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Heuristics for the Access Network Design Problem in UMTS Mobile Communication Networks

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■ Abstract ■

In this paper we study the access network design problem in Universal Mobile Telecommunication Systems (UMTS) networks. Given the location of radio base stations (node-Bs), their traffic demands, and the candidate facility centers for locating radio network controllers (RNCs), the problem is to determine the configuration of access network, including the number and location of facility centers, the number of RNCs in each facility center, and the links between RNCs and node-Bs, with the objective being to design such a network at the minimum cost. We provide a mathematical formulation of the problem with constraints on RNC and node-B capacities, along with a lower bounding method. We develop a heuristic algorithm with two different initial solution methods designed to strengthen the solution quality. The computational efficacy of their procedures is then demonstrated on a number of test problems.

Keywords : Access Network Design, Mathematical Programming, UMTS Networks

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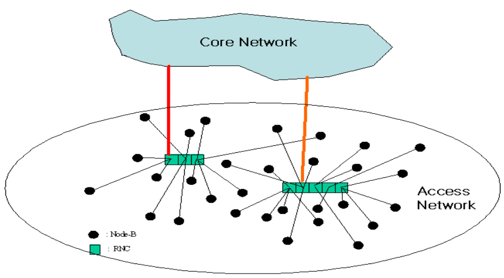
1. Introduction

During the last decade, the mobile telecommunications industry has experienced a significant growth in subscribers and technologies. The third-generation (3G) wireless networks, such as UMTS (Universal Mobile Telecommunication System), are expected to support a wide range of services, including voice, data, and multimedia services. The UMTS network can be generally divided into two main sub-networks : the core network and the access network. The scope of this paper will be restricted to the design problem of the access network.

The main purpose of the access network is to provide a connection between the handset and the core network and to isolate all the issues associated with the radio network from the core network. The access network consists of two types of nodes : radio base stations (node-B) and radio network controllers (RNC). The node-B handles the radio transmissions and the reception to/from the handset over the radio interface. The RNC is the node that manages most of the control activities and allocates system resources based on requests for services, making its role one of the most significant factors for the successful operation of 3G networks [1].



〈Figure 1〉 An outline of the UMTS network configuration

Some equipment that is used in 2G networks such as ATM switches could be put to practical use as part of the core network in 3G networks, but most of the equipment in the access networks has to be newly deployed to provide 3G multimedia services. Some reports estimate that the portion of the deployment cost of the access network in 3G networks could be as much as 50 percent for the incumbents and 40 percent for the new 3G entrants. Deploying access networks in cost-efficient way, therefore, plays a key role in getting a competitive advantage in the mobile telecommunication industry. Thus, the study of cost effective design of access networks is an important issue.

The design process of access networks can be divided into wireless and wireline parts. The main objective in the design of the wireless part is to determine the location and service coverage of node-Bs (or cells) by considering the traffic intensity and the radio propagation environment [2, 3]. In fact, due to the significant impact of the wireless part on service quality and the utilization of frequency resources, most studies in the literature have focused on this part [4, 5] (and the studies given in their references). The planning of wireline part in access networks is normally done after the planning on the wireless part has been completed [3, 6]. In this paper, we study the access network design problem focusing on the wireline parts of the network.

Given the locations of node-Bs, their traffic demands, and the candidate sites (the facility centers : FCs) for locating RNCs, the design objective is to minimize the total cost of constructing the wireline part of the access network, which includes the fixed cost of opening the FCs, the equipment cost of RNCs, and the link costs between RNCs and Node-Bs, while satisfying the constraints on the capacities of RNCs and FCs. In this paper, an FC could be any network operator's site in which the placement of the RNCs is possible, including the switching centers in which the transmission and switching equipment are located.

There are a number of factors that are usually vendor specific, which determine the capacity of a single RNC. Most common [1, 7] are the following : the amount of circuit switched (CS) traffic (measured in Erlangs), the amount of packet switched (PS) traffic (measured in bps), the number of node-Bs (or cells), the number of carriers, and so on. From the practical perspective, however, the capacity on the amount of CS and PS traffic is known to be one of the most critical factors, particularly in high traffic density areas such as metropolitan areas [7]. In this paper, we consider only the CS and the PS traffic factors for the RNC capacity. Other factors as the number or carriers can be easily incorporated into the model. We further consider only the links between RNCs and node-Bs. We do not consider the links between the RNCs (inter-RNC) in our design process.

