Planning Effective Cellular Mobile Radio Networks

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***Abstract*—This paper deals with the automatic selection and configuration of base station sites for mobile cellular networks. An optimization framework based on simulated annealing is used for site selection and for base-station configuration. Realistic path-loss estimates incorporating terrain data are used. The configuration of each base station involves selecting antenna type, power control, azimuth, and tilt. Results are presented for several design scenarios with between 250 and 750 candidate sites and show that the optimization framework can generate network designs with desired characteristics such as high area coverage and high traffic capacity. The work shows that cellular network design problems are tractable for realistic problem instances.**

***Index Terms*—Cell planning, heuristics, radio frequency assignment, radio network design.**

I. INTRODUCTION

ONE OF the most important cellular network planning activities is to select a set of sites from a list of candidate sites that have been identified as potential sites by marketing. The selected sites form the basis of a network that must satisfy certain network requirements such as high area coverage and high traffic capacity but that minimize infrastructure cost. The configuration of the selected base stations is also a complex problem and involves choosing among different antenna types, e.g., various directional or omnidirectional antennas, power control, tilt, and azimuth. This paper considers the use of an optimization framework based on simulated annealing for base-station selection and configuration for realistic-sized networks. Previous work has dealt with aspects of this design problem, e.g., [1]–[10], but none has considered the full complexity of the problem, either because they use simplified models—i.e., by only considering base-station selection without base-station configuration—or because they consider relatively small numbers of candidate sites.

Another aspect of the design problem is the relationship with the frequency assignment problem, which aims to generate a frequency plan that minimizes electromagnetic interference due to the reuse of frequencies in different parts of the network. Designing cellular radio networks that utilize their allocated frequencies effectively and efficiently is a difficult problem, even though the frequency assignment problem itself is well studied; e.g., [11]–[17]. If a radio network is poorly designed, then spectrum will be wasted and/or the quality of service will be degraded even if a good frequency assignment algorithm is used.

To produce a well-designed network, the designer needs to take into account several competing factors. For example, cost may be reduced by having a few omnidirectional antennas operating at full power. This may produce good area coverage and have a small amount of overlap between cells (and hence low interference). However, such a network will probably not be able to satisfy the traffic demands within the cell of each antenna. To try and overcome this problem, more antennas are required (perhaps using directional antennas at the same site or additional antennas at different sites). However, this increases the cost, the potential for interference, and hence the difficulty of finding a good frequency assignment. For example, if the network design is used to generate channel separation constraints between pairs of transceivers, then the required separations could have higher values on a poorly designed network relative to a well-designed network. Consequently, frequency assignment algorithms, e.g., [18] and [19], will find assignments that either use a larger range of frequencies than may be necessary (for minimum span assignment) or have a higher number of constraint violations (more interference) in fixed spectrum problems.

The cellular network optimization problem involves designing a network using an optimization algorithm that takes into account competing factors. For example, the final network can be optimized for area coverage, traffic capacity, cost, interference (giving consideration to frequency assignment), and handover. Other objectives can be included as necessary.

II. PROBLEM DESCRIPTION

A. The Model

The model used is based on models in [20] and [21]. A network is defined within a working area $\mathcal{P}$. Any point in $\mathcal{P}$ is defined by its Cartesian coordinates. For simplicity, points in $\mathcal{P}$ are only defined on a grid. Such data we shall refer to as mesh data. Points within $\mathcal{P}$ where propagation and service information is available are known as service test points (STPs). These are represented by

$$\mathcal{S} = \{S_1, S_2, \ldots, S_{n_\mathcal{S}}\}$$

where $n_\mathcal{S}$ is the total number of service test points in $\mathcal{P}$. We represent a typical service test point by S_i, with coordinates (x_i, y_i, h_i), where $1 \leq i \leq n_\mathcal{S}$ and h_i is the height above sea level. Mesh data are provided, at each service test point, for the following:

1) propagation loss estimates (line-of-sight path loss);
2) service threshold requirement;
3) traffic demand.

Other data, which we shall refer to as engineering data, are provided for the following:

1) a list of *candidate* sites, i.e., sites where base stations could potentially be located;

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TABLE I
TYPICAL SERVICE THRESHOLDS

Type of Service	Threshold S_q (dBm)
8 Watt outdoor	-90
2 Watt outdoor	-83
2 Watt in car	-82
indoor	-75
deep indoor	-65

2) candidate site legacy status, i.e., whether it forms part of a preexisting network or not;
3) a list of different antenna types defined by horizontal and vertical radiation patterns as well as transmission gain and loss.

Both the mesh and engineering data are described in more detail below.

1) A Network: Consider a number of candidate sites

$$\mathcal{L} = \{L_1, L_2, \ldots, L_{n_{\text{sites}}}\}$$

where n_{sites} is the total number of candidate sites available.

A network $\mathcal{N}$ is composed of sites chosen from the list of candidate sites $\mathcal{L}(\mathcal{N} \subseteq \mathcal{L})$. To define a network, we define a *configuration* $\mathcal{Z}$ where

$$\mathcal{Z} = \{z_1, z_2, \ldots, z_{n_{\text{sites}}}\}$$

where, for the ith candidate site in $\mathcal{L}$, we have (1), shown at the bottom of the page.

Therefore, a network is defined as follows:

$$\begin{aligned}\mathcal{N} &= \{L_i\colon z_i = 1, L_i \in \mathcal{L}, 1 \leq i \leq n_{\text{sites}}\}\\ &= \{N_1, N_2, \ldots, N_{n_{\text{operational}}}\}\\ &= \{N_m\colon 1 \leq m \leq n_{\text{operational}}\}\end{aligned}$$

where N_m represents an operational (active) site and $n_{\text{operational}}$ is the total number of sites selected by the optimization process to be active in the current configuration $(\leq n_{\text{sites}})$.

