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THE EFFECTS OF CONTROL NODE DENSITY IN CELLULAR NETWORK PLANNING USING THE COMBINATION ALGORITHM FOR TOTAL OPTIMISATION (CAT)

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ABSTRACT – The Combination Algorithm for Total Optimisation (CAT) solves the problem of optimised base-station location and density for different cellular configurations and environments. The algorithm relies on two main user supplied databases for its operation. The first is an over specified list of possible base-station locations and the second is a database of control nodes. Coverage is defined by a distribution of control nodes in the area of study. The control nodes represent the operator's capacity and coverage requirements at those points. This paper discusses the importance of control node distribution and density. A new approach based on introducing different classes of control node is proposed to improve the efficiency of the CAT algorithm. Results indicate that 400 control nodes per km^2 are required to ensure satisfactory operation. Introducing control node prioritisation is also shown to improve the quality and interpretation of the final solution.

I. INTRODUCTION

Planning tools are continuously being improved to meet the demands of cellular networks. However, as cellular systems evolve and upgrade to support new services and requirements, a planning tool revolution is required. The realisation of third generation network benefits will heavily depend on the flexibility and capabilities of next generation planning tools.

A planning tool is required to minimise the infrastructure costs and planning complexity of a cellular network [1]. Of special economic interest is the minimisation of the infrastructure cost per subscriber, while maximising the Quality of Service (QoS). An optimisation tool that can automatically solve the problem of resource dimensioning and base-station location is of great appeal. Many authors have investigated the application of various algorithms to solve this problem [2,3,4]. At the University of Bristol, work has concentrated on the development of a new algorithm, known as the CAT, which relies on the ideas of exhaustive search and combination theory [5]. In this paper, attention is given to the development of new features within the CAT algorithm that provide greater flexibility and enhance its capability to efficiency solve the base-station location and resource allocation problem.

The CAT algorithm relies on the use of two external modules (coverage and capacity) to provide the necessary information for its operation. The propagation module is currently based on a powerful three-dimensional ray-tracing model, previously developed at the University of Bristol. The capacity module uses an Erlang-B assumption and has been enhanced to support inhomogeneous traffic distributions.

II. PROBLEM DESCRIPTION

This section discusses the properties of the CAT algorithm and the assumptions made to automatically solve the base-station location problem.

The planning area is described by a universal set, U, that contains all points in the area. The points can take the form of control nodes or base-stations and are defined in equation 1.

$$U = \{CN_{c,n}, BS_{b,s}\} \quad (1)$$

A number of discrete user supplied points or *control nodes* are used to represent the capacity and coverage requirements in this area. This set is mathematically denoted by $CN_{c,n}$ and is defined in equation 2, where c represents the location of each control node (x, y) and n the total number of such nodes.

$$CN_{c,n} = \{c_i : i = 1 : n, c_i \in U\} \quad (2)$$

The number and location of all possible base-stations are user supplied and represented by the $BS_{b,s}$ set. $BS_{b,s}$ represents an over specified set of base-station locations and is defined in equation 3, where b represents their location (x, y) and s the total number in the study area.

$$BS_{b,s} = \{b_j : j = 1 : s, b_j \in U\} \quad (3)$$

The specification for user supplied base-station locations is used as a matter of practicality, due to the fact that network operators cannot deploy base-stations in arbitrary locations, such as protected buildings, difficult geographical locations and so on. The use of fixed base-station locations avoids this problem and assures a sensible solution based on locations where planning permission can, or has been, obtained.

The two elements described above, base-stations and control nodes, provide the basis for the problem definition. Given a set of control nodes and base-

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stations, the optimisation algorithm must deploy a *minimum* number of base-stations to satisfy the operator's requirements (which are defined in U in the form of control nodes). Every control node defined in the $CN_{c,n}$ set has to meet the planning requirements, R_n defined by the user in equation 4.

$$R_n = \{P_{\min}, \tau_{\max}, C_{\min}\} \qquad (4)$$

Where P_{min} represents the minimum power (dBm) target for each control node, τ_{max} indicates the maximum rms delay spread (ns) that the deployed system can tolerate and C_{min} represents the minimum capacity requirement in the area. The user can define one, two or all three parameters described in equation 4, and consequently the solution obtained will vary. More information on these different parameters is given in sections IV and V of this paper.