With the attention confined to studies on the optimization problem having an objective of minimizing the cost of constructing fixed networks (wireline part of the access network and the core network) of mobile communication networks, we highlight three representative studies [8-10]. Merchant et al. [8] provided a mathematical problem dealing with constructing an optimal topology of fixed network in the first generation network whose configuration is significantly different from the one in the 3G network. Krishnamachari et al. [9] dealt with the fixed network design problem and provided meta heuristics-based solution methods such as genetic, simulated annealing, and tabu search algorithms. However, they did not consider the capacity of equipment. In [10], the authors study a similar problem; however they assume that the topology is a tree structure for the node-B and RNCs which makes the problem significantly different. The primary contribution of this paper is in the formulation of the access design problem with capacity constraints and in developing efficient solution heuristics for the problem.

The organization of the rest of the paper is as follows. In Section 2, we provide a mathematical model for the problem of designing the wireline part of the access network and a lower bounding method. This method is meaningful by itself and will also be used to demonstrate the efficacy of our heuristic. In Section 3, the heuristic solution method is introduced, along with two methods for generating an initial solution. Extensive computational results for randomly generated problems are reported in section 4. Finally, Section 5 summarizes the paper and concludes.

2. Mathematical Model and Lower Bound

2.1 Problem Description and Model

Consider a large geographical service area covered by n cells in which there are two types of traffic demands, CS and PS. Assume that a node-B serves a single cell and must be connected to a RNC by a link, and that there are two factors that determine the capacity of the RNC : CS-type and PS-type, each representing the RNCs capacity for handling CS and PS traffic, respectively. Further assume that all the RNCs have the same capacity and are placed at one of the opened FCs that can accommodate at most a finite number of RNCs.

Given the number and locations of candidate FCs and node-Bs, the access network design problem (ANDP) is then defined as one of obtaining the optimal number and location of the opened FCs, the number of RNCs in each of opened FCs, and the configuration of RNCs and node-Bs, while satisfying the constraints on RNC capacity. The objective of ANDP is to minimize the total cost that composed of three factors : the fixed cost of opening the FCs, the equipment cost of RNCs, and the link cost between RNCs and node-Bs.

We now introduce some notation what will be used in formulating the problem and in the rest of the paper.

Let

$I = \{1, 2, \cdots, m\}$: the set of node-Bs

$J = \{1, 2, \cdots, n\}$: the set of candidate FCs

R : the maximum capacity of a FC (in terms of the number of RNCs)

$K = \{1, 2, \cdots, R\}$: the index set of RNCs located at FC

E_i : CS traffic demand (Erlangs) at node-B $\forall i \in I$

B_i : PS traffic demand (bps) at node-B $\forall i \in I$

E : CS-type RNC capacity (Erlangs)

B : PS-type RNC capacity (bps)

F_j : the fixed cost of opening a FC $\forall j \in J$

C : the equipment cost of a RNC

C_{ij} : the link cost between a node-B and the RNC in the FC $\forall i \in I, \forall j \in J$

The decision variables are

$$z_j = \begin{cases} 1, \text{ if FC at loction } j \text{ is opened } \forall j \in J \\ 0, \text{ otherwise} \end{cases}$$

$$z_j = \begin{cases} 1, \text{ if the } k^{th} \text{ RNC is location FC} \\ \quad J \ \forall k \in K, \ \forall j \in J \\ 0, \text{ otherwise} \end{cases}$$

$$z_j = \begin{cases} 1, \text{ if nodt} - \text{B } i \text{ is connected to the } k^{th} \\ \quad \text{RNC located at FC} \\ \quad j \ \forall i \in I, \ \forall k \in K, \ \forall j \in J \\ 0, \text{ otherwise} \end{cases}$$

We assume that the link cost of connecting a specific node-B to the RNCs is the same if the RNCs are in the same FC, and hereafter the link cost between node-B and FC simply means the cost between the node-B and the RNCs in the FC, if no confusion arises. We now present a mathematical formulation of our access network design problem (ANDP).

$$(ANDP) \ \ minimize \ \sum_{j=1}^{n} F_j z_j + C \sum_{j=1}^{n} \sum_{k=1}^{R} y_j^k + \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{R} C_{ij} x_{ij}^k \quad (1)$$

subject to

$$y_j^k \le z_j \ \ j = 1, 2, \cdots, n, \ k = 1, 2, \cdots, R \quad (2)$$

$$\sum_{i \in I} E_i x_{ij}^k \le E y_j^k \ \ j = 1, 2, \cdots, n, \ k = 1, 2, \cdots, R \quad (3)$$

$$\sum_{i \in I} B_i x_{ij}^k \le B y_j^k \ \ j = 1, 2, \cdots, n, \ k = 1, 2, \cdots, R \quad (4)$$