In cases where an existing network is to be altered to cope with new conditions—e.g., increased capacity requirements—we denote the preexisting network as the *legacy* network.

2) Service and Traffic: A network provides a service based upon criteria defined by the network operator. The nature of the expected service for a network defined on $\mathcal{P}$ is given by $\mathcal{S}$, and the values associated with the points in $\mathcal{S}$ give the service threshold (in dBm) for the required service. We represent the service requirement at an STP S_i by S_{q_i}. Typical service thresholds are given in Table I and are characterized by the type of mobile station assumed to be located at the STP (see Section II-A6).

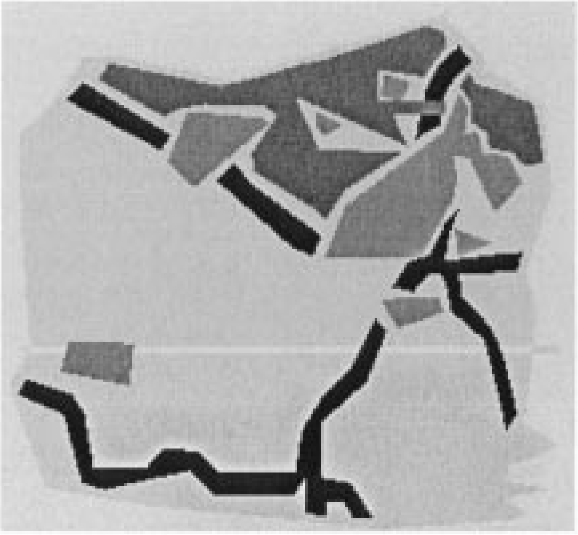

Fig. 1. Example STP data map.

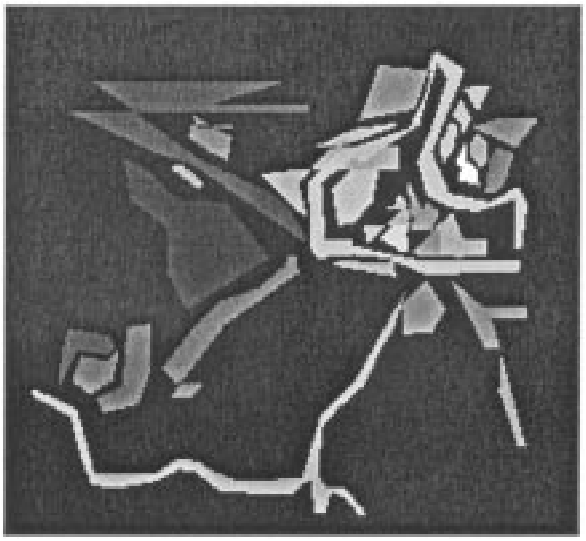

Fig. 2. Example traffic demand data map.

Also, during operation, the network must satisfy the capacity (traffic) requirements in an efficient way. The expected traffic demand, measured in Erlang, at each S_i is denoted by $e_i, 1 \leq i \leq n_{\mathcal{S}}$.

Fig. 1 shows an example of an STP data map. The darker the shade of gray, the higher the service threshold requirement at the test point. Similarly, Fig. 2 shows an example traffic demand data map, with lighter shades of gray indicating the increasing traffic demand (black indicates zero traffic demand).

$$z_i = \begin{cases} 0, & \text{if site } L_i \text{ is not used, i.e., not selected}\\ 1, & \text{if site } L_i \text{ is operational, i.e., it is used (contains}\\ & \text{at least one base station).}\end{cases} \tag{1}$$

3) A Site: Each operational site consists of one or more base stations (BSs). The model represents a base station by

$$\Gamma_{m,k_m}, \quad \text{where } k_m \in \{1, 2, \ldots, n_m^{\text{bs}}\} \tag{2}$$

where Γ_{m,k_m} is the k_m^{th} base station of operational site L_m and n_m^{bs} is the number of base stations at site L_m. For an operational site, we have $n_m^{\text{bs}} \geq 1$.

A candidate site L_i has a geographical position on $\mathcal{P}$ represented by

$$(X_i, Y_i, H_i)$$

where X_i and Y_i are the Cartesian coordinates of candidate site L_i and H_i its height above sea level.

The propagation loss from every candidate site to each STP defined on $\mathcal{P}$ is given by $\mathcal{Q}$, where

$$\mathcal{Q} = \{Q_1, Q_2, \ldots, Q_{n_{\text{sites}}}\}.$$

Q_i contains estimates of the propagation losses to each STP defined on $\mathcal{P}$ relative to site L_i, i.e., Q_i contains $n_{\mathcal{S}}$ propagation loss estimates (in dB). The propagation model used to generate the line-of-sight path-loss estimates is based on the COST 231 Walfish–Ikagami model [22], [23].

4) A Base Station: In addition to the set of sites, it is possible to consider a set of base stations

$$\mathcal{B} = \{B_1, B_2, \ldots, B_{n_{\mathcal{B}}}\}$$

where $n_{\mathcal{B}}$ is the total number of operational base stations. Previously, in (2), we defined the k_m^{th} operational base station of operation site L_m by Γ_{m,k_m}; therefore we have

$$\Gamma_{m,k_m} = B_j \quad \text{if } j = k_m + \sum_{i=1}^{m-1} n_i^{\text{bs}}.$$

A given base station B_j where $1 \leq j \leq n_{\mathcal{B}}$, situated at site L_m, has a number of operational parameters that are variables in the optimization process. These allow the configuration of the base station and include the following:

$B_j^{P_s}$	transmitting power (in dBm) of B_j, $(26 \leq B_j^{P_s} \leq 55)$;
B_j^{AT}	the antenna type of B_j, $1 \leq B_j^{\text{AT}} \leq n_{\mathcal{A}}$, i.e., there are $n_{\mathcal{A}}$ different types of antennas available;
B_j^{β}	angle of tilt of the antenna of B_j, $-15° \leq B_j^{\beta} \leq 0°$;
B_j^{δ}	azimuth of the antenna of B_j, $0° \leq B_j^{\delta} \leq 359°$;
B_j^{TRX}	number of TRX devices (transmitters) used by B_j, $1 \leq B_j^{\text{TRX}} \leq 7$ (this corresponds to the number of channels required by the base station). The traffic capacity (in Erlangs) per TRX is given in Table II[1] (see [24]).

