Research Article

Novel Heuristics for Cell Radius Determination in WCDMA Systems and Their Application to Strategic Planning Studies

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We propose and compare three novel heuristics for the calculation of the optimal cell radius in mobile networks based on Wideband Code Division Multiple Access (WCDMA) technology. The proposed heuristics solve the problem of the load assignment and cellular radius calculation. We have tested our approaches with experiments in multiservices scenarios showing that the proposed heuristics maximize the cell radius, providing the optimum load factor assignment. The main application of these algorithms is strategic planning studies, where an estimation of the number of Nodes B of the mobile operator, at a national level, is required for economic analysis. In this case due to the large number of different scenarios considered (cities, towns, and open areas) other methods than simulation need to be considered. As far as we know, there is no other similar method in the literature and therefore these heuristics may represent a novelty in strategic network planning studies. The proposed heuristics are implemented in a strategic planning software tool and an example of their application for a case in Spain is presented. The proposed heuristics are used for telecommunications regulatory studies in several countries.

1. Introduction

Mobile communications field is, nowadays, one of the most relevant technology research topics. Its fast evolution, from analog (like Advance Mobile Phone System), to digital systems (like Global Systems for Mobile (GSM) Communications or IS-95), and currently to 3G multiservice systems, such as Universal Mobile Telecommunication Systems (UMTSs) and 4G Long Term Evolution (LTE), has required the development of new technics, and produced the convergence of several telecommunication research areas. On the other hand, the high level of acceptance of the mobile technologies by customers (see Figure 1), and their need of new and more complex services, is a catalytic element for doing research to obtain more efficient technics in mobile communications.

The general architecture of a mobile network may be described in the same way as the traditional fixed network; it is formed by an access network and a backbone network. The access network is named *Base Station Subsystem* (BSSs) in 2G systems like GSM, and *UMTS Terrestrial Radio Access Network* (UTRAN) in 3G systems like UMTS. The backbone network corresponds to Network Switching Subsystems in GSM and to the Core Network in UMTS. Figure 2 shows an example of these architectures.

One critical problem in mobile network design is the determination of the cell radius [1]. The underestimation of the cell radius leads to an overestimation of the number of Base Stations (BTS) required to provide service in an specific area, and hence excessive deployment investment costs. This is obviously bad news for the business of the network operator. On the other hand, an overestimation of the cell radius results in the installation of fewer BTSs than needed, and then in shadow areas. This means the network operator provides bad Quality of Service (QoS) in terms of coverage, and customers will complain.
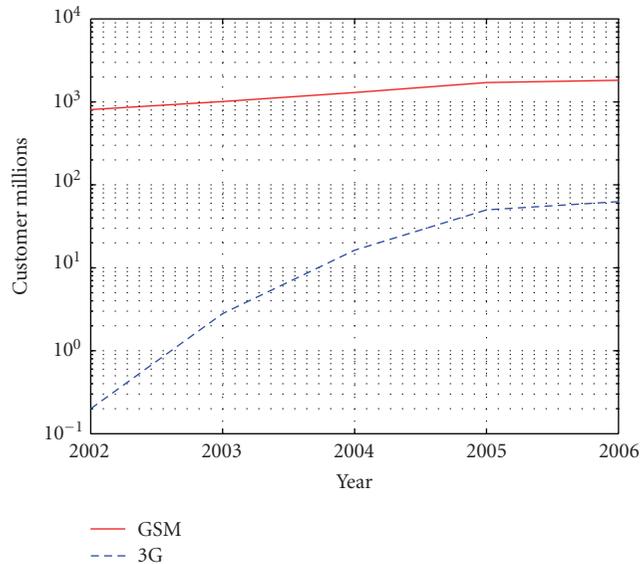
FIGURE 1: GSM and 3G customer evolution (millions).

Most of second generation systems, like GSM, use Time Division Multiple Access (TDMA) as radio access technology and therefore, they can be defined as hard blocking systems, that is, the number of users in the system is limited by the amount of hardware installed in the Base Station (BTS). Therefore, in GSM systems, the cell radius is mainly determined by the coverage planning (in this paper the term *coverage* refers to *radio propagation coverage*). In case that the QoS required (expressed as the blocking probability) is not fulfilled, the network operator must install more electronic equipment to incorporate more traffic channels to the BTS. It is a relatively simple task in TDMA systems.

Most of third generation systems, like UMTS, are based on WCDMA. These are soft blocking systems, where the number of users is not limited by the amount of channels in the BTS, but by the interference generated by their own users, and the users in neighbor cells. The maximum interference allowed in the system can be measured by a parameter named *interference margin*, which is used in the calculation of the link budget at the coverage planning process, and also to calculate the maximum number of users in the capacity planning process. Note that there is a tight relationship between the capacity and coverage planning processes in this case. Furthermore, the design of 2G systems is mainly oriented to the voice service [2], but 3G systems are designed to handle traffic from different sources, with different bit rates and, obviously, different requirements in terms of Grade and Quality of Service [3]. It is straightforward that this issue increases the planning complexity.

Cell radius calculation in WCDMA systems has been extensively studied before in the literature [4–8]. However, most of these models only consider a single service, which may result in a nonaccurate estimation of the cell radius in multiservice environments. In addition the studies of multiservice environments are usually based on simulation [9, 10], which requires a large set of input parameters.

Moreover, user and service simulation models are usually quite complex. As we will see in the body of the paper, the problem of the cell radius determination in WCDMA systems is equivalent to a problem of capacity assignment among different services. Another approach to this complex problem starts from the cell radius, and finds the optimal capacity assignment to the services [11] or to study the maximum throughput.

Currently most operators are deploying their *3G and beyond* networks in order to offer high speed data services to their customers. Furthermore in developing countries, or in some rural areas where the 2G deployment is not completely finished, the operators are studying whether implement a proper 3G infrastructure or subcontract it to the dominant operator. Note that a very relevant factor in this decision will be the price that the dominant operator establishes, which may be sometimes conditioned by the National Regulatory Authority (NRA). The determination of the interconnection, roaming or termination price must be based on technoeconomic studies under the so-called Bottom-Up Long Run Incremental Cost model (LRIC) [12, 13] which is recommended by the European Union [14]. The objective of the LRIC is to estimate the costs incurred by an hypothetical operator with the same market power of the operator under study, that tries to implement his network with the best suitable technology. To do this, a complete design of the network has to be done at a national level, that is, to calculate the network equipment for each city, town, rural area, highway, road, and so on. Based on this, the mobile operator will have enough information to make the decision about *built or buy*, and/or to claim to the NRA with objective data to obtain better price.

It is straightforward that constructing a LRIC model requires the calculation of a large number of different scenarios, where the cell radius of the Nodes B (the 3G Base Stations), has to be estimated. Therefore the heuristic model used for this estimation has to be general enough to be applied to a large set of scenarios with a reduced set of parameters, so simulation is not valid. Furthermore, note that obtaining a good LRIC model for a country involves thousands of B Nodes, so the heuristics applied must be computational efficient. Thus, modern heuristics as evolutionary computation are limited approach in this case. Finally the selected calculation method has to be able to provide a fair estimation of the cell radius.