$$\sum_{j=1}^{n} \sum_{k=1}^{R} x_{ij}^k = 1 \ \ i = 1, 2, \cdots, m \quad (5)$$

$$x_{ij}^k, y_j^k, z_j \in \{1, 2\} \quad (6)$$

$$i = 1, 2, \cdots, m, \ j = 1, 2, \cdots, n, \ k = 1, 2, \cdots, R$$

The objective function of Problem (ANDP) has three cost terms : the first term is the fixed cost of opening an FC; the second is the cost of installing RNCs; and the third is the cost of a link connecting a node-B to a RNC. Constraint set (2) denotes the fact that a RNC can be installed only if an FC is opened at a particular location. Constraint sets (3) and (4) ensure that the demand that is serviced by an RNC is less than or equal to its CS-type and PS-type capacities, respectively. Constraint set (5) requires that every node-B needs to be connected to a single RNC.

By letting $E_i' = E_i/E$ and $B_i' = B_i/B$, $i \in I$, the constraint sets (3) and (4) become the packing constraints of a typical bin packing problem [11]. Note that given n items, with each item consuming two kinds of resources, and bins with capacity limitations on both resources, the 2-dimensional vector packing problem (2-DVPP) is defined as one of packing all the items into a minimum number of bins [12]. If we correspond the item in the 2-DVPP with a node-B and the bin with a RNC in ANDP, the sub-problem of finding the minimum number of RNCs required to meet all the traffic demand of node-Bs can be considered as a 2-DVPP. The mathematical model for this problem with the set node-B I denoted by 2-DVPP (I) is given as :

$$(2-DVPP(I)) \quad \min \sum_{k+1}^{l} y^k \tag{9}$$

subject to

$$\sum_{i \in I} E_i' x_i^k \le y^k, \ k = 1, 2, \cdots, l \tag{10}$$

$$\sum_{i \in I} B_i' x_i^k \le y^k, \ k = 1, 2, \cdots, l \tag{11}$$

$$x_i^k, y^k \in \{0, 1\}, \ k = 1, 2, \cdots, l \tag{12}$$

where,

l is the upper bound on the number of the required RNCs.

$x_i^k = 1$ if node-B i is connected to the k^{th} RNC and $x_i^k = 0$ otherwise

$y^k = 1$ if the k^{th} RNC is established and $y^k = 0$ otherwise

Without loss of generality, in the 2-DVPP (I) we can set $l = n$ because $E_i' \le 1$ and $B_i' \le 1$. The problem 2-DVPP is known to be NP-complete and is a sub-problem of our original problem (ANDP). 2-DVPP (I) is then also NP-complete, making it difficult to obtain the optimal solution for the problem (ANDP) even for problems of reasonable sizes. For this reason, this paper will focus on developing fast heuristic algorithms for solving the problem (ANDP), instead of developing an exact solution method.

2.2 Lower bound

Let R^* be the optimal solution of problem 2-DVPP (I). That is, R^* is the minimum number of RNCs required to meet all the traffic demand. Considering the fact each FC can accommodate at the most R RNCs, and that $\lceil R^*/R \rceil$ is the minimum number of FCs to be opened, a lower bound for the problem (ANDP) can be deduced as follows :

$$LB = \sum_{j=1}^{\lceil R^*/R \rceil} F_{\phi(j)} + C \cdot R^* + \sum_{i=1}^{m} C_{i,j(1)} \tag{13}$$

where $\phi(l)$ is the l^{th} element in the ascending order of F_j, $\forall j \in J$ and $C_{i,i(1)} = \min_{j \in J}\{C_{ij}\}$.

The three terms on the right hand side of equation (13) represent the total cost of opening $\lceil R^*/R \rceil$ FCs, installing R^* RNCs, and the cost of the connecting links between node-Bs and

RNCs, respectively.

To obtain a lower bound on problem (ANDP) by equation (13), we need to know R^* which is an optimal solution of 2-DVPP (I). However, 2-DVPP (I) is known to be NP-complete [12]. We therefore, introduce R_L^*, which is a lower bound on R^* in order to get a lower bound of problem (ANDP). There are two studies on the lower bound for the problem 2-DVPP (I) that are worth noting. In [12], Spieksma provided the following lower bound :

$$R_L^* = \max\left\{ \left\lceil \sum_{i \in I} E_i' \right\rceil ,\ \left\lceil \sum_{i \in I} B_i' \right\rceil \right\} \quad (14)$$