TABLE II
CAPACITY PER TRX

TRX	1	2	3	4	5	6	7
Capacity	2.9	8.2	15	22	28	35.5	43

5) Antennas: Each base station B_j has one antenna. For the networks presented in the results section (Section V-A), it is assumed that an antenna can be omnidirective, small (narrow) panel directive, or large panel directive; hence $n_{\mathcal{A}} = 3$. The radiation pattern of an antenna is characterized by two functions, which define the horizontal and vertical losses (in dB) depending on the horizontal and vertical angles of the antenna relative to the STP and base station. Therefore, for a given antenna type, we define

$$D_{\text{horizontal}} \quad \text{and} \quad D_{\text{vertical}}$$

which represent the losses for each angle between 0° and 359° in the horizontal and vertical directions, respectively.

Finally, each antenna has an associated (and fixed) transmission gain and loss (in dB) represented, respectively, as

$$G_{\mathcal{A}} \quad \text{and} \quad \Lambda_{\mathcal{A}}.$$

6) Mobile: There are a number of different mobile station types that can be located at a service test point, for example 2 W, 8 W. Each mobile station type has an associated (and fixed) reception gain and loss (in dB) represented, respectively, by

$$g_{\mathcal{M}} \quad \text{and} \quad \lambda_{\mathcal{M}}.$$

The mobile type located at a given service test point is given in the set $\mathcal{S}$, i.e., the mobile type is a function of S_i. Therefore, we represent the mobile type at a given service test point S_i by S_i^{mob}, i.e., the mobile to be serviced at S_i. Note that S_i^{mob} has an associated service requirement S_{q_i} (see Section II-A2 and Table I).

B. Definitions

1) Downlink Field Strength: For a given base station B_j situated at site L_m, the downlink field strength at a service point S_i is given by

$$\begin{aligned} F_j(S_i) = {} & B_j^{P_s} + G_{\mathcal{A}}\left(B_j^{\text{AT}}\right) - \Lambda_{\mathcal{A}}\left(B_j^{\text{AT}}\right) \\ & - Q_m(S_i) - D_{\text{horizontal}} - D_{\text{vertical}} \\ & + g_{\mathcal{M}}\left(S_i^{\text{mob}}\right) - \lambda_{\mathcal{M}}\left(S_i^{\text{mob}}\right). \end{aligned} \tag{3}$$

The power of a base station is given in dBm; all other values in (3) are in dB.

2) Cell: A cell C_j is defined for base station B_j as the set of points such that

$$\begin{aligned} C_j = \{S_i \colon F_j(S_i) \geq S_{q_i} & \text{ and} \\ F_j(S_i) > F_k(S_i)\ \forall k, 1 \leq k \leq n_{\mathcal{B}}, k \neq j\} & \end{aligned}$$

i.e., for all points in cell C_j, B_j is the best server (provides the strongest signal).

3) Handover: A necessary feature of a mobile network is the concept of handover, i.e., the ability to transfer responsibility of a mobile signal from one base station to another. The handover set HAND_j operates on the cell C_j of the base station B_j and is defined as the subset of points in C_j such that the field strength

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[1] Sometimes an eighth TRX is used, which allows a capacity of 58 Erlang to be satisfied

at S_i received from base station B_j is within 7 dB of the field strength at S_i received from a neighboring base station $B_{j'}$, i.e.,

$$\mathrm{HAND}_j = \{S_i\colon S_i \in C_j \text{ and } \exists j' \neq j \text{ such that } |F_j(S_i) - F_{j'}(S_i)| \leq 7\}.$$

For a given cell, the handover may be satisfied by more than one base station. Here we set the target number of neighboring base stations satisfying handover for a point $S_i \in \mathrm{HAND}_j$ to four.

III. DESIGN OBJECTIVES

The objectives of a network design (cell plan) are as follows.

1) *Coverage:* All service test points receive at least one signal above its service threshold, i.e., for all service points S_i, we require

$$\sum_{j=1}^{n_{\mathcal{B}}} \mu_{ij} = n_{\mathcal{S}}$$

where

$$\mu_{ij} = \begin{cases} 1, & \text{if } S_i \in C_j \\ 0, & \text{otherwise.} \end{cases}$$

The point S_i is said to be *covered* if it receives at least one signal above its service threshold.

2) *Traffic Capacity:* The traffic load within a cell should be less than some maximum value corresponding to the capacity of the maximum number of TRX devices (channels) available. Currently, the value used corresponds to 43 Erlang, the capacity of seven TRX devices (see Table II), i.e., for all cells C_j, we require

$$\sum_{S_i \in C_j} e_i \leq 43.$$

A maximum capacity per cell allows us to calculate the theoretical minimum number of sites and base stations that must be active for any network design to satisfy the traffic capacity objective. We define the minimum number of base stations (cells) required by

$$n_{\mathrm{bs}}^{\mathrm{minimum}} = \left\lceil \frac{1}{43} \sum_{i=1}^{n_{\mathcal{S}}} e_i \right\rceil.$$

Therefore, the corresponding theoretical number of sites that must be active is

$$n_{\mathrm{sites}}^{\mathrm{minimum}} = \left\lceil \frac{n_{\mathrm{bs}}^{\mathrm{minimum}}}{max\_cells\_per\_site} \right\rceil \tag{4}$$

where *max_cells_per_site* is the maximum number of base stations that could occupy a single site (three is used throughout this paper).