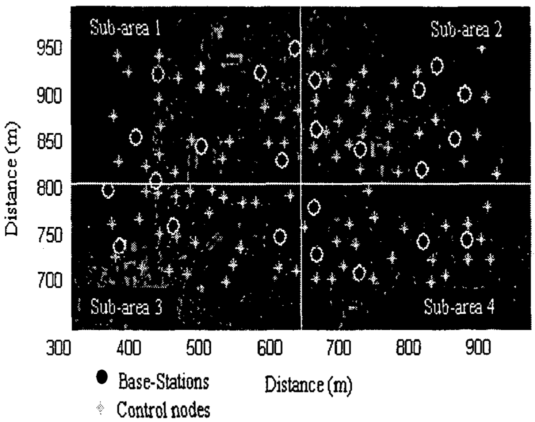


Figure1. Typical microcell scenario

Figure 1 shows a typical area, U, in which a number of control nodes have been evenly distributed in areas that need to satisfy certain capacity and coverage constrains. Likewise, a number of base-stations have been located where planning permission and or agreements have been made. The fine white lines represent the limits of the different sub-areas.

III. THE CAT ALGORITHM

In this paper the CAT algorithm was selected from a number of optimisation algorithms [5] to solve the base-station location and loading problem described in section II. The algorithm is based on a combinatorial approach. The basic idea relies on analysing all possible base-station combinations in the $BS_{b,s}$ set. The optimum combination is the smallest sub-set that meets the target coverage and capacity demands. The fundamental theory of the CAT algorithm is based on equation 5.

$$sC_r = \sum_{r=1}^{r=s} \frac{{}_sP_r}{r!} = \sum_{r=1}^{r=s} \frac{s!}{(s-r)!r!} = \binom{s}{r} \qquad (5)$$

Where s denotes the total number of base-stations in the $BS_{b,s}$ set, r the number of elements taken without repetition, ${}_sP_r$ the number of permutations given s base-station taken r at a time, and ${}_sC_r$, the number of combinations given s base-stations taken r at a time.

An exhaustive search of all combinations arising from equation 5 leads to an optimum solution, however the computation time grows exponentially with the number of possible base-stations. For this reason equation 5 becomes impractical. To overcome this problem the CAT algorithm uses complex selection and merging processes to reduce the computation time and enable the calculation of a minimum solution [5].

The CAT algorithm finds a minimum base-station sub-set, BSM, from the over specified set $BS_{b,s}$ (as denoted by equation 6). This subset must contain all the elements of $CN_{c,n}$ and must fulfil the target requirements defined in equation 4.

$$BSM \subset BS_{b,s} \qquad (6)$$

IV. THE PROPAGATION MODULE

A powerful three-dimensional propagation model is used to provide data to the coverage module. This new model can predict propagation in macrocells using radar cross-section modelling and microcells, using classical vector based ray tracing [6]. Coverage and interference effects can be modelled using these propagation models.

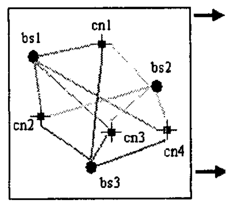
In the studies presented in this paper, emphasis is placed on a microcellular scenario, where the need to efficiently deploy a large number of base-stations is at its highest. The ray-tracing model operates using three-dimensional vector mathematics and factors such as polarisation and angle of arrival are fully incorporated. The model predicts power, time dispersion, coherence bandwidth and spatial multipath [6].

The CAT algorithm achieves an optimum solution via interaction with the coverage module, which is used to analyse the links between potential base-stations and control nodes. Initially coverage information based solely on power was introduced into the CAT algorithm.

The search for a minimum group of base-stations to cover all the control nodes is a difficult task. The received power at the control nodes varies enormously depending on the location of selected base-stations and controls nodes. Two closely spaced control nodes served by the same base-station can have very different power levels depending on building structures and terrain variations.

A second parameter has now been added to the coverage module in the form of rms delay spread, τ_{max}. The ray tracing model predicts point to point values for the rms delay spread. So consequently every control node has assigned to it a value of rms delay spread that will vary accordingly to the serving base-station.

The CAT algorithm interacts with the coverage module to analyse the links between potential base-stations and control nodes. Using this information, it is possible to obtain two different matrices, one for power and one for rms delay spread, as shown in figure 2. The power of every control node i for every base-station j serving the area is mathematically represented by P_{ij}. The rms delay spread in every control node i for every base-station j is defined as τ_{ij}. The final group of selected base-stations must ideally meet the P_{min} and τ_{max} targets at every control node.



