is:

$$\text{Maximize} \quad Y = \sum_{i \in I} a_i y_i \tag{3}$$

subject to:

$$\sum_{j \in N_i} x_j \geq y_i \;\; \forall i \in I \;\; \wedge \;\; \sum_{j \in J} x_j = p \;\; \forall i \in I, \forall j \in J. \tag{4}$$

As additional notation for the MLCP we use:

Y	the weighted coverage;
y_i	$= \begin{cases} 1 & \text{if demand node } i \text{ is covered} \\ 0 & \text{otherwise} \end{cases}$,
p	the number of base stations to be deployed, and
a_i	the population at demand node i.

All other variables and parameters are the same as defined in the SCP. The objective of Eqn. (3) is to maximize the sum of covered demand nodes. The first constraint in Eqn. (4) states that demand node i cannot be covered unless at least one server is located within the standard range *PL*. The second constraint of Eqn. (4) defines the budget constraint by forcing the number of placed base stations to be exactly p.

Due to the factors a_i, the MCLP maximizes the weighted objective coverage function Eqn. (3). In the Demand Node Concept the weights a_i are, due to Definition 1, equal for all nodes i. Using different values for the weights a_i introduces a prioritization of certain nodes. This can be used to favor the coverage of important areas within in the planning region, for example airports or train stations.

C. Heuristic Solutions for the Coverage Problem in Mobile Network Planning

The *Integrated Approach* considers a greedy heuristic for solving the maximum coverage location problem. For motivating the heuristic, we first give a set theory definition of the SCP accordingly to Chvatal (1979).

In the SCP, the data consists of finite sets $P_1, \ldots, P_n$ and positive numbers $c_1, \ldots, c_n$ which denote the cost of using the sets P_j. In the Integrated Approach, these sets correspond to the supplying areas of transmitters, cf. Definition 2. For the SCP, the union of all P_j is $I = \bigcup(P_j : 1 \leq j \leq n)$ and $I = \{1, \ldots, m\}$ and $J = \{1, \ldots, n\}$. A subset J^* is called a *cover* if:

$$\bigcup(P_j : j \in J^*) = I; \tag{5}$$

The cost of this cover is $c(J^*) = \sum(c_j : j \in J^*)$. The problem is to find a cover J^* with minimum cost. Since the SCP is NP-complete, cf. Garey and Johnson (1979), a combinatorial algorithm cannot find an optimal solution in polynomial time.

A Greedy Heuristic for the Set Covering Problem

The heuristic algorithm assumes that the desirability of using the set j in an optimal cover increases with ratio $\mid P_j \mid / c_j$, i.e. the better the ratio of covered demand nodes per cost unit for a set j, the higher the probability that the set is in the optimal cover J^*. The original greedy algorithm for the SCP is:

Step 0 Set $J^* = \emptyset$

Step 1 If $P_j = \emptyset$ for all j then stop: J^* is a cover. Otherwise find an index k maximizing the ratio $\mid P_j \mid / c_j$ and proceed to *Step* 2.

Step 2 Add k to J^*, replace P_j by $P_j - P_k$, $\forall j \in J$ and return to *Step 1*.

This set theory definition of the SCP reveals directly a major shortcoming of this approach. The union of all the sets P_j has to comprise every demand node in the considered area. However, in a wireless network, not every demand node can be supplied with a sufficient service level. Thus, a different problem definition is required, the *Maximal Coverage Location Problem*.

A Greedy Heuristic for the Maximal Coverage Location Problem

A greedy heuristic for the MCLP was proposed by Vohra and Hall (1993). In contrast to the SCP the MCLP uses the sum of the weights of the covered nodes $w(S)$ as the objective function. The greedy algorithm for the MCLP is:

Step 0 Initialize the variables: $J^* = \emptyset, r = 0, x_j = 0, \forall j = \{1, \ldots, n\}$.

Step 1 Find the index $k \in \{1, \ldots, n\}$, that maximizes $w(S) = \sum(w_i : i \in S)$ with $S = \bigcup(P_j : j \in J^* \cup \{k\})$

Step 2 Add k to J^*, and set $x_k = 1$ and $r = r + 1$. If $(r = p)$ then stop: J^* is a feasible solution.