We should note that in this model, we assume that the traffic at a test point can only be served by the base station that presents the strongest signal at its location. Therefore, the element of choice is eliminated and network capacity is easy to calculate. However, in a protocol such as GSM, a mobile station may choose from a number of base stations whose signal strength is above an acceptable threshold. Therefore, an evaluation in which only the base station with highest signal strength was an acceptable server may give a conservative estimate of network capacity.

3) *Site Cost:* The number of sites used in the design or their associated financial cost should be minimized, i.e.,

$$\min \sum_{i=1}^{n_{\mathrm{sites}}} f_i z_i$$

where f_i is the cost associated with site L_i and z_i is defined by (1).

4) *Handover:* Currently, this objective is implemented simply (for computational efficiency rather than network effectiveness) by requiring that each cell C_j should have at least one service test point in C_j such that

$$\mathrm{HAND}_j \neq \emptyset$$

i.e., there exists at least one service test point such that each signal from four base stations is within 7 dB. The objective is to have as many cells as possible satisfying the handover condition.

5) *Interference:* This objective attempts to minimize a measure of potential interference in the design. Our measure is to minimize *overlap*, i.e., at each service test point S_i, minimize the number of interfering base stations

$$I = \sum_{j=1}^{n_{\mathcal{B}}} \sum_{i=1}^{n_{\mathcal{S}}} \mu_{ij} \tag{5}$$

where

$$\mu_{ij} = \begin{cases} 1, & \text{if } F_j(S_i) > R_s \\ 0, & \text{otherwise.} \end{cases}$$

where R_s is the receiver sensitivity (set to -99 dBm). An interfering base station is defined as a base station providing a signal strength at a service test point that is greater than R_s but is not the best server nor one of the base stations providing handover.

IV. THE DESNET FRAMEWORK

DESNET[2] incorporates a simulated annealing algorithm together with problem-specific neighborhood structures. Specific neighborhood structures are used to improve solutions that are deficient in specific areas—for example, coverage or capacity not satisfied. A random neighborhood is also used to diversify the search.

A weighted objective function is used to guide the search toward solutions that satisfy the design objectives as well as possible. Typically, elements of the objective function that correspond to important objectives in the model (e.g., coverage and capacity) are weighted higher than the lower priority objectives.

All customizable aspects of the design algorithm are specified by a list of parameters. Fig. 3 contains the overall optimization framework.

A. Initialization

There are several methods that can be used to initialize a network, i.e., generate a starting network.

1) *Legacy:* The initial network is given by a preexisting design.

2) *Partial:* The number of sites to be randomly selected in the initial network is specified as a percentage of the theoretical minimum number of sites required to fulfill the

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[2] DESNET 1.0 is the name of the system implementing the design procedure.

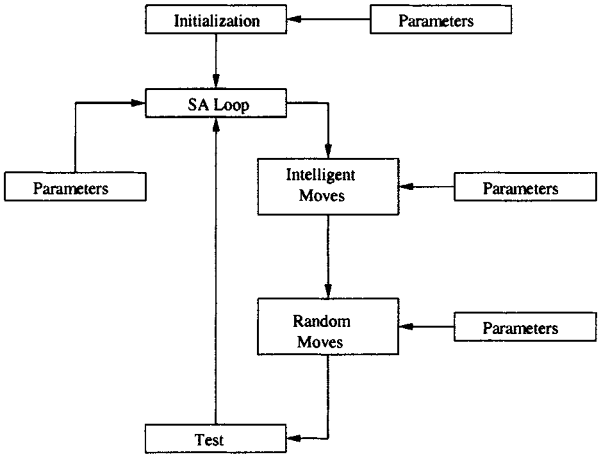

Fig. 3. DESNET solution framework.

```
    Initialize network.
    Calculate network cost, $E_{old}$.
    While not_finished
      Select Move Neighbourhood (probability
based, in sequence)
        - hole filler
        - cell splitter
        - traffic filler
        - small cell remover
        - random.
      Perform selected move.
      Calculate network cost, $E_{new}$.
      IF $E_{new} < E_{old}$ keep new network
        ELSE IF $e^{\frac{E_{new}-E_{old}}{T_{SA}}} > random$ keep new network
    End while.
```

Fig. 4. SA algorithm.

traffic requirement, i.e., $\omega n_{\text{sites}}^{\text{minimum}}$, where $0 \leq \omega \leq 1$. The actual sites are then randomly configured.

3) *Full:* A special case of partial initialization, i.e., $\omega = 1$.
4) *Full coverage:* The hole filler neighborhood (see Section IV-D1) is used until all service points in the network are covered (no other objectives are considered).

B. Simulated Annealing Algorithm

A simulated annealing algorithm (see [25]) controls the choice and acceptance of new solutions (network designs). The overall procedure is given in Fig. 4. T_{SA} is the current temperature and *random* is a uniformly distributed random number in the range [0, 1]. A standard geometric temperature reduction rule is used to lower the temperature parameter, i.e., $T_{\text{SA}} = 0.9 * T_{\text{SA}}$, and the number of trial networks N_{trial} tested at each temperature is set to $2n_{\text{sites}}$.

1) Starting and Finishing Temperatures: The starting temperature is determined as follows.

