Connectivity Management on Mobile Network Design*

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Abstract

This paper deals with a mathematical model for designing cellular network. The model allows us to find the optimal location for sites and the optimal parameterization for radio transmitters. The problem is modeled by discretizing the radio coverage areas into receiver locations, service locations and site locations. We use a concentrator location approach in which a set of test points must be attached to sites in order to supply a given service. The model includes specific constraints to deal with network and cells connectivity problems. Network connectivity will ensure mobility inside the network designed. When cells connectivity takes into account the different components of cells to reduce interference between cells. The final model defines an objective function to minimize the number of sites and integrates connectivity and service constraints.

1 Introduction

The deployment of cellular networks is one of the most challenging deal of this last decade. A high competition between radio operators all over the world leads them to find the optimal way of designing their network at the lower cost, when ensuring the best Quality of Service (QoS). It could be achieved by considering the radio planning problem as an optimization problem.

The radio planning of cellular network implies two conception stages: dimensioning and designing. The dimensioning step defines the financial needs to design a cellular network regarding at traffic and coverage objectives. Whereas the aim of the design is to find the locations and the parameters of radio Equipment for network deployment. After dimensioning, when all resources are defined, the problem of designing can be considered as a resource optimization problem. In fact the complexity of cellular network design strongly depends on the number of sites and base stations (BS). There is consequently a strong incentive to develop designing tools which minimize the number of BS and optimize their location to achieve traffic and coverage objectives.

Now the next step of the network design is to integrate in the process the management of connectivity consideration. One of the most important problem in the design is to ensure the mobility inside the network with a constant Quality of Service. Every subscriber must be able to move inside the cover area without loosing the signal. It could be done by integrating in the design specific constraints to take into account the requirements of network and cells connectivity. Network connectivity is directly involved in the mobility, it will allow the subscriber to continuously move from one point of the network to another point. Cells connectivity is linked to the Quality of Service. Adjacent cells generate interference, they overlap each other. Reducing the number of adjacent cells could be done by reducing the number of connected components of each cell. To manage with connectivity constraints on network and cells during the process of design is the aim of the proposal described in this paper.

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In the first Section, we introduce an inventory of the data required to describe the cellular network environment and resources. Then we present a minimal set of connectivity constraints on the network then on cells, which should ensure mobility and a high Service Quality on the mobile network. Finally, we develop a concentrator location model of design which includes the connectivity constraints.

2 Data

This section defines the required data for the theoretical design of cellular networks. These data are of various types. They are organized in three different classes: data from environment, data from dimensioning and data from engineering.

2.1 Environment

A working area described by a Digital Map Database is defined by $\mathcal{P}$. Any point from $\mathcal{P}$ is known by its coordinates (x, y).

Three sets of points are identified on $\mathcal{P}$:

- A set of sites which are candidate for the positioning $\mathcal{L} = \{L_i / i \in \mathbb{N}\}$. Each site is defined by its coordinates (x,y) and eventually by z (height above sea level).

- A set of Service Test Points (STP) in which the expected service have to be tested $\mathcal{ST} = \{ST_i / i \in \mathbb{N}\}$. $\mathcal{ST}$ defines the set of STP where the network must overcome a signal quality threshold to ensure a given QoS. This threshold depends on the expected service on this point anticipated by the Marketing.

- A set of Reception Test Points (RTP) in which the radio signal will be tested $\mathcal{R} = \{R_i / i \in \mathbb{N}\}$. $\mathcal{R}$ defines the set of RTP. Every RTP may be used as a signal test point to compute the overall cover of the network. The following inclusion between sets, illustrated in the figure 1, is always true:

$$\mathcal{ST} \subset \mathcal{R}$$

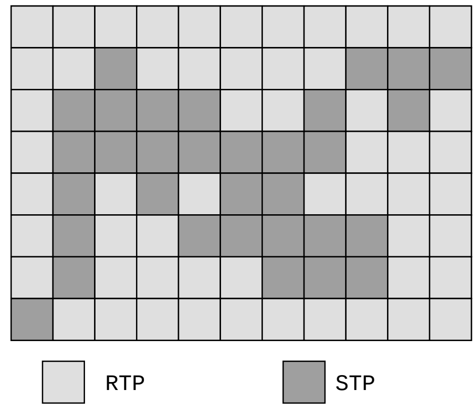

Figure 1: Grid view of relationships between STP and RTP.