This paper proposes several novel algorithmic approaches to the cell radius determination problem under the constraints presented previously. Our approach starts from a multiservice scenario and the maximum capacity of the cell, and based on the services parameters we obtain the optimal capacity assignment for each service, and then, as final objective, we obtain the optimal cell radius. We propose the following heuristics. First, an iterative load factor reassignment heuristic is presented, which is able to solve the problem giving encouraging results. An analytical algorithm is also proposed and compared with the iterative heuristic. Finally, a combination of both algorithms is also tested, where the analytical approach is used to generate an initial solution for the iterative approach. We will show
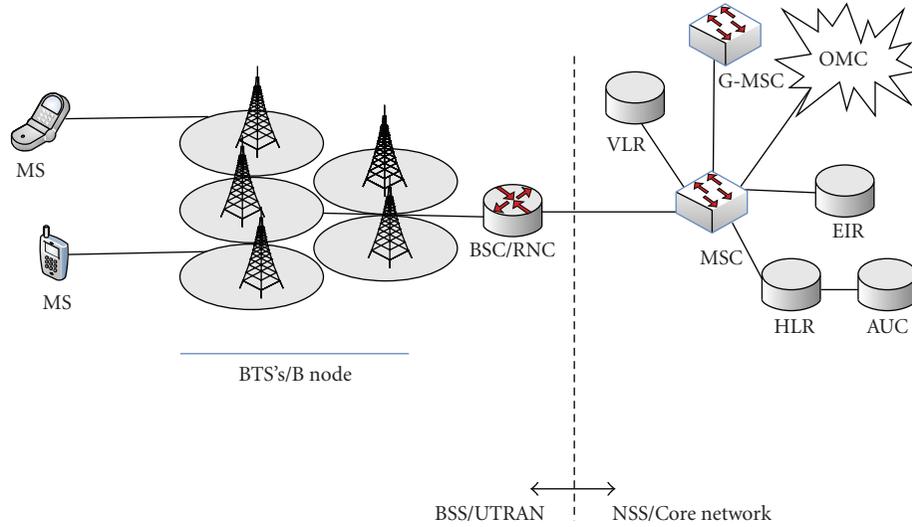
Figure 2: Mobile network general architecture.

the performance of our approaches in several test problems considering WCDMA multiservice scenarios. With the proposed heuristics we fulfil all the requirements defined in the paragraph previously, that is, a fast procedure that is able to provide good estimations of the cell radius using a limited set of input parameters, and hence easy to use in different scenarios.

The rest of the paper is structured as follows. Next section defines the cell radius determination problem in WCDMA networks. In Section 3 we propose the heuristics for solving the problem, and in Section 4 we show the performance of the heuristics proposed by performing some experiments in WCDMA multiservice scenarios. We also present the implementations of our heuristics in a software tool named DIDERO and their applications in different regulatory projects. Section 6 concludes the paper giving some final remarks.

2. Cell Radius Determination in WCDMA Networks

Let us consider a 3G mobile network based on WCDMA technology, where the mobile operator provides a set of S services (voice, data 16 kbps, data 64 kbps, etc.) each one defined by a set of parameters P (binary rate, user density, quality of service, etc.). The mobile operator needs to have an estimation of the number of B Nodes in each area and thus it is required to calculate the cell radius for each B Node. As it is mentioned in the introduction, cell radius determination in WCDMA is a complicated process because, opposite to TDMA, the number of users and the total throughput is limited by the amount of interference in the radio interface. Of course, this interference not only limits the capacity of the system, but also the coverage by propagation, because the total noise in the system increases as more users are active.

Propagation coverage studies mainly imply two steps. The first one is to calculate the maximum allowed propaga-

tion loss in the cell, defined here as L_{pathloss}, and the second is to use an empirical propagation method to calculate the cell radius for this pathloss. Typical methods are the Okumura Hata COST 231 model, [15], or the Walfish and Bertoni [16].

The value of L_{pathloss} is calculated using a classical link budget equation

$$P_{Tx} + \sum G - \sum L - \sum M - L_{\text{pathloss}} = R_{\text{Sens}}, \quad (1)$$

where P_{Tx} is the transmitter power, $\sum G$ is the sum of all gains in the chain, transmitter antenna, receiver antenna, and soft handover gain, $\sum L$ is the sum of all the losses in cables, body losses, and in-building losses, R_{Sens} is the receiver sensitivity which includes the required Eb/No, thermal noise, receiver noise figure, and processing gain, and finally, $\sum M$ is the different margins we need to take into account, fast fading margin, log-normal fading margin, and the interference margin, M_i. This interference margin is a very relevant value, because it measures the maximum interference allowed in the system due to its own users. Therefore this value indirectly limits the maximum number of users in the system. Note that all the parameters in (1) are inputs of the system and therefore L_{pathloss} can be obtained from this equation.

As it was mentioned before the cell radius by propagation is obtained applying the L_{pathloss} into an empirical propagation method. In our work we have used the 231-Okumura Hata model because it is broadly considered as the most general one in mobile networks applications [17]

$$L_b = 46.3 + 33.9 \cdot \text{Log}(f) - 13.82 \cdot \text{Log}(h_{\text{BTS}}) - a(h_{\text{Mobile}})$$
$$+ (44.95 - 6.55 \cdot \text{Log}(h_{\text{BTS}})) \cdot \text{Log}(R^p) + C_m, \quad (2)$$

where f is the frequency in MHz, h_{BTS} is the height of the Node B in meters, h_{Mobile} is the height of the mobile user in meters, and R^p is the cell radius by propagation in Km. Note

that $a(h_{\text{Mobile}})$ and $C(m)$ are parameters defined in the COST 231 specification. They provide the influence of the height of mobile terminal and the type of city, respectively, and they are defined as follows:

$$
\begin{aligned}
a(h_{\text{Mobile}}) &= (1.1 \cdot \text{Log}(f) - 0.7) \cdot h_{\text{Mobile}} \\
&\quad - (1.56 \cdot \text{Log}(f) - 0.8),
\end{aligned}
\tag{3}
$$

$$
C_m = \begin{cases} 0\,\text{dB} & \text{for medium sized cities} \\ & \text{and suburban centres,} \\ 3\,\text{dB} & \text{for metropolitan centres.} \end{cases}
$$

Note that as the value of Eb/No changes for the different services, the propagation coverage study has to be done specifically for each one, and of course for the uplink and the downlink. Therefore the formulation explained previously, and the value R^p, has to be applied for each service i and each direction (Uplink (UL) and Downlink (DL)) obtaining a set of two vectors containing, for each service, the cell radius by propagation, (R^p_{UL} and R^p_{DL})

$$
\begin{aligned}
\mathbf{R^p_{DL}} &= \left\{ R^p_{\text{DL\_}i}; i = 1, \ldots, S \right\}, \\
\mathbf{R^p_{UL}} &= \left\{ R^p_{\text{UL\_}i}; i = 1, \ldots, S \right\}.
\end{aligned}
\tag{4}
$$

Now we focus on capacity studies. As it is done in propagation studies, cell radius must be calculated independently for the uplink and the downlink. The equations that determines the radius in both directions are quite similar. Then for simplicity reasons, this paper focuses in the calculation of the cell radius for the downlink case, since this is the most restrictive direction [18–20].