1) Set the initial temperature to 1.0.
2) Examine N_{trial} trial networks and count the number of accepted ones.
3) If the acceptance ratio χ, which is defined as the number of accepted trials divided by N_{trial}, is less than 0.3, double the temperature.
4) Goto Step 2) until the observed acceptance ratio exceeds 0.3.

The algorithm terminates when the temperature falls below some user-specified minimum temperature $T_{\min}$, or if the number of frozen temperatures exceeds another user-specified value N_{frozen}. A frozen temperature occurs when no new trial networks have been accepted at a given temperature.

The parameters mentioned here for algorithm implementation are largely selected by experimentation since at present, there are no general rules that guide the choice of annealing parameters. The way they are selected is a matter of experience for the practitioner (see [25] for a detailed discussion).

C. Objective Function

To endeavor to meet the objectives of a network design, the objective function used is a weighted additive objective function (to be minimized) of the form

$$E = \sum_{i=1}^{5} E_i \tag{6}$$

where E_i is the cost of component i (and includes its associated weight W_i). The components used in this function are related to the design objectives in Section III and are as follows.

1) *Coverage:* A normalized cost based on the number of service test points covered, i.e.,

$$E_1 = W_1 \left[\frac{n_{\mathcal{S}} - S_{\text{covered}}}{n_{\mathcal{S}}} \right]$$

where $n_{\mathcal{S}}$ is the total number of service test points and S_{covered} is the number of covered service test points in the current network.

2) *Site cost:* The normalized site cost component in the objective function reflects the relative financial cost of utilizing site locations. For a given configuration of sites $\mathcal{Z}$, the site-cost component for a Greenfield scenario (see Section V) is given by

$$E_2 = W_2 \frac{\sum_{i=1}^{n_{\text{sites}}} f_i z_i}{\sum_{i=1}^{n_{\text{sites}}} f_i} \tag{7}$$

where f_i is the financial cost associated with site L_i.

If a preexisting network is to be changed and augmented, i.e., an expansion scenario (Section V), the site cost component is given by

$$E_2 = W_2 \frac{\sum_{i=1}^{n_{\text{sites}}} f_i z_i}{7 n_{\text{sites}}} \tag{8}$$

where f_i is shown in (9) at the bottom of the next page. f_i reflects the relative cost of adding, removing, or changing a site.[3]

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[3] Figures provided by France Telecom; other operators may attach different relative importance to adding, removing, or changing sites.

3) *Traffic:* A normalized cost based on the traffic capacity of the current network relative to the total traffic capacity required, i.e.,

$$E_3 = W_3 \left[\frac{T_{\text{required}} - T_{\text{capacity}}}{T_{\text{required}}} \right]$$

where $T_{\text{required}} = \sum_{i=1}^{n_{\mathcal{S}}} e_i$ is the total traffic capacity required by a network design and

$$T_{\text{capacity}} = \sum_{j=1}^{n_{\mathcal{B}}} \min \left\{ 43, \sum_{S_i \in C_j} e_i \right\}$$

is the traffic capacity of the current network design and reflects the sustainable capacity in the network (any over capacity >43 Erlangs in a cell is discounted).

4) *Interference:* This cost based on the total interference in the network, normalized by a user-specified scaling factor, is given by

$$E_4 = W_4 \left(\frac{I}{I_{\max}} \right)$$

where I is the interference of the current network design [see (5)] and $I_{\max}$ is a parameter specifying a maximum interference level for the network (only used for normalization in E_4) and equals the value of I obtained when an omnidirectional antenna, at maximum power, is placed at all candidate sites.

5) *Handover:* A normalized cost based on the proportion of cells satisfying the handover condition, i.e.,

$$E_5 = W_5 \left(\frac{n_{\mathcal{B}} - n_{\mathcal{B}}^{\text{handover}}}{n_{\mathcal{B}}} \right)$$

where $n_{\mathcal{B}}^{\text{handover}}$ is the number of cells in the current network design that satisfy the handover condition and $n_{\mathcal{B}}$ is the number of base stations in the current network design.

D. Neighborhood Structures

Currently, four specific neighborhood structures (move generators) are used to improve solutions in two specific areas of network statistics: coverage and traffic. The usage and preference of each neighborhood is governed by four probabilities. Each neighborhood is only considered if the necessary conditions are present and a random number between zero and one is less than the corresponding probability $P_{\text{hole}}, P_{\text{cell}}, P_{\text{traffic}}, P_{\text{small}}$. Details of this move selection procedure are given in Fig. 5.

Note that the networks formed by applying any of these neighborhood structures are subject to the same acceptance criterion as the random neighborhood (which simply randomly changes any single network characteristic, i.e., turns on or off a site or any aspect of a base station configuration, e.g., assigns a random power to a randomly selected base station).

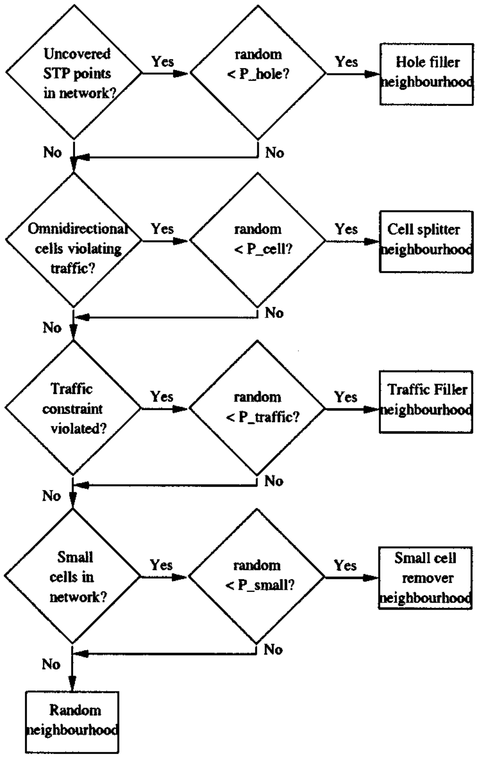

Fig. 5. Network design procedure.