Step 3 For all $j \in \{1, \ldots, n\}$, set $P_j = P_j - P_k$ and return to *Step* 1.

The variable w_i in *Step 1* is the weight of demand node i.

D. The Objective Cost Function

The proposed Greedy-like heuristic algorithms assume that the desirability of having set j in an optimal cover increases with ratio $\mid P_j \mid / c_j$. Hence, the algorithms are maximizing the the coverage per cost unit.

From an economical viewpoint, the cost of using set j, i.e. have a specific transmitter configuration at location with index j, depends usually on three factors: *a)* the specific hardware costs, e.g. high-power transmitters are more expensive than low-power base stations, *b)* the costs of leasing or purchasing real estate, and *c)* the infra-structural costs of deploying and connecting the cell site to the network, e.g. providing electrical power or data connections to the transport network is much more expensive in remote regions than in developed areas.

Besides the monetary costs of a transmitter configuration, it is possible to define other virtual cost factors of base stations. In this way, interference objectives can also be included into the optimization. For example, a high-power transmitter which is located on a hill top deteriorates the interference situation in the whole network scenario and decreases the cellular capacity. Therefore, using this transmitter in a solution would be very "expensive". The *interference cost* of an investigated base station j can be evaluated by calculating the average interference level of an intermediate solution J extended by transmitter j at distinct demand node locations.

E. The SCBPA Algorithm

Based on the greedy algorithm for the MCLP presented above, we now define the complete *Set Cover Base Station Positioning Algorithm (SCBPA)*. The algorithm comprises four phases:

- *Phase* 0 Calculate all possible coverage sets P_j
- *Phase* 1 Verify the traffic and hardware constraints for all P_j
- *Phase* 2 Compute a first coverage by using the greedy heuristic for the MCLP
- *Phase* 3 Optimize the coverage by changing transmitters (optional)

In Phase 0, the algorithm computes for all valid cell site locations, all transmitter power levels, and all possible antenna types the supplying areas P_j of these configurations. Phase 1 verifies whether the transmitters obey the traffic and hardware constraints or not, cf. Section V. In Phase 2, a *first coverage* of the planning region is computed using the greedy algorithm for the MCLP. Due to the heuristic nature of this procedure, the obtained solution might only be suboptimal. An improvement can be found by the application of an optional Phase 3, where the result is improved by exchanging transmitter using a *local search algorithm*, cf. Papdimitriou and Steiglitz (1982).

V. Results

A. The ICEPT planning tool

To prove the capability of the *Integrated Approach* for cellular mobile network design, a planning tool prototype was implemented at the University of Würzburg, cf. Tutschku et al. (1997). The abbreviation *ICEPT* stands for *Integrated CEllular network Planning Tool*. The tool's core components are the automatic network design algorithm *SCBPA* and the traffic estimation and characterization procedure as described in Section II. In the ICEPT prototype, the design constraints and objectives are implemented as exchangeable modules. These modules are indicated in Figure 6 by the names of the design aspects, like *Radio Wave Propagation*. ICEPT uses the common radio wave propagation model of Hata (1980) and the COST231 model, cf. Stüber (1996).