The interference margin used in (1) determines the maximum load of the cell, η_{DL}, by means of the following relation, [18, 21]

$$
\eta_{\text{DL}} = \frac{1}{10^{M_i/10}} - 1.
\tag{5}
$$

This factor indicates the load of the cell. If $\eta = 0$ there is no user in the system. On the opposite if $\eta_{\text{DL}} \simeq 1$, the amount of interference in the system grows to ∞ and hence the system goes to an unstable state. Therefore typical values of the M_i are between 3 and 6 dB, which means a load of 0.5–0.75.

Although in the real operation of the system, there is no capacity reservation between the different services, in the dimensioning process it is required to allocate part of the capacity to each service. Therefore the load factor, that is, the capacity of the cell, must be allocated to the different services, resulting the load factors of the each service $L_{\text{Total\_DL\_}i}$

$$
\eta_{\text{DL}} = \sum_{i=1}^{S} L_{\text{Total\_DL\_}i} < 1.
\tag{6}
$$

The number of active connections of each service is calculated by dividing the total load factor of each service type i over the average individual downlink load factor of the connections of the service

$$
Nac_{\text{DL\_}i} = \frac{L_{\text{Total\_DL\_}i}}{L_{\text{DL\_}i}},
\tag{7}
$$

where the downlink load factor is defined by the following equation:

$$
L_{\text{DL\_}i} = \frac{(Eb/N_0)_{\text{DL\_}i} \cdot \sigma_i}{(W/Vb_i)} \cdot \left[\left(1 - \overline{\phi} \right) + \overline{f} \right],
\tag{8}
$$

where $\overline{\phi}$ is the so-called downlink orthogonality factor, Vb_i is the binary rate, σ_i is the so-called activity factor of the service i, $\overline{f}$ is the average intercell interference factor, and W is the bandwidth of the WCDMA system.

The total offered traffic demand, $A_{\text{DL\_}i}$ in Erlangs, is obtained by using the inversion of the Erlang B Loss formula [22]. The inputs for this algorithm are the maximum number of active connections in the cell $Nac_{\text{DL\_}i}$ and the Quality of Service (QoS) of the service expressed by the blocking probability Pb_i

$$
\frac{A_{\text{DL\_}i}}{1 + \overline{f}} = \text{Erlang}\, B^{-1} \left(Pb_i, Nac_{\text{DL\_}i} \cdot \left(1 + \overline{f} \right) \right).
\tag{9}
$$

Note that in (9) the total offered traffic demand, $A_{\text{DL\_}i}$, is divided by the factor $(1 + \overline{f})$ and the maximum number of active connections, $Nac_{\text{DL\_}i}$, of the service i is multiplied by it. This is included to considerer the soft blocking feature inherent to the WCDMA system, [23].

Multiservice traffic in UMTS has been extensively studied in the literature [24]. However in the strategic planning mobile operators trend to use simplified models that provides under estimations of the cell capacity to be in the safe side when they estimate the number of Node B's to provide service to the customers in the area under study, [25]. Because of the reasons stated in the previous sentence, in this proposal we use the Erlang B formulation. However it is and independent part that can be substituted by any other traffic model formulation.

The number of users in the cell ($M^{\text{users}}_{\text{DL\_}i}$) is obtained from the division of the total offered traffic demand for service i, ($A_{\text{DL\_}i}$ in Erlangs), by the individual traffic of a single user of this service (obtained from the connection rate α_i and the mean service time ts_i):

$$
M^{\text{users}}_{\text{DL\_}i} = \frac{A_{\text{DL\_}i}}{\alpha_i \cdot ts_i}.
\tag{10}
$$

The cell radius for each individual service is calculated as a function of the number of sectors in the BTS, N_{Sectors}, the number of users of service i per sector M^{users}_i and the user density ρ_i as follows (note that a Node B may be divided into several sectors. Each sector corresponds to a cell):

$$
R^t_{\text{DL\_}i} = \sqrt{\frac{M^{\text{users}}_{\text{DL\_}i} \cdot N_{\text{Sectors}}}{\pi \cdot \rho_i}}.
\tag{11}
$$
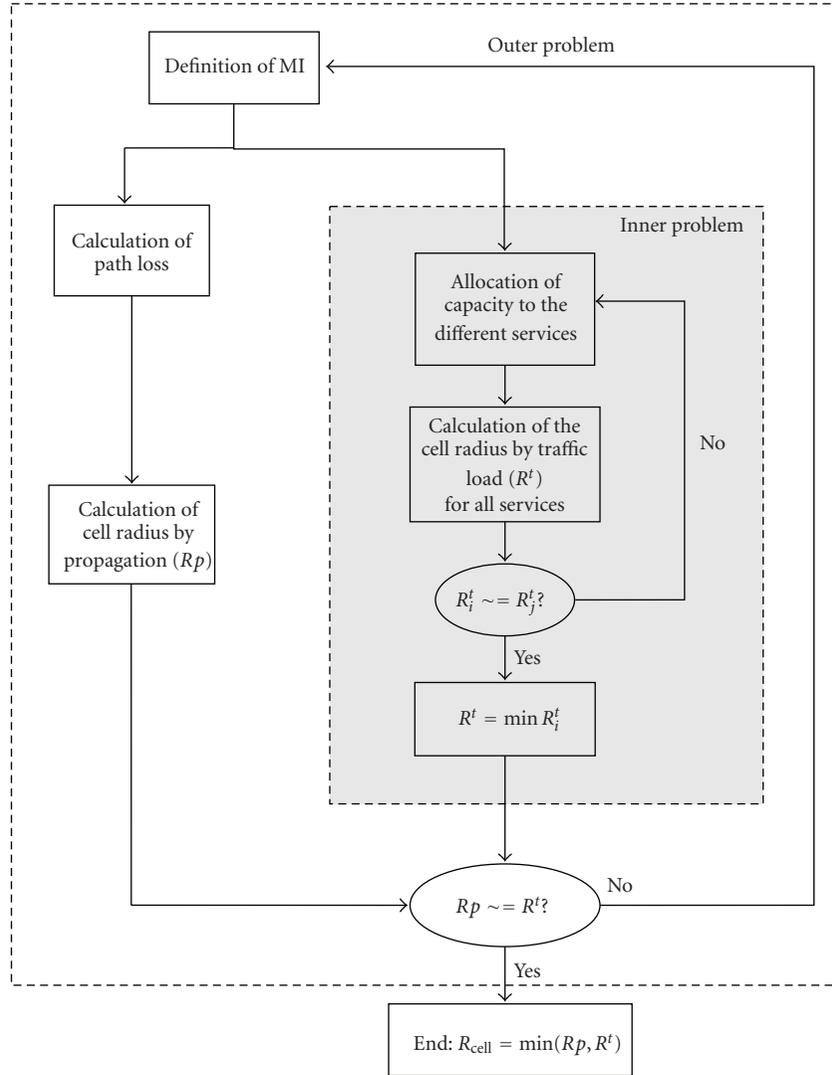
FIGURE 3: Inner and outer WCDMA problems in dimensioning process.