1) Hole Filler Neighborhood: The hole filler attempts to fill coverage holes in the network. To cover as much of the hole as possible, the site closest to the center of mass[4] of the hole is selected (this also can be restricted to the closest active site or the closest inactive site). An omnidirectional antenna is placed at the site (any previous antennas are removed if the site is already active). The power is set to be the smallest value that covers the maximum number of service points of the hole—using a lower-powered antenna helps reduce the interference in the network. Fig. 6 details the operation of the hole-filling move.

The following hole-filler parameters can be used to tune the operation of the neighborhood.

1) *HRType:* The method used to select the site to be added and selected from:
    a) *Closest:* closest site to center of mass of hole (default);
    b) *Closest_on:* closest active site to center of mass of hole;
    c) *Closest_off:* closest inactive site to center of mass of hole;

$$f_i = \begin{cases} 0, & \text{if site } L_i \text{ is not used in the legacy and expanded network} \\ 1, & \text{if there is no change to site } L_i \text{ in the legacy network} \\ 2, & \text{if there is any change on site } L_i \text{ in the legacy network} \\ 5, & \text{if site } L_i \text{ is newly installed} \\ 7, & \text{if site } L_i \text{ is removed from the legacy network.} \end{cases} \tag{9}$$

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[4] The "center of mass" of a hole is calculated using the assumption that each service test point in the hole has unit mass.

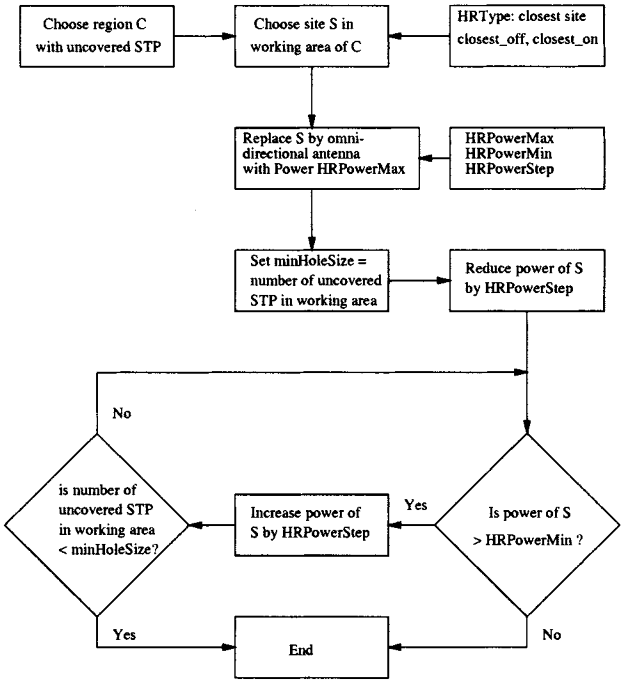

Fig. 6. Hole filler procedure.

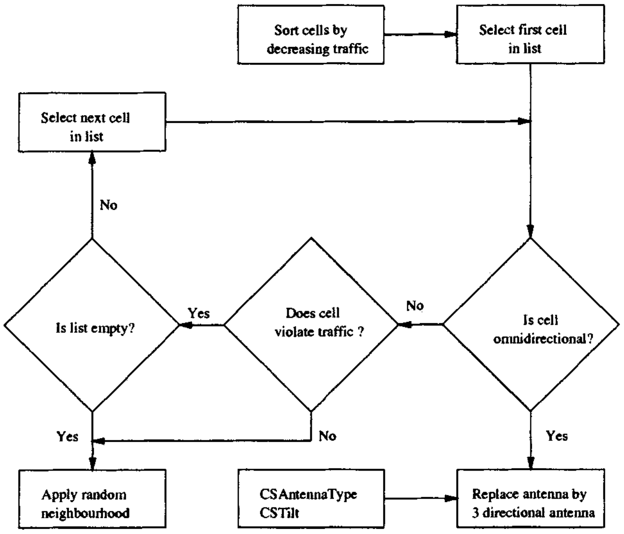

Fig. 7. Cell-splitting procedure.

2) *HRPowerMax:* Maximum power allowed at the new site (default—55 dBm).
3) *HRPowerMin:* Minimum power allowed at the new site (default—26 dBm).
4) *HRPowerStep:* Increment used to vary power at the new site (default—2 dBm).

Note that no azimuth needs to be set as a hole filler always places an omnidirectional antenna.

2) Small Cell Removal: Base stations corresponding to cells whose size, given by the number of STPs it contains, is below a specified size, e.g., ten service points, are removed. Stations that cover no service points are automatically removed.

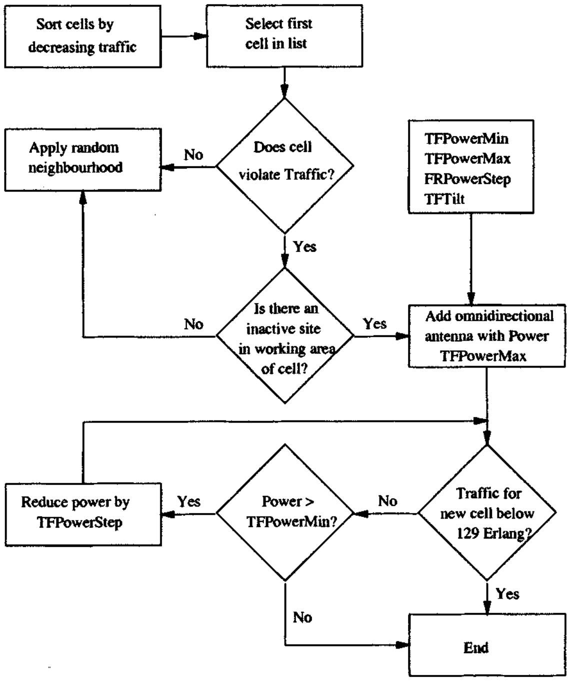

Fig. 8. Traffic filling procedure.