Carprara and Toth [13] showed that the lower bound given in (14) is equal to the upper rounding of the optimal solution of the LP relaxation of 2-DVPP (I), and provides a new tighter lower bound. However, their method requires very long computational times even for problems of moderate size. We therefore adopt the bounding method provided by [12]. On substituting $\lceil R^*/R \rceil$ by $\lceil R_L^*/R \rceil$ in equation (13), we obtain the following equation which will be used as the lower bound of problem (ANDP) from this point forward.

$$LB = \sum_{j=1}^{\lceil R_L^*/R \rceil} F_{\phi(j)} + C \cdot R_L^* + \sum_{i=1}^{m} C_{i,j(1)} \quad (15)$$

The computation of R_L^* requires $O(n)$ calculations [12]. Both the ascending ordering of F_j, $\forall j \in J$ and the calculation of $\sum_{i=1}^{m} C_{i,i(1)}$ can be found with running time $O(n \log n)$. Thus, the computation of LB needs $O(n \log n)$ calculations.

3. Solution Methods

Since the problem (ANDP) is NP-complete, it is difficult to develop an exact solution method even for problems of reasonable size. The aim is therefore to develop a heuristic that generates a good approximate solution.

3.1 Initial Solution Methods

The decision variables of ANDP contain three cost factors; the number and location of opened FCs, the number of RNCs in each opened FCs, and the link configurations of RNCs and node-Bs. It is reasonable to get an initial solution by focusing on some of the three parameters. We develop two cases. The first case focuses on minimizing the link cost between the RNCs and node-Bs, which may yield a good initial solution when the link cost is much higher relative to the cost associated with the other factors. The second case is to focus on minimizing the number of the opened FCs. The methods of getting an initial solution based on the first and second cases are called *IO-td* and *IO-bu*, respectively. We introduce some notation before presenting the two initial solution methods.

J' : set of opened FCs ($J' \subseteq J$)

$R(j)$: number of RNCs installed in FC j ($\in J$)

$I_k(j)$: set of node-Bs connected to the k^{th} RNC, $k = 1, 2, \cdots, R(j)$, placed at FC j ($\in J'$)

$b_k(j)$: remaining PS-type capacity of the k^{th} RNC, $k = 1, 2, \cdots, R(j)$, placed at FC j ($\in J'$)

$e_k(j)$: remaining CS-type capacity of the k^{th} RNC, $k = 1, 2, \cdots, R(j)$, placed at FC

$j(\in J')$

$I(j)$: set of node-Bs connected to the RNCs placed at FC j $(\in J')$, i.e. $I(j)=\cup_{k=1,2,\cdots,R(j)} I_k(j)$

I' : set of node-Bs connected to a RNC, i.e., $I'=\cup_{j\in J'} I(j)$

The *IO-td* method begins with sorting the link costs of connecting the node-Bs to the candidate FCs in an ascending order. For a specific node-B, the first FC in the ordered list is selected, and the possibility of placing the node-B to the RNCs in the selected FC is examined. If the placement fails, which may because of the fact that the selected FC does not have available RNCs to accommodate an additional node-B, and there is no room for installing a new RNC, the same procedure is repeated with the FC that is next in the ordered list.

■ *IO-td* method

[Step 1] Set $J'=I'=\phi$.

[Step 2] For each $i\in I$, make a list sorted in ascending order by C_{ij}, $j\in J$, i.e.,

$$C_{i,i(1)} \leq C_{i,i(2)} \leq \cdots \leq C_{i,i(n)}, \tag{16}$$

where $i(k)$ is the FC with the k^{th} smallest link cost of connecting the node-B i to the FCs.

[Step 3] Set $i=1$.

[Step 4]

[Step 4.1] If $I'=I$, stop. Otherwise, set $l=1$.

[Step 4.2] If $i(l)=j/j'$, set $R(i(l))=1$, $J'=J'\cup\{i(l)\}$, $I_1(i(l))=\{i\}$, $I'=I'\cup\{i\}$, $b_1(i(l)=1-B_1'$, $e_1(i(l)=1-E_1'$, and go to [Step 5].

[Step 4.3] If there exists a $k(=1,2,\cdots,R(i(l)))$ such that $B_i'\leq b_k(i(l))$ and $E_i'\leq e_k(i(l))$, set $I_k(i(l))=I_k(i(l))\cup\{i\}, I'=I'\cup\{i\}, b_k(i(l))=b_k(i(l))-B_i'$, $e_k(i(l))=e_k(i(l))-E_i'$, and go to [Step 5]

[Step 4.4] If $R(i(l))<R$, set $R(i(l))=R(i(l))+1$, $I_{R(i(l))}(i(l))=I_{R(i(l))}(i(l))\cup\{i\}$, $I'=I'\cup\{i\}, b_{R(i(l))}(i(l))=1-B_i'$, $e_{R(i(l))}(i(l))=1-E_i'$, and go to [Step 4.6].