In order to assess the quality of signal on each point, radio wave propagation models are used.

2.2 Dimensioning

The dimensioning step supplies the amount of resources for the design: expected number of sites, expected network cost, etc. Those data define constraints on resources to be used for network design.

The dimensioning also describes the nature of the services on the different sub-areas of the working area so where the STP are. By the way, each subarea of the network is constrained by S_q, a field strength threshold for an expected service.

Manifold thresholds will be defined in this paper. Most of the time, thresholds will depend on the type of constraints or objectives we will try to define. When different thresholds appear in the same location (one STP), we use the more constraining threshold. If no threshold is defined, we usually refer to Sm, the reception threshold of the Mobile Station (MS), or to Ss, the reception threshold of the Base Station (BS).

2.3 Engineering

Engineering data are technical data which describe the systems used in the network. These data fully define BS and MS. The field strength is always computed between a BS on a site and a MS on a RTP. The assessment of the field strength is fully depending on the characteristics of these systems. Some characteristics are constants, others have to be optimized during the design.

A BS is defined by the following data: Ps: BS Transmitter Power, Gs: BS Transmitter Gain, As: BS Transmitter Loss, Ss: BS Receiver Sensibility, gs: BS Receiver Gain, as: BS Receiver Loss. Each site may receive zero or one BS.

As well, the MS is defined by the following data: Pm: MS Transmitter Power, Gm: MS Transmitter Gain, Am: MS Transmitter Loss, Sm: MS Receiver Sensibility, gm: MS Receiver Gain, am: MS Receiver Loss.

All these data are used in the following mathematical model of design.

3 Mathematical Model

In these Sections, we introduce some basic definitions on cell and cover for the global understanding of the problem. Then, we present the connectivity constraints we have defined on the network and on the cells to ensure network mobility and interference management. In the last Section, the model for cellular network design is presented.

3.1 Cell definition

The cellular network may be defined at three levels:

- the test point (STP),
- the cell,
- the network.

Each level gives a specific view of the problem of design. The network is the global view. Each network is composed of a set of cells. Each cell of the network is itself composed of a set of points or STP. It is necessary to give a definition of cells to achieve the assignment rules of STP to cells.

Definition 1 *A cell C_j is the set of reception points R_i where the signal received from a single BS B_j of site L_j is higher than a given reception threshold $S_{reception}$:*

$$C_j = \{R_i : Cd_{ij} \geq S_{reception}\}$$

where $S_{reception} \geq\ S_q$.

This concept of assignment may be extended to sites to define S_j a prediction of cover from a single site, considering propagation loss threshold instead of field strength threshold, it can be written as:

$$S_j = \{R_i : AFF(S_j, R_i) \geq S'_{reception}\}$$

where $S'_{reception} \geq \min(UL, DL)$,

and UL is the uplink level (propagation from the MS to the BS), and DL is the downlink level (from the BS to the MS).

3.2 Cover definition

The downlink DL represents communication from the BS to the MS. On the opposite, the uplink UL represents communication from the MS to the BS. Providing good quality for downlink and uplink communications is an important requirement to design. We summarize this requirement of cover by the following definition:

Definition 2 *We say that a single STP is covered by a BS iff downlink and uplink requirements on communications are satisfied on this point.*

In order to supply downlink and uplink communications, system parameters of MS and BS antennae have to be correctly addressed. MS antenna (fixed parameter) and BS antenna (to be defined by the design) are described by their transmitting power, their reception sensibility and their electromagnetic gains and losses. All these parameters are used to estimate cover requirement while BS and MS are successively considered as transmitter and receiver to compute DL and UL. The cover requirement on STP is given by the following constraint:

Constraint 1 *Each STP must be covered by at least one BS to carry out its communications.*

3.3 Network connectivity

As we told above, a cellular network is defined by a set of cells. We can describe the network by $\mathcal{R}$ where ($\mathcal{R} = \bigcup C_j$). Because every MS must be able to move from any point A to any point B inside the network while keeping its communications, the network must be a connected set of points. It gives the following constraint on design:

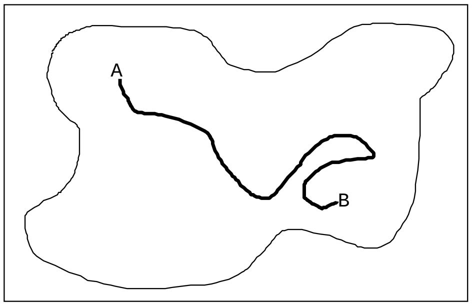

Figure 2: Cellular network with one connected component $\mathcal{R}^c = 1$, a connected path exists.