3) Cell Splitter: The cell-splitter neighborhood (see Fig. 7) aims to improve the traffic capacity of the network by replacing an omnidirectional antenna by three directive antennas at the same site. The azimuth and tilt of the new antennas are chosen randomly, but the power is taken to be the same as that of the original omnidirectional antenna. This is to try and ensure that the number of service points covered by the new site is at least as many as the original site configuration.

The following cell-splitter parameters are available to tune the operation of the neighborhood:

1) *CSAntennaType:* the type of directional antenna to be used (default—small directive);
2) *CSTilt:* the tilt value to be used (default—0°).

4) Traffic Filler: The traffic filler neighborhood (see Fig. 8) aims to improve traffic capacity by activating a new site within a defined area of the cell violating traffic by the largest amount. The new site is initialized with an omnidirectional antenna and the power is set so that the traffic capacity of the cell is less than 129 Erlang. The cell-splitter neighborhood is then applied to the new site.

Parameters available to tune the traffic filler neighborhood include:

1) *TFPowerMax:* maximum power allowed at the new site (default—55 dBm);
2) *TFPowerMin:* minimum power allowed at the new site (default—26 dBm);
3) *TFPowerStep:* increment used to vary power at the new site (default—2 dBm);
4) *TFTilt:* tilt to be used for new antenna (default—0°).

Note that the antenna type does not need to be specified as a small directive is always used.

V. DATA SETS AND RESULTS

Four real-world data sets have been used for study. All data sets were provided by the CNET[5] and two design scenarios have

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[5] France Telecom Research and Development Center, Belfort, France.

TABLE III
GREENFIELD NETWORK CHARACTERISTICS

	$Road_{greenfield}$	$Town_{greenfield}$
n_S	29954	17393
n_{sites}	250	568
Size of region (km)	40 x 170	50 x 46
Mesh increment (m)	200	200
Service threshold (dBm)	-90	-90
Total required traffic capacity (Erlangs)	3210.94	2988.08
Minimum number of sites, $n_{\text{sites}}^{\text{minimum}}$	25	24
Minimum number of cells, $n_{\text{bs}}^{\text{minimum}}$	75	70

TABLE IV
EXPANSION NETWORK CHARACTERISTICS

	$Road_{expansion}$	$Town_{expansion}$
n_S	29954	42492
n_{sites}	250	747
Size of region (km)	40 x 170	50 x 46
Mesh increment (m)	200	200
Service threshold (dBm)	-82	-75, -82, -83, -90
Total required traffic capacity (Erlangs)	3210.94	8087.00
Minimum number of sites $n_{\text{sites}}^{\text{minimum}}$	25	113
Minimum number of cells $n_{\text{bs}}^{\text{minimum}}$	75	337

TABLE V
LEGACY NETWORK DETAILS

	Road	*Town*
$n_{\text{operational}}$	87	96
ODA	13	6
LDA	152	81
SDA	15	174

been tested. The first scenario considers a *greenfield* design, i.e., where there is a need to design a completely new network. The second scenario considers an *expansion* design, i.e., where a preexisting network needs to be augmented by additional sites and base stations to provide an increased service in terms of area coverage and traffic capacity.

There are two geographic and demographic problems considered for the network design (both greenfield and expansion scenarios). The first, *Road,* characterizes a road network, while *Town* considers the service requirements of a medium-sized town. The characteristics of each type of region, for both greenfield and expansion scenarios, are given in Tables III and IV, respectively.

For the expansion problems, the legacy (preexisting) design consisted of 87 operational sites (corresponding to 180 cells) for $\text{Road}_{\text{expansion}}$ and 96 sites used (corresponding to 261 cells) for $\text{Town}_{\text{expansion}}$. Full details of the legacy networks are given in Table V (where ODA is number of omnidirectional antenna sectors, LDA is number of large panel directive antennas, and SDA is number of small panel directive antennas).

TABLE VI
COST COMPONENT WEIGHTS

Component	Weight
W_1 (coverage)	10.0
W_2 (site cost)	1.0
W_3 (traffic)	10.0
W_4 (interference)	1.0
W_5 (handover)	2.0

TABLE VII
$\text{Road}_{\text{greenfield}}$ DESIGNS

design	1	2	3	4
% coverage	100	100	100	100
% capacity	96.7	97.2	96.8	98.3
% handover	100	100	100	100
interference	17.4	19.8	17.6	17.3
$n_{\text{operational}}$	94	100	95	93
ODA	38	38	38	37
LDA	31	34	33	33
SDA	97	111	98	95

TABLE VIII
$\text{Town}_{\text{greenfield}}$ DESIGNS

design	1	2	3	4
% coverage	100	100	100	100
% capacity	98.4	98.1	97.7	96.6
% handover	100	100	100	100
interference	36.3	45.9	33.7	34.8
$n_{\text{operational}}$	84	83	85	86
ODA	21	22	24	23
LDA	30	34	34	33
SDA	135	127	126	132

A. Results

For each network scenario, a series of four designs were generated. The weights for each of the objective function components used in (6) are given in Table VI and were selected, through experimentation, to produce networks with area coverage and traffic capacity relatively dominant. For all designs, the neighborhood probabilities $P_{\text{hole}}, P_{\text{cell}}, P_{\text{traffic}}, P_{\text{small}}$ are set to 0.5. For both greenfield scenarios, ω was set to 0.1, and the cost of each site is unity, i.e., $f_i = 1 \; \forall i$ in (7).