Links between potential base-stations and control nodes

	cn1	cn2	cn3	cn4
bs1	P_{11}	P_{12}	P_{13}	P_{14}
bs2	P_{21}	P_{22}	P_{23}	P_{24}
bs3	P_{31}	P_{32}	P_{33}	P_{34}

Power Matrix

	cn1	cn2	cn3	cn4
bs1	τ_{11}	τ_{12}	τ_{13}	τ_{14}
bs2	τ_{21}	τ_{22}	τ_{23}	τ_{24}
bs3	τ_{31}	τ_{32}	τ_{33}	τ_{34}

Delay Spread Matrix

Figure2 Power and rms delay spread matrix for every control node and base-station in U

Information based on power and rms delay spread is introduced into the CAT algorithm database, and the relevant calculations are performed to find the optimum group of base-stations that meet the target requirements. Coverage requirements can be based on power, rms delay spread or a combination of the two. As will be seen in later sections, capacity requirements can also be introduced into the optimisation process.

V. THE CAPACITY MODULE

The CAT algorithm interacts with a capacity module to calculate the traffic distribution and load for each cell. The capacity model considers an inhomogeneous traffic distribution throughout the planning area. The traffic density in an area is commonly defined on a two-dimensional area grid (in Erlangs per square km.). This information is user-provided to the CAT algorithm and can be determined either through network measurements or via statistical methods [7].

In real networks the traffic distribution throughout the planning area is inhomogeneous, however, certain characteristics are shared within small distances or grid areas. Based on this traffic information, areas with different traffic distributions are identified and included in the model.

For every sub-area (see section II) a specific number of Erlangs is defined. The traffic demand for a particular control node is derived as the linear portion of the total traffic in the sub-area (i.e. the sub-area traffic divided by the number of control nodes in that area). After applying this calculation every control node will have a traffic value Cc_i, associated to it. The sum of all the individual control node traffic demands in an area will give the total traffic demand for that sub-area.

The number of base-stations necessary in each sub-area depends on the capacity target levels, C_{min}. To calculate this value a suitable QoS must be defined. The blocking probabilities for handover and initial call access can be used to describe the corresponding QoS [8].

The CAT algorithm currently makes use of the Erlang-B formula. The Erlang-B formula, E_B, relates the average channel occupancy (in Erlangs), Te, the number of channels, N, (an integer) and the blocking probability, B, under the assumption that the instants of call establishments and the duration of calls follow Poison processes [8]. That is:

$$E_B(Te, N) = B \qquad (7)$$

The traffic in the different sub-areas and the desired blocking probability are passed to the CAT algorithm. With this information, and by making use of the Erlang-B formula, the number of channels required in each base-station and consequently the number of base-stations in each sub-area can be calculated.

VI. THE USE OF DIFFERENT TYPES OF CONTROL NODE

The operation of the CAT algorithm is highly dependent on the possible base-station and control node lists. In this section the influence of the control nodes is considered in detail.

Control nodes represent coverage and capacity requirements in an area. Their location and distribution can alter the final solution offered by the CAT algorithm. Within a planning area, there may be many sub-areas each having individual target requirements (higher or lower traffic demands, mandatory coverage, areas such as a train station, or simply desirable coverage regions). The network operator must be familiar with these requirements and the location and density of control nodes should reflect this. To improve the user's ability to define target coverage, a new prioritising feature has been added to the control nodes.

To facilitate the distribution of control nodes, they have been split into three different categories depending on their level of importance (i.e. first, second and third order control nodes). Each category defines a specific type of coverage and their numbers are unlimited. The different classes of control node refer to coverage restrictions, although each control node still supports a given traffic demand (see section V).

The first order control nodes are the most important and they must be placed in locations where coverage is mandatory. The CAT algorithm will deploy sufficient base-stations and resources to meet the requirements of all first order control nodes. Second order control nodes represent locations in which coverage is highly desirable. If additional base-stations are needed to satisfy these requirements the decision to deploy is made by the user as a cost performance compromise. Third order control nodes are less important, and represent locations in which coverage is desirable, however no extra base-stations should be deployed to cover such control nodes. As mentioned previously the user is required to define the number and location of each type of control node.

The practicality of this differentiation is of particular interest in situations where 100% coverage cannot be achieved. For these particular scenarios, the algorithm searches for minimum solutions that satisfy the first order control nodes and then if possible, the second order nodes. Finally, the algorithm tries to support as many third order control nodes as possible.

The number of control nodes is not as important as their density. In the following section it is assumed that there is a critical density of control nodes below which the quality of the final solution will suffer. This minimum is then determined through experimentation.