Note that this process has to be done also for the uplink direction (UL). Therefore, at the end we have obtained another set of two vectors (one for the uplink and one for the downlink), with the cell radius by capacity of each service:

$$\mathbf{R_{DL}^t} = \{R_{DL\_i}^t; i = 1 \cdots S\},$$
$$\mathbf{R_{UL}^t} = \{R_{UL\_i}^t; i = 1 \cdots S\}. \tag{12}$$

Note that the values of $R_{DL\_i}^t$ and $R_{UL\_i}^t$ largely depend on the distribution of the capacity over the different services by means of the total load factor allocated to each service $L_{Total\_UL\_i}$ and $L_{Total\_DL\_i}$. A bad allocation will lead to large differences in the values of the radius, while an equilibrated one will produce approximately the same value for all the S services.

Note that at the end of this process we have obtained a set of four vectors, $\mathbf{R_{UL}^p}$, $\mathbf{R_{DL}^p}$, $\mathbf{R_{UL}^t}$, and $\mathbf{R_{DL}^t}$. The final cell radius, R_{Cell} will be the minimum value between R_T^p and R_T^t which represents the most restrictive cell radius under propagation and traffic criteria respectively

$$R_T^t = \text{Min}[\mathbf{R_{UL}^t}, \mathbf{R_{DL}^t}],$$
$$R_T^p = \text{Min}[\mathbf{R_{UL}^p}, \mathbf{R_{DL}^p}], \tag{13}$$
$$R_{Cell} = \text{Min}[R_T^p, R_T^t].$$

As a conclusion of this section we have identified two problems in the cell radius dimensioning, that can be named *outer problem* and *inner problem*, as it is shown in Figure 3.

(1) The *outer problem* is to find the best value for the Interference Margin, M_i. This will be the value when the cell radius by capacity (traffic), R_T^t, is the same as by propagation, R_T^p.

(2) The *inner problem* that is to find the best capacity allocation, given a value of the M_i over the complete set of services S. With this the cell radius by capacity, R_T^t, is maximized.
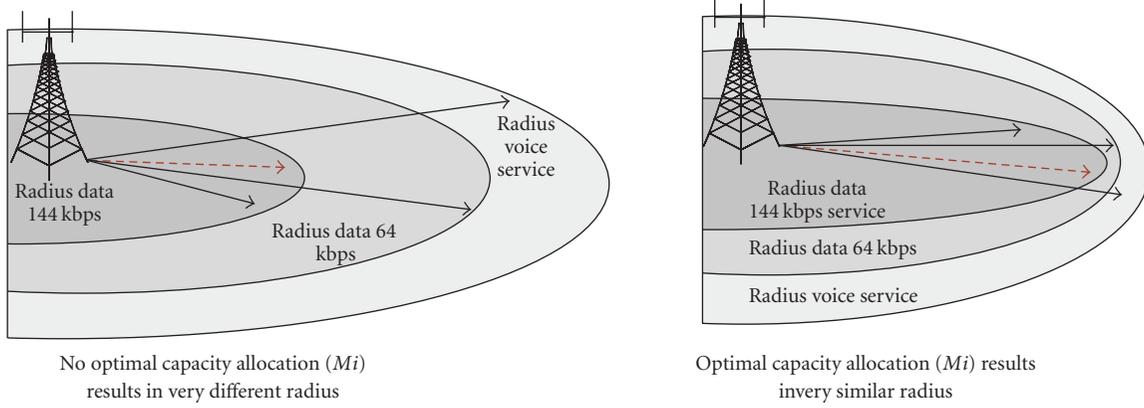
FIGURE 4: Scheme of the cell radius with optimal and no optimal capacity allocations.

The outer problem is solved just making an iterative process to equilibrate the value of the cell radius between the resulting value calculated by propagation studies and the resulting one calculated by capacity studies. This is done by means of increasing the value of the interference margin, M_i, when the cell radius by propagation is higher than by capacity or vice versa. The *inner problem* is much more complicated because it implies the use of the traffic concepts and nonlinear process which underlies to (9)–(12).

This paper focuses on the design of heuristics for solving the inner problem (from now on we will focus on the donwlink direction, we therefore do not include the DL subindex in the formulation since it is assumed). With the definitions given before, the cell radius determination problem by capacity criterium can be defined as follows:

Find $L_{\text{Total}\_i}, i = 1, \ldots, S$, such that

$$\eta = \sum_{i=1}^{S} L_{\text{Total}\_i} < 1 \qquad (14)$$

which maximizes R_{Cell}. Note that we focus on the inner problem, where the traffic is the most restrictive factor, therefore, $R_{\text{Cell}} = R_T^t$ in this case.

Note that if we allocate optimally the capacity to the services, by means of the L_{Total_i} values, the cell radius of all service will have almost the same value, and hence the cell radius by capacity will be maximized. Note that a suboptimal allocation leads to very different values of the cell radius of the different services, and hence to a bad estimation of the final radius. This situation is shown in Figure 4, where the dashed red arrow determines the final cell radius.

3. Proposed Heuristics

3.1. Iterative Load Factor Redistribution Heuristic. This first heuristic we propose for the cell radius determination problem starts from an initial load factor assignment, usually

provided by estimations of the network planner [7]. From this initial assignment $\mathbf{L_{Total}} = [L_{\text{Total}\_1}, \ldots, L_{\text{Total}\_S}]$, we can calculate an initial solution for the cell radius using (7) to (11). If this initial cell radius is not the optimal one, the only service which is using its total capacity is the one with minimum value of R_i^t associated. The following example shows it in detail.

Let us consider a scenario with three services, S_1 = voice at 12.2 Kbps, S_2 = data at 64 Kbps and S_3 = data at 144 Kbps. Let us also consider that a initial load factor assignment is $L = [0.105, 0.271, 0.373]$. With this, the values of the cell radius are $R^t = [343, 976, 721]$ meters. Note that the limiting value is the cell radius of the first service S_1, that is 343 meters. With this value of the cell radius $R_T^t = 343$ m, the load factors that the services are really using are $L = [0.105, 0.56, 0.111]$. So it is obvious that the initial load factor assignment is not correct, because we are not optimizing the cell usage (note that this example is a hard simplification of the complete process).

Note that the rest of the services will use less capacity than they have initially assigned. Let us call this capacity as L_{Real_i}. Therefore, there is some remaining capacity, L_{rem} defined as

$$L_{\text{rem}} = \eta - \sum_{i=1}^{S} L_{\text{Real}\_i}. \qquad (15)$$

This remaining capacity has to be redistributed over the considered services, so that a new cellular radius can be calculated using (11). This will produce new values of L_{Real_i}. This iterative process is followed until the difference between two consecutive cell radius is less than a given threshold ϵ, usually $\epsilon = 0.01$.