[Step 4.5] Set $l=l+1$, and go to [Step 4.2].

[Step 5] Set $I'=I'\cup\{i\}$, $i=i+1$, and go to [Step 4].

The above procedure of the *IO-td* method is similar to the so-called *First-Fit* procedure for the traditional bin packing problem which is known to be computationally efficient; however it is weak on the solution quality [14]. Note that $|J|\times R$ must be greater than or equal to R^* in order to guarantee the existence of a feasible solution. In this paper, we assume that $|J|\times R$ is sufficiently larger than R^* thus enabling the *IO-td* method to provide feasible solutions in most cases.

The next method for generating an initial solution is aimed at reducing the number of opened facility centers and can be summarized as follows.

■ *IO-bu* method

[Step 1] Set $J'=I'=\phi$.

[Step 2] Repeat the following until $I'=I$

[Step 2.1] For each $j\in J/J'$, make a list sorted in ascending order by C_{ij}, $i\in I/I'$, i.e.,

$$C_{j(1),j} \leq C_{j(2),j} \leq \cdots \leq C_{j(m'),j}, \tag{17}$$

where $m' = |I/I'|$ and where $j(k)$ is the node-B with the k^{th} smallest link cost of connecting FC j to the node-B.

[Step 2.2] Let i^* be the largest index satisfying the following :

$$\sum_{k=1}^{i^*} E'_{j(k)} \le R \text{ and } \sum_{k=1}^{i^*} B'_{j(k)} \le R. \quad (18)$$

Calculate

$$AddCost(j) = F_j + C \cdot R + \sum_{k=1}^{i^*} C_{j(k),j^*} \quad (19)$$

[Step 2.3] Let $j^* = \arg\min\{AddCost(j) : j \in J/J'\}$ and update $J' = J' \cup \{j^*\}$.

[Step 2.4] Apply the 2FFD algorithm in [12] for the problem 2-DVPP ($\{j(1), j(2), \cdots, j(i^*)\}$) and denote the resulting objective function value by $R(j)$. If $R(j) > R$ set $R(j) = R$. Update appropriately $I_k(j)$, $b_k(j)$, and $e_k(j)$ according to the solution of 2FFD.

[Step 2.5] Set $I(j) = \cup_{k=1,2,\cdots R(j)} I_k(j)$ and $I' = I' \cup (j)$.

In the above method, i^* is the maximum number of node-Bs to be connected to FC j when all of R RNCs are placed at FC j and the node-Bs are connected to the RNCs in the order $j(1), j(2), \cdots, j(i^*)$. The $AddCost(j)$ in equation (19) then indicates the potential total cost of opening FC j, placing R RNCs, and then connecting i^* node-Bs to the RNCs in the order $j(1), j(2), \cdots, j(i^*)$. A new FC ($j^*$) to open is selected on the basis of the values of $AddCost(j)$, $j \in J/J'$ ([Step 2.3]). To check whether the traffic demands of node-Bs $j(1), j(2), \cdots, j(i^*)$ would actually be accommodated with R RNCs, the problem 2-DVPP ($j(1), j(2), \cdots, j(i^*)$) is solved. Due to the NP-complete complexity of 2-DVPP a heuristic like the 2FFD algorithm, provided by Carprara and Toth [13] is used, instead of the exact solution method ([Step 2.4]).

3.2 Basic sub-modules

Before describing the entire solution heuristic, we first describe some key sub-modules of our heuristic, each of which plays a role in improving the initial solution while keeping the solution feasible.

■ *Add_node-B_to_RNC*

This is the module of assigning a node-B to the existing RNC in the most economical way without changing the configuration of other node-Bs. Given a node-B i, the following steps are performed.

[Step a] Make a list sorted in ascending order of FCs, i.e.,

$$C_{i,i(1)} \le C_{i,i(2)} \le \cdots \le C_{i,i(n)},$$
$$i(k) \in J',\ k = 1, \cdots, n.$$

[Step b] Set $l = 1$.

[Step c] Set $l = l + 1$. If $l > n$, stop.

[Step d] Find the RNC, say k, satisfying $E_i \le e_k(i(l))$ and $B_i \le b_k(i(l))$ in the order $1, 2, \cdots, R(i(l))$. If there is no such RNC, go to [Step c].