A sensitivity study for the density of control nodes is described in section VII. In this study the importance of control node density and the improvement offered using different control node classes are shown.

VII. CASE STUDY

An area centred around the town of Malvern in the UK is shown in figure 1 and has been used in this case study. The study is focused on the effects of control node density for coverage and capacity. The use of different types of control node to avoid problems at lower control node densities is also explored. The number of possible base-stations or elements in the $BS_{b,s}$ set is made equal to 24, and the initial number of control nodes is set to 93. The density of control nodes varies between 0 and 1600 control nodes per km^2 in different areas. The location of base-stations has been set based on sites where development is practical and would be allowed. The control nodes have been distributed in areas where coverage and capacity are needed. Initially all the control nodes are considered to have the same priority (i.e. mandatory class). In the second part of this study different control node classes will be introduced to enable variable priorities.

The capacity module assumes inhomogeneous traffic distribution in the different sub-areas, however the values remain fixed throughout this study. The area is divided into four sections, each containing a unique traffic requirement. Figure 1 shows the different sub-areas. Although the shapes used here are rectangular and have similar sizes, this can be modified and the areas can adopt different sizes and shapes to satisfy more complex traffic requirements.

Table 1. Number of Erlangs per sub-area.

	Sub-area 1	Sub-area 2	Sub-area 3	Sub-area 4
Erlangs	42	125	85	40

Table 1 shows the different sub-areas contained in U and the number of Erlangs assigned to each. In the study presented here, the number of Erlangs per area is user defined. The blocking probability is set at 2%, a typical value for cellular studies. This information is now used to set the C_{min} parameters for each control node as defined in section V.

The study was performed at 1.8GHz, assuming omnidirectional antennas and a base-station transmit power of 100 mW. All control nodes were placed outdoors and configured with P_{min} set at −70 dBm (based on typical GSM assumptions for fade margins and building penetration) and τ_{max} at 400 ns (a more typical value for GSM is 4 us, however for testing purposes a more stringent value was used)

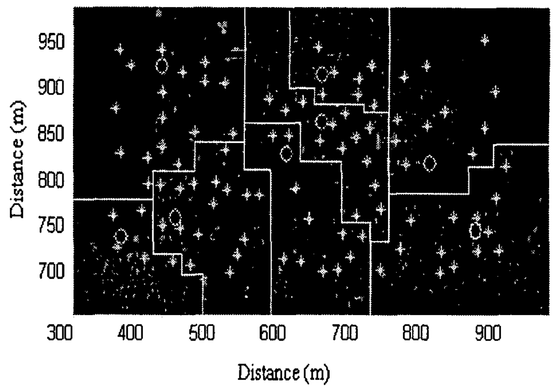


Figure 3. Solution for 100%, 90% and 80% of control nodes

For the first case the number of control nodes was set to 100% (93) and the solution obtained can be seen in figure 3. Eight base-stations were required to achieve these planning requirements. The fine white lines indicate the boundaries between cells.

For the second case the number of control nodes was reduced by 10%, 9.3 control nodes (9 were removed). The control nodes were eliminated from areas with the highest density, maintaining a minimum of 400 control nodes per km^2. The solution obtained for a 10% reduction was identical to that obtained previously with 100% of the control nodes. A 15% reduction in control nodes was performed by removing 14 control nodes. This reduction was again performed in the higher density areas (keeping a minimum of 400 control nodes per km^2). For this reduction the same solution was found. This trend continued for a 20% reduction.

However when a 30% reduction was performed (that is 28 control nodes were excluded) some control nodes were removed from areas with just 400 control nodes per km^2. The solution obtained by the CAT algorithm now contained one fewer base-station, i.e. seven. This scenario can be seen in figure 4. The fine white lines indicate the different sub-areas for traffic requirements. For this case some of the control nodes removed were now crucial to ensure a correct final solution.

This indicates that for these conditions the algorithm performs well with four hundred or more control nodes per km^2. However as the conditions change this value may need to be modified. There is obviously a limit in the density of control nodes to ensure the quality of the final solution. This limit can be calculated through experimentation. The use of different types of control node is now proposed to help ease the problem.

When using different types of control node the user must identify the areas of coverage and the priorities that must be allocated to each one. From this information, generally provided in a statistical form, the different types of control node can be deployed to satisfy the user's necessities from the earlier study. The density of the control nodes must not fall below 400 control nodes per km^2. However if any of the parameters used, particularly transmit power, vary then this value will need to be reviewed.