Several procedures can be applied for the L_{rem} distribution over the different services. The simplest one is to find the balanced distribution of L_{rem} among all services in the system. This method leads, however, to suboptimal solutions, since the service with the most restrictive cell radius in one

assignment is kept again as the most restrictive one in the new assignment. A better distribution can be obtained by assigning a larger part of the exceeding load factor, L_{rem}, to the service j with most restrictive cell radius, R_T^t, by means of a prioritizing factor f_{assign} ($0.5 < f_{assign} < 1$), and a balanced division among the rest of services:

$$L_{Total\_j} = L_{Total\_j} + f_{assign} \cdot L_{rem},$$

$$\frac{j}{R_{DL\_j}^t} = \text{Min}(R_{DL\_i}^t),$$

$$L_{Total\_i} = L_{Total\_i} + \frac{\left(1 - f_{assign}\right) \cdot L_{rem}}{S - 1}, \quad i \neq j, \tag{16}$$

$$f_{assign} > \frac{\left(1 - f_{assign}\right)}{S - 1}.$$

The value of the prioritizing factor, f_{assign}, depends on the differences of the values of the cell radius of the different services. If the difference $\text{Max}(R_{DL\_i}^t)$-$\text{Min}(R_{DL\_i}^t)$ is large the value of f_{assign} will be near to 1; otherwise, it will be near to 0.5.

The main drawback of this method is the dependency on the initial solution, that is, the dependency on the initial load factor assignment. Note also that the convergence of the algorithms depends on how the remainder capacity (given by L_{rem}) is distributed over the different services. A poor distribution procedure may result in a high number of iterations or even may fail to find the solution.

3.2. The Reduced Algorithm.

The second approach we propose to solve the cell radius determination problem is to find a mathematical model, which calculates an accurate value of the cell radius, under any service scenario and any initial conditions, expressed in terms of the load factor η and the parameters of the services **S**.

The proposed model is named *reduced algorithm*, since it reduces all the services in the system to a single artificial service to solve the problem. The method starts considering an arbitrary cell radius, typically $R = 1000$. Then, the model calculates the total traffic demand offered to the cell, A_i, for each service i, by means of the user density of each service, ρ_i, the individual call rate, α_i, and the mean call duration, ts_i.

The reduction of the set of services to a unique artificial/equivalent one is performed by a procedure based on a proposal of Lindberger for ATM networks [28]. This proposal is obviously extended to the singularities of the WCDMA cell design. The artificial service is defined in terms of equivalent parameters: binary rate, Vb_{eq}, call rate, α_{eq}, mean call duration, ts_{eq}, blocking probability, Pb_{eq}, activity factor, σ_{eq} and user density, ρ_{eq}. Following the Lindberger formulation, the parameters of the artificial service are calculated on the basis of the traffic, A_i, and the binary rate, Vb_i, of each service i considered in the scenario.

The complete set parameters are defined by the following equations:

$$Vb_{eq} = \frac{\sum_{i=1}^S A_i \cdot Vb_i^2}{\sum_{i=1}^S A_i \cdot Vb_i},$$

$$Pb_{eq} = \frac{\sum_{i=1}^S Pb_i \cdot A_i \cdot Vb_i}{\sum_{i=1}^S A_i \cdot Vb_i},$$

$$\alpha_{eq} = \frac{\sum_{i=1}^S \alpha_i \cdot A_i \cdot Vb_i}{\sum_{i=1}^S A_i \cdot Vb_i},$$

$$ts_{eq} = \frac{\sum_{i=1}^S ts_i \cdot A_i \cdot Vb_i}{\sum_{i=1}^S A_i \cdot Vb_i}, \tag{17}$$

$$\rho_{eq} = \frac{\sum_{i=1}^S \rho_i \cdot A_i \cdot Vb_i}{\sum_{i=1}^S A_i \cdot Vb_i},$$

$$\sigma_{eq} = \frac{\sum_{i=1}^S \sigma_i \cdot A_i \cdot Vb_i}{\sum_{i=1}^S A_i \cdot Vb_i},$$

$$\left(\frac{Eb}{No}\right)_{eq} = \frac{\sum_{i=1}^S (Eb/No)_i \cdot A_i \cdot Vb_i}{\sum_{i=1}^S A_i \cdot Vb_i}.$$

Considering this new artificial service, the reduced method calculates a corresponding value of the cell radius, $R_{Reduced}$, assigning the whole load factor, η, to the artificial service. From the obtained $R_{Reduced}$, the load factors for each individual service, $L_{Reduced\_i}$, can be calculated inverting the cell radius calculation process shown in Section 2, see [18, 21] which is summarized as follows. From the $R_{Reduced}$, it is possible to calculate the maximum number of users of each service i per sector, and hence the total traffic offered to the system. Using the Erlang formula, with the blocking probability, Pb_i, the number of active connections, Nac_i, of each service i is obtained. Finally the value $L_{Reduced\_i}$ is calculated by means of the individual load factor of the service, L_i, times the number of active connections, Nac_i.

The total load factors of each service are obtained by simple reduction to the whole load factor, η,

$$L_{Total\_i} = \frac{L_{Reduced\_i}}{\sum_{i=1}^S L_{Reduced\_i}} \cdot \eta. \tag{18}$$

Considering these values of the load factors, a new solution of the cell radius for each individual service is calculated following the process in Section 2, obtaining the solution vector, which minimum value is the cell radius.

3.3. Combined Heuristic.

The third heuristic we consider is to find the hybridization of the two algorithms previously described. The reduced algorithm, which does not require an initialization of the load factors, is used for calculating the starting point for the Iterative load factor redistribution heuristic. Thus, it is expected a better performance of the iterative heuristic since it starts from a better initial solution.

TABLE 1: Radio propagation parameters.

Node B parameters		Mobile terminal parameters	
Height B (m)	50	Height (m)	1.75
Power (W)	10	Power (W)	0.25
Antenna gain (dB)	10	Antenna gain (dB)	0
Cable loss (dB)	3	Skin loss)	3
Noise figure (dB)	5	Noise figure (dB)	7
Frequency (MHz)	1950	Frequency (MHz)	2140
Common parameters			
Log normal fading margin (dB)	7.3	Fast fading margin (dB)	2
UL intercell interference ratio	0.88	Soft handover gain	3
DL intercell interference ratio	0.88	Interference margin (dB)	6.02
Sectors	1		

TABLE 2: Service parameters.