[Step e] Update the current solution in an appropriate way, i.e., set $I_k(i(l)) = I_k(i(l)) \cup \{i\}$, $b_k(i(l)) = b_k(i(l)) - B_i$, $e_k(i(l)) = e_k(i(l)) - E_i$, $I(i(l)) = I(i(l)) \cup \{i\}$, $I' - I' \cup \{i\}$. Stop.

■ *Drop_FC*

[Step a] Calculate $Cost(j)$ given in equation (20), $j \in J'$ and set $K \in J'$.

$$Cost(j) = (F_j + C \cdot R(j) + \sum_{i \in I(j)} C_{ij}) / |I(j)| \tag{20}$$

[Step b] Set $j^* = \arg\max\{Cost(j), j \in K\}$.

[Step c] Set $J' = J' - \{j^*\}$, $I' = I' - I\{j^*\}$.

[Step d] Apply sub-module *Add_node-B_to_RNC* for all $i (\in I(j^*))$. If all node-Bs in the FC j^* could be connected to the RNCs in the FCs other than j^* and the objective value of the corresponding solution becomes less than the current one, update appropriately the current solution. Otherwise, set $J' = J' \cup \{j^*\}$, $I' = I' \cup I\{j^*\}$.

[Step e] Set $K = K - \{j^*\}$. If $K = \phi$, stop. Otherwise, go to [Step b].

Note that $Cost(j)$ given in equation (20) can be interpreted as the unit cost of connecting a node-B to the RNCs placed at FC j. With this cost criterion, the sub-module ***Drop-FC*** attempts to drop the existing opened FCs in order to enhance the objective value.

■ *Move_FC*

This sub-module was devised to address the possibility of enhancing the objective value by transferring all the RNCs placed at a specific FC into another single FC.

[Step a] Let $K = \{(j_1, j_2) | Z - Z([j_1, j_2]) > 0, j_1, j_2 \in J', j_1 \neq j_2, R(j_1) + R(j_2) \leq R\}$, where Z and $Z([j_1, j_2])$ denote the objective values of the current solution and the new solution obtained by moving all the RNCs in FC j_1 into FC j_2, respectively.

[Step b] If $K = \phi$, stop.

[Step c] Let (i_1^*, j_2^*) be the (j_1, j_2) at which the maximum of $\{Z - Z([j_1, j_2]) | (j_1, j_2) \in K\}$ is attained. Update the current solution accordingly, i.e., $J' = J' - \{j_1^*\}$, $R(j_2^*) = R(j_2^*) + R(j_1^*)$, $I(j_2^*) = I(j_2^*) \cup I(j_1^*)$, $I_{R(j_1^*)+k}(j_2^*) = I_k(j_1^*)$, $e_{R(j_1^*)+k}(j_2^*) = e_k(j_1^*)$, $b_{R(j_1^*)+k}(j_2^*) = b_k(j_1^*)$, $k = 1, 2, \cdots, R(j_1^*)$.

[Step d] Set $K = K - \{(i_1^*, j_2^*)\}$ and go to [Step b].

■ *Drop_RNC*

A procedure similar to ***Drop_FC*** would be applied to drop RNCs, as shown in the following sub-module ***Drop_RNC***.

[Step a] Set $r(j) = \{1, \cdots, R(j)\}, j \in J'$

[Step b] Set

$$\kappa = \arg\max\{C + \sum_{i \in I_k(j)} C_{ij}) / I_k(j), k \in r(j), j \in J'\} \tag{21}$$

[Step c] For each of node-Bs assigned to RNC κ, apply sub-module ***Add_node-B_to_RNC*** in order to find another RNC. If all node-Bs can be moved to RNCs other than RNC κ while decreasing objective value, update solution. Set $r(j) = r(j) - \{\kappa\}$.

[Step d] If $r(j) = \phi$, $\forall j (\in J')$ stop. Otherwise go to [Step b].

The two sub-modules given below are procedures for obtaining better solutions by moving or exchanging node-Bs.

■ *Move_node-B*

[Step a] Set $\iota = \{1, 2, \cdots, n\}$.

[Step b] Let be the index of node-B at which $\max\{C_{ij}; i \in \iota, j \in J'\}$ is attained. For node-B κ, apply sub-module ***Add_node-B_to_RNC***. If this decreases the objective value, update the solution. Set $\iota = \iota - \{\kappa\}$.

[Step c] If $\iota = \phi$, stop. Otherwise go to [Step b].