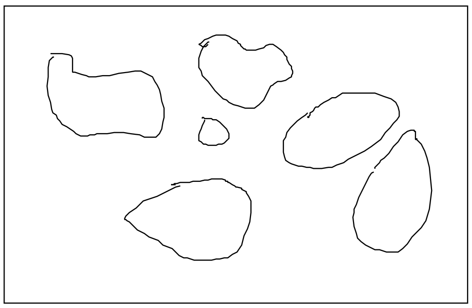

Figure 3: Cellular network with n connected components $\mathcal{R}^c = 6$.

Constraint 2 *The network must be composed of one and only one connected component, that is* $\mathcal{R}^c = 1$.

If this requirement is not achieved the network is a composition of disconnected sub-networks. The figures 2 and 3 give an illustration of networks composed of one or several connected components.

We will now define the concept of path and connectivity between two STP inside the same network.

STP are located on each network by using a grid applied on the working area. We use the notions of 4-connectivity and 8-connectivity to define paths between the test points. On the figure below (figure 4), the grey meshes around A define the 4-connectivity. As well, the grey meshes around B define the 8-connectivity. The connectivity relationships allow us to define paths between test points owing to its mathematical quality of transitivity.

Definition 3 *We define a connectivity relationship between two RTP R_i and R_j iff we can identify*

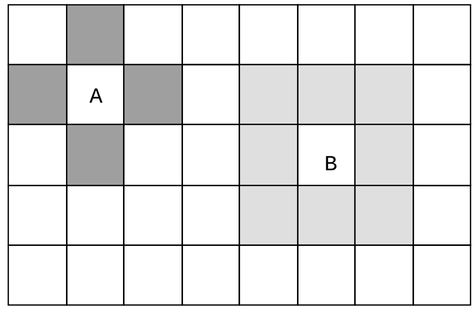

Figure 4: Sets of connected points to A (4-connexity) and B (8-connexity).

between R_i and R_j a path of connected points providing continuous 4-connectivity (or 8-connectivity) relationships from R_i to R_j, and for which requirements on field strength are satisfied for each of those points.

$$R_i \xrightarrow{connectedpath} R_j$$

$$Cd_{i'j} \geq Sq, \forall j \in \mathbb{N}, \forall R_{i'} \in \{R_i \xrightarrow{connectedpath} R_j\}$$

3.4 Cells connectivity

We introduce now the concept of cell connectivity to manage the interference between cells. For each cell, we define the number of connected components of the cell by the following idea, considering that it could be applied with 4 or 8-connectivity relationship,

Definition 4 *We define C_j^c as the number of connected components of a single cell. We call main component the set C_j^{c1} which is the connected component of larger size. C_j^{c1} holds the larger number of RTP. Other connected components of the cell are sub-components. The next component C_j^{c2} is the first component, etc. We must have the following sequence:*

$$|C_j^{c1}| \geq |C_j^{c2}| \geq \ldots \geq |C_j^{cn}|$$

To reduce interference between cells, the design must take into account the following constraint:

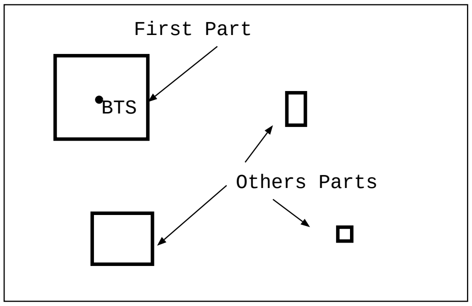

Figure 5: Cell with several connected components.