P	S_1	S_2	S_3	S_4	S_5	S_6
Voice/data	Voice			Data		
Vb	12.2	12.2	64	64	144	384
Us	0	3	0	3	0	0
$\left(\dfrac{Eb}{N_0}\right)_{\mathrm{DL}}$	4.4	7.0	2.5	5.3	2.3	2.4
$\overline{\phi}$	0.5	0.5	0.5	0.5	0.5	0.5
Pb	0.01	0.01	0.05	0.05	0.05	0.05
σ	0.67	1	1	1	1	1

4. Computational Experiments and Results

In order to validate the heuristics presented in this paper, we have tested them in several experiments based on scenarios with different service combinations. Specifically, we have defined mixtures of two, three and four services, each one having its own requirements in terms of binary rate, quality of service, user movement speed and user density in the area under study. Furthermore we have modified the traffic figures of the services to consider balanced and unbalanced traffic. Balanced traffic means that the individual throughput of each service is similar to the throughput of the other services.

We have used an interference margin of 6 dB which means a cell load factor of 0.75. We have also configured the radio propagation parameters to make the capacity the most restrictive criteria. This set of radio propagation parameters is shown in Table 1.

The parameters P of the different services S_i are shown in Table 2, with Vb being the binary rate, Us the user speed in Km/h (services in which users have different speeds can be considered as different services. This is because they have different values of Eb/N_0 and therefore different values of individual load factor L_i), $(Eb/N_0)_{\mathrm{DL}}$ the bit energy-to-noise ratio in the downlink, $\overline{\phi}$ the orthogonality factor and σ the activity factor. The quality of service is defined by the Blocking/Loss probability Pb. The value of the total downlink load factor, η, is 0.75 according to the M_i previously defined.

TABLE 3: Traffic figures for balanced traffic experiments.

P	S_1	S_2	S_3	S_4	S_5	S_6
α	1	1	1	1	1	1
ts	180	180	240	240	360	500
ρ	300	84	147	45	90	46

TABLE 4: Traffic figures for unbalanced traffic experiments.

	S_1	S_2	S_3	S_4	S_5	S_6
α	1	1	1	1	1	1
ts	162	162	23.4	23.4	7.92	7.92
ρ	1008	335	80	26	70	35

Finally, the value of the average intercell interference factor $\overline{f}$ to 0.88 [29].

As we have mentioned before the complete set of scenarios are divided into balanced and unbalanced traffic scenarios. Tables 3 and 4 provides the traffic figures for the different services in these two general categories. In this case α and ts are the call attempt rate and the service time in the business hour, respectively, and ρ is the user density in the considered area. Table 5 shows the combination of the services involved in each experiment. Note that the third column in the table shows if the experiment is based on balanced (B) or unbalanced (U) traffic.
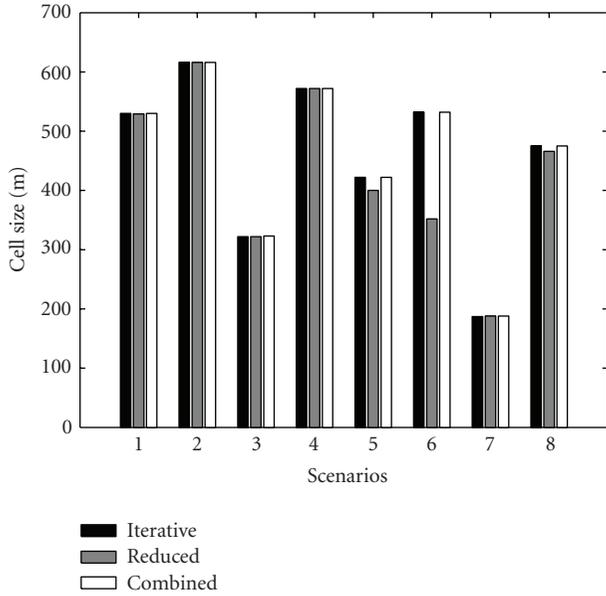
FIGURE 5: Comparison of the cell radius obtained by the different heuristics considered in all scenarios.

TABLE 5: Experiments definition.

Scenario	Services	Traffic
Exp-1	S_1, S_3	B.
Exp-2	S_1, S_3	U.
Exp-3	S_1, S_3, S_5	B.
Exp-4	S_1, S_3, S_5	U.
Exp-5	S_1, S_2, S_3, S_4	B.
Exp-6	S_1, S_2, S_3, S_4	U.
Exp-7	S_1, S_3, S_5, S_6	B.
Exp-8	S_1, S_3, S_5, S_6	U.

The results of the different experiments are shown in Table 6 and Figure 5. For the iterative and combined algorithms, Table 6 also shows the number of iterations. The reduced algorithm obtains the optimal value of the cell radius in all experiments, excluding those scenarios in which users are moving at different speeds. This low performance of the reduced algorithm is due to the fact that the differences in the individual load factors of a service with different user speeds are very small. Therefore the algorithm is not able to distinguish between them.

As it was mentioned in Section 2, the optimum value of the cell radius is obtained when there are quite small differences in the cell radius of the different services. We will illustrate this in Experiment 3. In this experiment, we have compared the results obtained by the three heuristics proposed against the cell radius calculated with an assignment done using the binary rate and the user density, let us name it *free assignment* (FA) following the equation

$$L_{\text{Total}\_i} = \frac{Vb_i \cdot \rho_i}{\sum_{i=1}^{S} Vb_i \cdot \rho_i}.$$ (19)
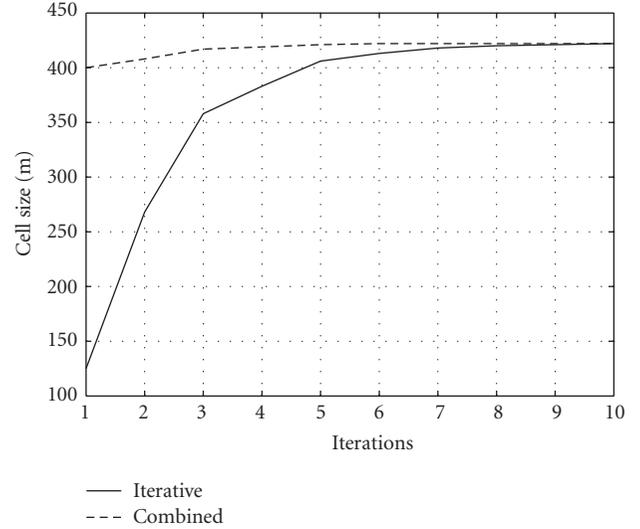
FIGURE 6: Number of iterations to convergence for the iterative and combined heuristics (experiment Exp-5).

The initial values of the load factors L_{Total_i} are $L_{\text{Total}\_1} = 0.105$ for the service S_1, voice, $L_{\text{Total}\_i} = 0.271$ for S_2, data 64 Kbps and $L_{\text{Total}\_i} = 0.373$ for S_3, data 144 Kbps. The results for the downlink cell radius per traffic are shown in Table 7.

Note that the cell radius of each service is quite similar in the three proposed heuristics but in the FA the cell radius of the S_1 is almost 50% larger than S_3.

Another interesting point to observe is the final occupancy level of the load factor. In case of an optimal allocation, the sum of the individual load factors, allocated to the services after the cell radius is calculated has to tend to the limit established in the design, in our experiments $\eta = 0.75$. The results are shown in Table 8. Note that the proposed heuristics use more than 99% of the total available capacity, while the FA only uses 62%.