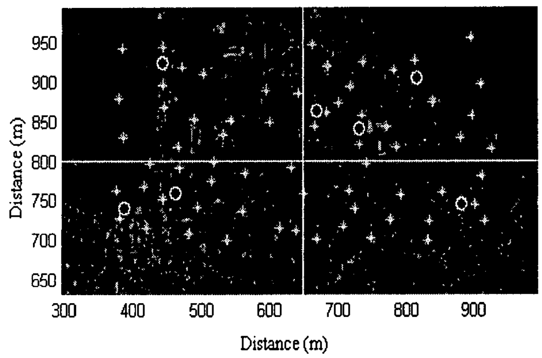


Figure 4. Solution for a 30% reduction in control node number

The interpretation of the solution is made easier when different types of control node are used. This occurs because of the definition of the different types of control node. First order control nodes are placed to guarantee coverage in the most important areas. Second order control nodes provide flexibility to the user. They can be located to observe the potential number of base-stations required and a final choice can then be made as a trade-off in coverage and cost. Finally, third order control nodes in desirable areas would tell the user whether the network would benefit from additional base-stations.

For the case presented in figure 4, for a 30% reduction, two of the original control nodes lose their coverage. If different types of control node were deployed then the viability of this solution would depend on their priorities.

(i) For first order control nodes the algorithm would not permit the solution and an extra base-station would be deployed to satisfy the conditions of these control nodes.

(ii) For second order control nodes the user would be asked to decide if another base-station should be deployed.

(iii) For third order control nodes, the final solution would remain based on seven base-stations with 100% of the first and second order control nodes covered.

Note that the distribution of the base-stations is not homogeneous and this is due to the fact that the traffic restrictions must be meet. In areas where the capacity requirements are higher, a higher number of base-stations will be needed to comply with the initial specifications. It can also be noted that for solutions containing eight base-stations there is an excess of capacity in some of the sub-areas. The capacity restrictions were kept low in this study to allow the effects of reducing control node density to be observed.

VIII. CONCLUSIONS

The density of control nodes has been considered and the effect on the final solution obtained by the CAT algorithm shown to be substantial. A minimum limit regarding the number of control nodes per km^2 was established through experimentation, but this limit (400 control nodes per km^2) is expected to vary depending on other parameters such as transmit power. A new concept based on assigning different priorities to each control node has been introduced. The different classes of control node help the user to locate control nodes in a more rational manner. It allows decisions to be made based on cost-performance trade-offs in the network.

It was determined that the number of control nodes is not as important as their density. The key aim of this paper was to ensure that important locations were assigned a suitable number of control nodes to ensure a correct final solution. Using the techniques and rules developed in this paper, automatic cellular planning and optimisation has been shown to be a practical proposition.

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X. REFERENCES

[1] W.C.Y Lee, "Mobile Cellular Telecommunication Systems," McGraw-Hill, 1989.

[2] S.F. Fortune, D.M. Gay, B.W. Kernighan, O. Landron, R.A. Valenzuela, M.H. Wright, "WISE Design of Indoors Wireless Systems: Practical Computation and Optimisation," IEEE Computational Science & Engineering, Spring'95.

[3] W.J. Cook, W.H. Cunningham, W.R. Pulleyblank, A. Schrijver, "Combinatorial Optimisation," John Wiley & Sons, inc.

[4] P. Reninger, S. Iksal, A. Caminada, J.J. Korezak, "Multi-stage Optimisation for Mobile Radio Network Planning," IEEE 49th Vehicular Technology Conference, May 1999.

[5] A. Molina, G.E. Athanasiadou, A. Nix, "The Automatic Location of Base-Stations for Optimised Cellular Coverage: A New Combinatorial Approach," IEEE 49th Vehicular Technology Conference, Vol. 1, pp. 606-610. May 1999.

[6] G.E.Athanasiadou, E.K. Tameh, A.R.Nix, 1999 "Channel Impulse Three-dimensional Rural-Urban Simulator (CITRUS): An integrated micro-macro ray-based propagation model which employs raster and vector building databases simultaneously", IEEE PIMRC' 99, pp. 1072-1076 Japan, September 1999.

[7] A. Baier, K.Bamdelow, "Traffic engineering and realistic network capacity in cellular radio networks with inhomogeneous traffic distributions", IEEE 47th Vehicular Technology Conference, Vol. 2, pp 780-784, May 1997.

[8] M.Mouly, M.B. Paulet, "The GSM Systems Mobile Communications". Ed. Cell & Sys.