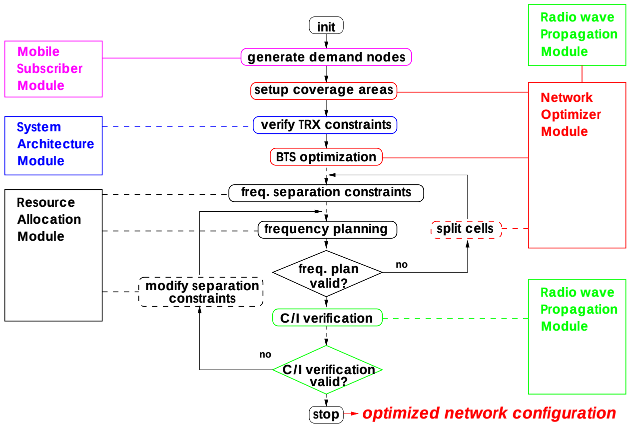


Figure 6: ICEPT's network design sequence

Network Design Sequence

The *network design sequence* of ICEPT is depicted in Figure 6. In contrast to the conventional cellular design method, the demand-based approach of ICEPT starts with the traffic estimation. Therefore, the tool generates at first the demand node distribution of the planning region. Afterwards, the tool computes the supplying areas for all possible transmitter configurations. In the next step, ICEPT checks whether the traffic and hardware constraints are obeyed at these configurations or not, cf. Section II. Invalid configurations are removed and are not considered in the optimization step. After completing the verification, the optimizer generates the cellular configuration using Phase 2 of the SCBPA algorithm. Subsequently, the tool computes the carrier separation constraints and constructs a frequency allocation plan. If the tool is unable to calculate a valid frequency plan, it has to split certain cells.

If the frequency allocation plan is valid, ICEPT verifies the carrier-to-interference (C/I) values of the configuration. In case the C/I constraints are not obeyed, then the separation constraints have to be increased. If the C/I specifications are met, the network design stops with the output of the cellular radio network configuration.

B. Planning result

ICEPT was tested on the topography around the city center of Würzburg. The task was to find the optimal locations of nine transmitters. The result of the SCBPA algorithm is depicted in Figure 7. The base station locations are marked by a ◇ symbol. The lines indicate the convex hull around the set of demand nodes which are supplied by the base station. SCBPA was able to obtain a 75% coverage of the teletraffic of the investigated area. The total computing time for the configuration, including the traffic estimation and characterization, was 4min on a SUN Ultra 1/170.

VI. Conclusion

This paper presents a demand-based engineering method for the design of radio networks of cellular mobile communication systems. The proposed procedure is based on a forward-engineering procedure, the *Integrated Approach*

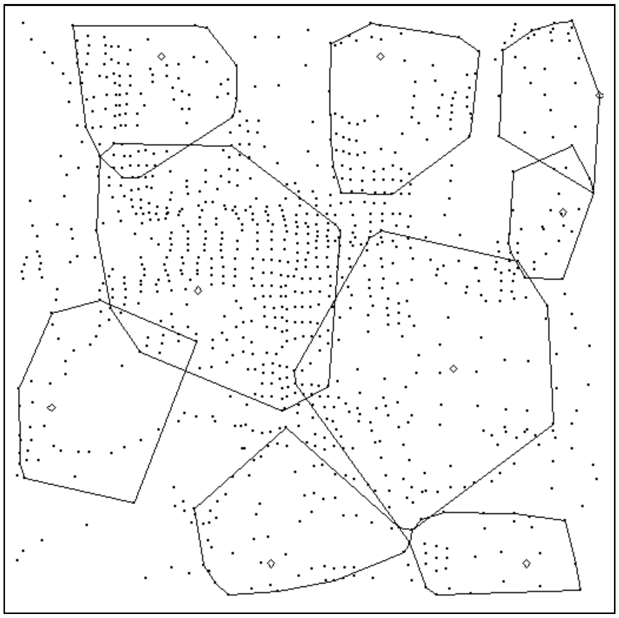


Figure 7: ICEPT planning result: base station locations

to cellular network planning and is facilitated by the application of a new discrete population model for the traffic description, the Demand Node Concept. This concept enables the formulation of the transmitter location task as a Maximal Coverage Location Problem (MCLP), which is well known in economics to model and solve facility location problems. For the optimization task of locating base stations, we introduced the Set Cover Base Station Positioning Algorithm (SCBPA), which is based on a greedy heuristic for solving the MCLP problem. Furthermore, we presented the planning tool prototype ICEPT, which is based on these ideas and we showed a first result from a real world planning case.

Due to the Demand Node Concept and the use of the SCBPA algorithm the Integrated Approach is able to obey all the RF design objectives as well as the capacity and the network deployment constraints. The new approach is able to find trade-offs between the different design objectives. It can obtain an overall optimized network configuration in acceptable computing time. Thus, the Integrated Approach meets the requirements for the planning methods of future generation networks. The automatic network design component enables the Integrated Approach to generate *synthetic networks*.

In the future, our focus is on including more planning objectives in the Integrated Approach. Especially, the interference minimizing design of the radio networks is an important challenge.

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