Finally note that the combined algorithm always obtains the optimal value even in scenarios with different users speeds, and it requires fewer number of iterations than the iterative algorithm. Figure 6 shows a comparison of the number of iterations needed to obtain the optimum cell radius in problem Exp-5. Note that the combined heuristic obtains the optimum cell radius faster than the iterative algorithm, since it starts from the result obtained by the Reduced heuristic.

Finally, regarding the computation time, the three algorithms we propose in this paper for the cell radius determination problem obtain the solution to the problem in less than 1 second. This is a very important point for the inclusion these algorithms in a strategic network planning tool, where a large number of scenarios have to be calculated.

4.1. Validation and Limitations of the Proposed Heuristics. In order to validate our heuristics we have compared the combined algorithm (the one that yields better results in

TABLE 6: Cell radius (in metres) for each experiment calculated using the proposed heuristics.

Experiment	Iterative	Reduced	Combined
	Radius (m)/Iters	Radius (m)	Radius (m)/Iters
Exp-1	530/4	529	530/2
Exp-2	616/7	616	616/1
Exp-3	322/6	322	323/2
Exp-4	572/9	572	572/2
Exp-5	422/10	400	422/6
Exp-6	532/13	352	532/13
Exp-7	187/6	188	188/1
Exp-8	475/7	466	475/3

TABLE 7: Cell radius (in metres) for the different services in Experiment 3.

Experiment	S_1 (Voice)	S_3 (Data 64 Kbps)	S_5 (Data 144 Kbps)
	Radius (m)	Radius (m)	Radius (m)
Iterative	324	324	322
Reduced	322	325	322
Combined	325	324	323
FA	335	303	224

TABLE 8: Resulting load factors for the different services.

Experiment	S_1 (voice)	S_3 (data 64 Kbps)	S_5 (data 144 Kbps)	Sum
Iterative	0.074	0.222	0.448	0.744
Reduced	0.072	0.223	0.448	0.743
Combined	0.075	0.222	0.449	0.746
FA	0.047	0.137	0.280	0.464

TABLE 9: Services mixtures in [26].

Service combination	Mix 1	Mix 2	Mix 3
Voice	95	80	10
Data 64 Kbps	3	15	30
Data 144 Kbps	1.5	4	30
Data 384 Kbps	0.5	1	30
Total bandwidth (Kpbs)	557	809	1104

TABLE 10: Comparison of the resulting cell radius.

Service combination	Value in [26]	Combined heuristic
Mix 1	535	552
Mix 2	528	544
Mix 3	527	520

the previous experiments), with the results in [26, 27]. In [26] the authors study the cell radius with three different combination of services as it is shown in Table 9. In [26] the capacity study is not based on a customer basis but considering the total bandwidth offered to the cell. This means that there is no significative impact of service combination in the cell radius. This is not completely accurate, because the service combination and the customer distribution all over the cell have a major relevance in the cell radius. However, the experimental frame given in [26] can be useful for benchmarking purposes. Thus, in order to apply our combine heuristic to the problems in [26] we have used the configuration parameters as the ones given in [26], specifically, the interference margin (M_i) has been fixed to 4.31 dB.

The comparison results are shown in Table 10. Note that in service combination Mix 1 and Mix 2 the combined heuristic outperforms the result obtained in [26]. In the service combination Mix 3 the cell radius calculated by our proposal is slightly lower. The reason for this is that, as we mentioned in the previous paragraph, the authors in [26] only use the total bandwidth required from the cell and do not consider each individual connection. This makes that the influence of the services mixture is quite low in their results. However, note that in the formulation of this paper, we do consider each service individually, and therefore, the influence of service mixture is much important in our heuristic, which reflects better the real behavior of a WCDMA system.

In order to carry out a second comparison, we have used the evolutive algorithm developed in [27]. Evolutionary programming is a population based heuristic, which was first proposed as an approach to artificial intelligence [30]. It

TABLE 11: Result comparison between the combined algorithm and the EAP in [27].

Experiment	EA in [27]	Combined
	Radius (m)	Radius (m)
Exp-1	530	530
Exp-2	616	616
Exp-3	322	323
Exp-4	573	572
Exp-5	425	422
Exp-6	505	532
Exp-7	183	188
Exp-8	475	475

has been successfully applied to a large number of numerical optimization problems including telecommunications problems [31]. In this case we have used the same set of experiments as in Section 4, comparing the performance of the evolutionary algorithm (EA) in [27] against the combined algorithm proposed in this paper. The results are shown in Table 11. Note that the differences between the results of the combined algorithm and the evolutionary algorithm are quite small (about 1%) in all experiments but in the Exp-7, where the combined algorithm proposed obtains a result about 5% better. In this case the EA falls into a local solution near the optimum solution.

As final remarks for this section, note that the main limitation of the proposed heuristics in this paper is that they consider trunk reservation for the capacity assignment. This means that the capacity allocated to service i is reserved for this service exclusively, and no other can use it, even when there is some free capacity. In the practical operation of the UMTS system, the capacity is available for all services and only when the system goes to a heavy loaded situation, the capacity reservation will be activated. This also means that, in practice, the cell radius will be slightly larger than the one calculated with the proposed algorithms. However, since the algorithms provide a conservative estimation, they are valid to estimate the maximum network investment.

5. Implementation, Application, and Real Cases

5.1. Implementation and Application. The proposed algorithms are implemented in a software tool for the strategic design of hybrid 2G and 3G networks. An earlier version software tool named DIDERO, was originally presented in [32].

Using this tool we present a study carried out for Spain. The objective of this study is to compare the differences in the number of Node Bs and in the total network investment cost using different allocations of the load factors to the services. We will use the combined heuristic presented before and three different assignments (A_1, A_2, A_3) for comparison purposes, based on the binary rate, user density and the traffic, that are the assignments done by a common network planner.

The A_1 assignment is done considering the binary rate of the service, that is, a service with higher binary rate gets more capacity following the equation

$$L_{\text{Total}\_i} = \frac{Vb_i}{\sum_{i=1}^{S} Vb_i}. \tag{20}$$

The assignment A_2 takes into account also the user density:

$$L_{\text{Total}\_i} = \frac{Vb_i \cdot \rho_i}{\sum_{i=1}^{S} Vb_i \cdot \rho_i}. \tag{21}$$

Finally the third assignment A_3 considers also the individual traffic

$$L_{\text{Total}\_i} = \frac{Vb_i \cdot \rho_i \cdot a_i}{\sum_{i=1}^{S} Vb_i \cdot \rho_i \cdot a_i}. \tag{22}$$

The scenario is composed of the 50 most important counties in Spain, which corresponds to the capitals of the 50 Spanish provinces. We are considering the main cities and the surrounding towns under their administrative influence. The cities, their extension and the number of inhabitants are shown in Table 12.