Tables VII and VIII contain the results of four designs for the $\text{Road}_{\text{greenfield}}$ and $\text{Town}_{\text{greenfield}}$ scenarios, respectively (the entries in the "interference" row correspond to I/n_S to give an indication of the relative amount of interference per STP for each design). We observe that all designs satisfy the coverage and handover objectives (100% in each case) with the traffic capacity almost 100% in all designs. For both the Road and Town scenarios, all designs use a relatively high number of small directive antennas, a characteristic partially explained by the setting of the *CSAntennaType* parameter in the cell-splitter neighborhood to small directive (see Section IV-D3). The average number of interferers per STP in the Town designs is higher than that in the Road network. This can be explained by the fact that

TABLE IX
$\text{Road}_{\text{expansion}}$ DESIGNS

design	1	2	3	4
% coverage	100	100	100	100
% capacity	99.7	99.9	99.9	99.9
% handover	100	100	100	100
interference	9.1	26.7	8.7	25.0
$n_{\text{operational}}$	96	97	90	93
ODA	22	10	16	19
LDA	144	155	149	152
SDA	22	44	16	15
changed	4	8	2	1
added	14	10	5	6
removed	5	0	2	0
cost	191	145	126	118

TABLE X
$\text{Town}_{\text{expansion}}$ DESIGNS

design	1	2	3	4
% coverage	100	100	100	100
% capacity	91.2	97.0	96.1	93.7
% handover	97.5	98.7	98.6	98.9
interference	121.2	169.6	161.5	150.5
$n_{\text{operational}}$	201	207	188	169
ODA	64	0	0	0
LDA	111	105	93	88
SDA	242	449	428	393
changed	4	6	6	96
added	117	112	83	73
removed	12	1	1	0
cost	757	668	573	557

the Road network is axial in nature, i.e., many cells only require a relatively small number of adjoining cells.

Tables IX and X show the designs generated for the two expansion scenarios. For each design, the relevant legacy network is used as the starting network. The rows labeled "changed," "added," "removed," refer to the number of sites changed, added, and removed in the legacy network, respectively; "cost" denotes the cost of these legacy alterations by summing the relevant values for f_i using (9).

The results for the Road expansion problem differ only slightly from the legacy network since the initial network required relatively small improvements in area coverage and capacity (a few percent in each case). However, substantial improvements were required in the Town network (approximately 25% in coverage and 10% in capacity); hence the significantly different designs for the final networks relative to the legacy network.

In all network designs, the number of iterations (trial networks tested) needed to generate the final design lies between 5000 and 20 000 and requires a total computation time of no more than 48 h on a 400-MHz computer with 512 MB RAM running C++ code. Figs. 9–12 contain illustrative graphics representing cell designs produced by the design process for the four problem instances.

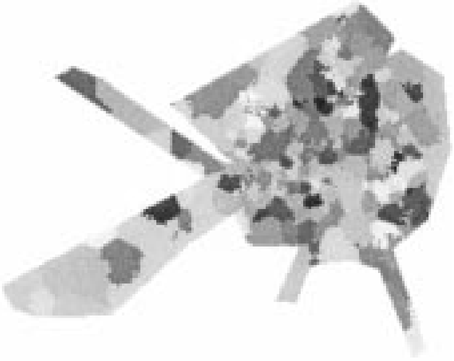

Fig. 9. Example design for $\text{Town}_{\text{greenfield}}$.

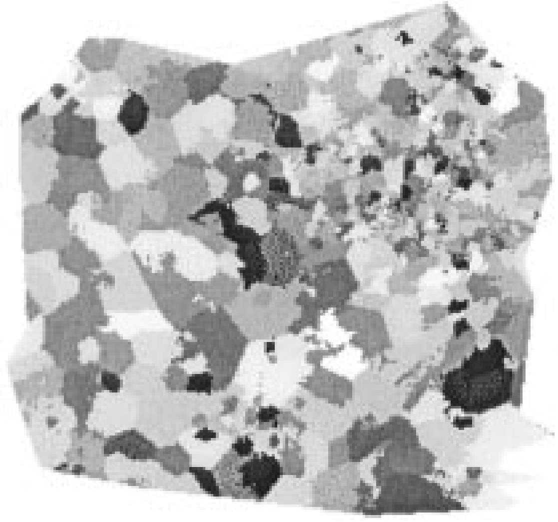

Fig. 10. Example design for $\text{Town}_{\text{expansion}}$.

VI. CONCLUSION

We have presented a framework based on simulated annealing for generating cellular network designs. Within the framework, several neighborhoods are used for specific aspects of the design. The framework can be used to generate completely new networks or to augment preexisting networks (by adding new sites and amending the existing network or just by adding new sites and keeping the existing network unchanged). Results indicate that the problem is tractable and that the framework is capable of producing designs with very high area coverage and traffic capacity but at the expense of a high number of sites (relative to the lower bound on the minimum necessary) and a large amount of interferers at each service test point. The effect of these interferers can be reduced by an efficient frequency plan; however, reducing the amount of interference would make the generation of such a plan much easier. Future work will investigate 1) network interference metrics, which, if included in the design framework, will be sympathetic to producing an effective frequency plan, and 2) a more effective implementation of the handover objective.

Fig. 11. Example design for $\text{Road}_{\text{greenfield}}$.

Fig. 12. Example design for $\text{Road}_{\text{expansion}}$.

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