■ *Exchange_node-B*

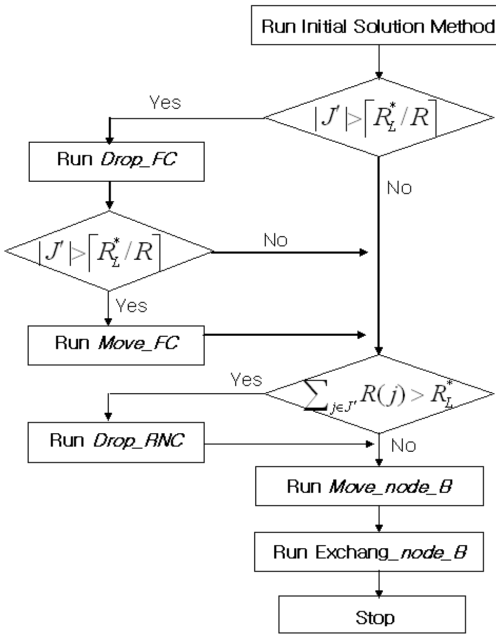
[Step a] Set $K = \{(i_1, i_2); i_1, i_2 \in I', i_1 < i_2, j(i_1) \neq j(i_2)\}$, where $j(i)$ is the FC containing the RNC connected to node-B i.

[Step b] Denote a randomly selected pair of node-Bs from the set K by κ. If the exchange of two node-Bs in the pair κ improves the objective value, update the current solution.

[Step c] Set $K = K - \{\kappa\}$ If $K = \phi$, stop, otherwise go to [Step b].

3.3 Heuristics

Combining the initial solution methods and the sub-modules, we now present our heuristic (H), which generates an approximate solution of the problem (ANDP). Heuristic (H) starts with the initial solution obtained by either the *IO-td* or *IO-bu* methods. The lower bound on the number of FCs required to meet all traffic demand is then calculated. If the number of the opened FCs in the initial solution is greater than $\lceil R_L^*/R \rceil$, the possibility of improving the objective function of problem (P) using the sub-modules *Drop_FC* and/or *Move_FC* is examined. The sub-module *Drop_RNC* is the next step of heuristic (H) to see the chances of decreasing the objective value by eliminating some RNCs. This would be the case if the number of RNCs in the current solution is greater than the minimum number of RNCs required to satisfy all traffic demand. Finally, the procedures for moving and exchanging node-Bs are applied to improve the objective value. The summary of heuristic (H) is given in <Figure 2>.



<Figure 2> Summary of heuristic algorithm (H)

4. Computational Results

The solution procedure was coded in Visual C++ and run on a desktop Pentium IV PC with a 2.8 GHz CPU. For a comprehensive test, we considered twelve types of problems that have different combination of the number of node-Bs (n), the number of candidate FCs (m), and the capacity of FC (R) as shown in <Table 1>.

We randomly located the corresponding number of candidate FCs and node-Bs for each of twelve types of problems on a plane in such a way that the x- and y-axes of the locations of node-Bs and FCs are generated from a uniform distribution $U(0,1)$. The link cost from node-B i and FC j, C_{ij}, was obtained by multiplying the distance between them by a constant 5,000 for all types of problems. The fixed cost of opening a FC, F_j, is generated from the uniform distribution with lower and upper values 50,000 and 1,000,000, respectively. We consider two cases for RNC capacity, $R=5$ and $R=10$. Both the CS-type and PS-type capacities of an RNC are set at 500. Both types of traffic demands at each node-B are generated independently from a uniform distribution $U(10, 90)$. <Table 1> provides a summary of the test problems.

<Table 2> shows the computational results for each of twelve types of problems with the initial solutions obtained by *IO-td* method. Each of these results is obtained by averaging the results of ten independent heuristic (H) runs. The fifth column of <Table 2> reports the numbers of opened FCs in the solution of heuristic (H). It is worth noting the fact that the upper rounding values of opened number of FCs and the minimum number of FCs required to meet all traffic demands (the sixth column of <Table 2>), $\lceil R^*/R \rceil$, are the same except one case, indicating the sub-modules, *Drop_FC* and *Move_FC*, are very effective on reducing the number of opened FCs that might have been overestimated in the initial solution method *(IO_td)*. The numbers of RNCs in the solution of heuristic (H) and the values of R^* are shown in seventh and eighth columns in <Table 2>, respectively. The lower bounds on the objective function obtained by equation (15) listed in the ninth column (LB) and the objective values of the solution given by heuristic (H) are shown in the tenth column ($\nu(H)$). As shown in eleventh column of <Table 2>, our heuristic (H) with initial solution method *(IO_td)* gives a ratio of $\nu(H)$ and LB as less than 1.2 for all types of problems. Moreover the computational times are very fast for real-world sized problems.