For this study we have selected the (Exp-3), Experiment 3 with the same propagation parameters exposed in Section 4. The values of the market share of the operators, the holding time ts and the call attempt rate α for the different services are shown in Table 13.

With these premises, the values of the load factors calculated from A_1, A_2, and A_3 are shown in Table 14, note that the combined heuristic does not require an initial assignment. The results of the complete Node B deployment for all experiments are shown in Table 15. Note that even for an assignment where several parameters are considered, A_3, the resulting number of Node Bs is almost 35% higher than using the combined heuristic proposed.

The total population of the cities in the considered scenario is 15 258 049. Current Spanish population is 45.12 million (official data of Spanish National Statistic Service), therefore we can extrapolate our results to obtain a fair estimation of the number of Node Bs for the whole country. Considering that the unit investment cost of a Node B rounds 135000 euros (€), and that the investment in the cell deployment is about 60%, [33] of the total network investment in a mobile network we can estimate the total network investment for the four cases presented. These results are shown in Table 16.

The most impact result is the big difference in the total investment in the different cases. Comparing with the second best, that is, with the scenario A3, the difference is about 547 million (€). This is equivalent to the 0.05% of the total Spanish Gross Domestic Product which is 1.12 billion of euros. This result shows the relevance for the network operator of an accurate network planning.

TABLE 12: Set of 50 cities considered in the scenario.

City	Area Km^2	Inhabitants	City	Area Km^2	Inhabitants
Vitoria	277	235 622	Logroño	80	147498
Albacete	1126	171 450	Lugo	9856	99571
Alicante	201	333 250	Madrid	607	3294932
Almeria	296	189 669	Malaga	395	584158
Avila	232	55 433	Murcia	882	446483
Badajoz	1470	152 549	Pamplona	24	203111
Palma de M.	213	388 512	Ourense	85	108421
Barcelona	91	165 2876	Oviedo	187	233453
Burgos	108	175 894	Palencia	95	82195
Caceres	1768	95 834	Palmas de G.C.	101	376116
Cadiz	12	137 138	Pontevedra	117	80441
Castellón	108	181 181	Salamanca	39	163641
Ciudad Real	285	78 642	S.C. Tenerife	151	223406
Cordoba	1252	330 410	Santander	35	184435
Coruna	37	252 542	Segovia	164	57349
Cuenca	954	54 917	Sevilla	141	739016
Girona	39	99 561	Soria	272	38778
Granada	88	249 530	Tarragona	62	144006
Guadalajara	36	76 249	Teruel	438	35253
San Sebastian	61	190 099	Toledo	232	83811
Huelva	149	153 699	Valencia	135	819969
Huesca	15	50 704	Valladolid	198	324334
Jaén	424	125 212	Bilbao	41	355064
León	402	136 845	Zamora	11	65025
Lleida	212	131 985	Zaragoza	1059	667781

TABLE 13: Values for spanish scenario.

	S_1	S_3	S_5
Vb	12.2	64	144
α	0.2	0.5	1
ts	180	240	360
$MarketShare\%$	25	2	1.5

TABLE 14: Load factors in the assignments.

	A_1	A_2	A_3
$S1$	0.04	0.39	0.09
$S3$	0.22	0.14	0.11
$S5$	0.49	0.23	0.55
Total	0.75	0.75	0.75

5.2. Real Cases. The combined heuristic presented here has been applied in three regulatory processes with National Regulatory Authorities for the study of the mobile termination charges and comparisons between 2G and 3G network deployments. Specifically it has been applied by a work team with the University of Cantabria and the German consulting firm WIK Consult in the following countries.

(1) Peru, with the N.R.A, with the N.R.A. *Organismo Supervisor de Inversión Privada en Telecomunicaciones,* (OSIPTEL), [34].

(2) Australia, with the N.R.A. *Australian Competition and Consumer Commission*, (ACCC), [33].

(3) Switzerland, with the N.R.A. *Bundesamt fr Kommunikation*, (BAKOM).

6. Conclusions

This paper proposes three different algorithms for the calculation of the cell radius under traffic criteria in multiservices scenarios, named iterative, reduced and combined. We have shown that the three algorithms are able to solve the cell radius determination problem, providing good quality solutions. However, the reduced algorithm is not able to produce optimal solutions when the users are moving at different speeds. The iterative and combined heuristics provides the optimal solution in all the cases studied, but the combined approach converges faster than the iterative heuristic.

The combined heuristic has been implemented in existing strategic planning software tool to calculate the Node B deployment in a whole country. We have presented a work scenario in Spain were our proposed heuristic obtains better

TABLE 15: Resulting number of Node B's.

City	Combined	A_1	A_2	A_3	City	Combined	A_1	A_2	A_3
Vitoria	44	108	72	44	Logroño	23	72	44	44
Albacete	23	72	73	45	Lugo	107	107	107	107
Alicante	44	150	107	73	Madrid	394	973	557	557
Almeria	23	72	72	44	Malaga	72	200	107	107
Avila	9	23	23	24	Murcia	73	150	72	72
Badajoz	23	72	44	45	Pamplona	44	72	44	44
Palma de M.	44	200	107	72	Ourense	23	44	23	23
Barcelona	257	973	557	321	Oviedo	45	72	44	44
Burgos	23	72	72	44	Palencia	24	45	23	23
Caceres	24	44	45	23	Palmas de G.C.	72	107	72	72
Cadiz	23	150	150	44	Pontevedra	24	46	23	23
Castellón	23	72	72	44	Salamanca	23	72	44	44
Ciudad Real	24	44	23	23	S.C. Tenerife	45	72	44	44
Cordoba	44	150	107	73	Santander	23	77	44	44
Coruna	44	150	107	72	Segovia	9	23	24	24
Cuenca	9	23	23	24	Sevilla	109	200	150	150
Girona	23	44	44	23	Soria	9	24	9	9
Granada	44	107	107	44	Tarragona	23	44	45	45
Guadalajara	23	44	23	23	Teruel	9	24	9	9
San Sebastian	45	107	72	44	Toledo	24	45	23	23
Huelva	23	72	44	45	Valencia	107	257	150	150
Huesca	9	44	23	23	Valladolid	44	107	73	73
Jaén	23	73	44	23	Bilbao	72	107	72	72
León	23	73	44	23	Zamora	9	44	23	23
Lleida	23	72	44	23	Zaragoza	72	200	107	107

Total number of Node Bs			
Combined	A_1	A_2	A_3
2396	7297	5283	3219

TABLE 16: Load factors in the assignments.

	Combined heuristic	A_1	A_2	A_3
Total number of Node Bs	2396	7297	5283	3219
Node Bs, whole country	7085	21578	15623	9519
Node Bs investment M€	956.51	2913.05	2109.03	1285.06
Total network investment M€	1594.18	4855.08	3515.06	2141.77
Difference	0	3260.89	1920.87	547.58
Node B				

solutions in terms of number of Node Bs, which represents a great investment cost saving. This heuristic has been applied in several regulatory processes under the supervision of the corresponding National Regulatory Authority.

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