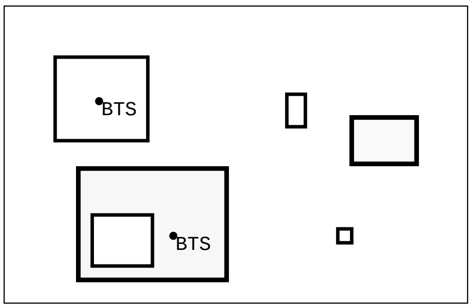

Figure 6: Interference between cells due to sub-components.

Constraint 3 *To avoid interference between cells due to random space distribution of sub-components, we must define the cellular network as a set of cells of one connected component* $C_j^c = 1$.

The above constraint may be adapted to handover requirements. The constraint is harder if we consider that C_j^{ck} is the number of connected components of the deeper cell

$$C^{\odot} = C_j \cup \{k \geq |Cd_{ij'} - Cd_{ij}| \geq 0\}$$

with reference to a maximum difference of k dBm (known as handover margin) between the field strength received from C_j and the field strength received from the BS considered as the best server (best level of field strength on the considered point).

In order to relax this difficult connectivity constraint on cells, we may finally consider a minimal size for a connected component.

Definition 5 *Considering* $MINC^c$ *as a minimum size of points for a connected component, a connected set of points of a cell not considered in the main component is defined as a sub-component of the cell iff* $|C_I^{cn}| \geq MINC^c$.

Hence, if $|C_I^{cn}| \leq MINC^c$ *we may consider that* $|C_I^{cn}| = 0$.

Network and cells connectivity constraints are now introduced in the final model presented below.

3.5 Concentrator Location Model

The following mathematical model deals with radio network optimization as a Concentrator Link Problem (CLP) [1]. RTP have to be concentrated on BS satisfying cover, handover, interference and traffic constraints.

This approach may be criticized compared to well known approaches using classical regular patterns. We already known that regular patterns give poor solution regarding at combinatorial aspects of optimal design. CLP approach is perfectly addressed to model the problem if we keep in mind that any MS has to be connected, or concentrated, to at least one BS to allow the communication.

The final model is defined by:

$$\min \sum_{j \in \mathcal{L}} y_j$$

Such as:

$$\sum_{j \in \mathcal{L}} x_{ij} = 1, \forall i \in \mathcal{ST}$$

$$x_{ij} \in \{0,1\},\ y_j \in \{0,1\}\ ,\ \forall i \in \mathcal{ST},\ \forall j \in \mathcal{L}$$

$$x_{ij} = \begin{cases} 1, & \text{if } ST_i \text{ received the best signal} \\ & \quad \text{from } L_j, \\ & Cd_{ij} = \max_{k \in \mathcal{L}} \{Cd_{ik}\},\ Cd_{ij} \geq S_q \\ & \quad \text{and } Cu_{ij} \geq S_q \\ 0, & \text{else} \end{cases}$$

$$y_j = \begin{cases} 1, & \text{if } L_j \text{ is used} \\ 0, & \text{else} \end{cases}$$

$$\mathcal{R}^c = 1$$

$$C_j^c = 1$$

Where,

- n is the number of STP $|\mathcal{ST}| = n$
- $m(\leq n)$ is the number of sites $|\mathcal{L}| = m$
- $C_j = \{R_i / x_{ij} = 1\}$ (so $y_j = 1$)
- $\mathcal{R}^c$ is the number of connected components of the cellular network with 8-connexity hypothesis.
- C_j^c is the number of connected components of a single cell with 8-connexity hypothesis.

4 Conclusion

In this paper we presented a formulation for the problem of designing a cellular network. This formulation guarantees a minimum number of sites and a good cover referring to downlink and uplink requirement. In real problems, cover is not sufficient to ensure a good Quality of Service. Mobility and interference problems are not achieved by cover objectives. So we introduced specific network connectivity constraints based on 4-connectivity and 8-connectivity computation to achieve mobility in the network. And finally, we also gave cells connectivity constraints to avoid multi component cells which are mainly involved in interference. The management of interference allow to achieve a better frequency plan. The final model given at the end is based on a concentrator location approach. In this approach, the design of cellular network is a complex optimization problem in which objective function and system states are discretely defined.

Our aim for further work is to introduce antennae variety, directional antennae and traffic constraints. Furthermore, the model will be tested on different macro cellular environments.

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