〈Table 1〉 Sample data for computational experiments

Type	problem	n	m	F_j	R	E_i	B_i	C	E	B
A	A1	50	100	U(500000, 1000000)	5	U(10, 90)	U(10, 90)	10000	500	500
	A2	50	200	U(500000, 1000000)	5	U(10, 90)	U(10, 90)	10000	500	500
	A3	50	300	U(500000, 1000000)	5	U(10, 90)	U(10, 90)	10000	500	500
	A4	50	400	U(500000, 1000000)	5	U(10, 90)	U(10, 90)	10000	500	500
B	B1	100	400	U(500000, 1000000)	5	U(10, 90)	U(10, 90)	10000	500	500
	B2	100	600	U(500000, 1000000)	5	U(10, 90)	U(10, 90)	10000	500	500
	B3	100	800	U(500000, 1000000)	5	U(10, 90)	U(10, 90)	10000	500	500
	B4	100	1000	U(500000, 1000000)	10	U(10, 90)	U(10, 90)	10000	500	500
C	C1	100	400	U(500000, 1000000)	10	U(10, 90)	U(10, 90)	10000	500	500
	C2	100	600	U(500000, 1000000)	10	U(10, 90)	U(10, 90)	10000	500	500
	C3	100	800	U(500000, 1000000)	10	U(10, 90)	U(10, 90)	10000	500	500
	C4	100	1000	U(500000, 1000000)	10	U(10, 90)	U(10, 90)	10000	500	500

<Table 3> summarizes the computational results obtained by heuristic (H) with the initial solution method *IO-bu*. It is interesting to see that the *IO_td* method is superior in solution quality and computational times to the *IO-bu* method for most types of problems. This may be because of our cost structure where the link cost contributes to a larger degree that the cost of opening FCs. Our computational experience suggests that the heuristic solution procedure proposed in the paper yields good solutions for the problems

〈Table 2〉 The computational results of heuristic (H) with initial solution method *IO__td*

problem	n	m	R	Opened FCs	$\lceil R^*/R \rceil$	RNCs	R^*	LB	$v(H)$	$V(H)/LB$	Time (sec)
A1	50	100	5	3	2.7	11.3	10.7	250889	289982	1.16	0.06
A2	50	200	5	5	4.6	21.8	20.6	461382	522278	1.13	0.27
A3	50	300	5	7	6.4	32.3	30.5	666199	750336	1.13	1.50
A4	50	400	5	9	8.5	42.8	40.6	902795	993545	1.10	3.03
B1	100	400	5	9	8.7	42.7	40.8	881370	959580	1.09	3.72
B2	100	600	5	13	12.4	63.5	60.5	1290451	1401207	1.09	12.03
B3	100	800	5	17.2	16.5	84.5	80.5	1722287	1858694	1.08	35.02
B4	100	1000	10	11	10.3	105.4	100.0	1586936	1758905	1.11	42.91
C1	100	400	10	5	4.4	42.2	40.2	643485	748814	1.16	2.11
C2	100	600	10	7	6.5	63.5	60.6	969962	1088890	1.12	7.36
C3	100	800	10	9	8.7	84.8	81.1	1297650	1423772	1.10	20.38
C4	100	1000	10	11	10.5	106.0	101	1603348	1760089	1.10	53.42

〈Table 3〉 The computational results of heuristic (H) with initial solution method *IO__bu*

problem	n	m	R	Opened FCs	$\lceil R^*/R \rceil$	RNCs	R^*	LB	$v(H)$	$V(H)/LB$	Time (sec)
A1	50	100	5	2.9	2.7	10.8	10.7	250889	289050	1.16	1.70
A2	50	200	5	5.1	4.6	21.0	20.6	461382	538869	1.17	1.96
A3	50	300	5	7.4	6.4	31.3	30.5	666199	784653	1.18	4.90
A4	50	400	5	9.6	8.5	41.2	40.6	902795	1049273	1.16	8.41
B1	100	400	5	9.8	8.7	41.4	40.8	881370	1025882	1.17	9.18
B2	100	600	5	14.3	12.4	62.6	60.5	1290451	1507193	1.17	126.99
B3	100	800	5	19.4	16.5	85.6	80.5	1722287	2058396	1.19	98.98
B4	100	1000	10	12.9	10.3	106.9	100.0	1586936	1900346	1.20	45.44
C1	100	400	10	5.2	4.4	43.1	40.2	643485	774140	1.21	4.51
C2	100	600	10	7.9	6.5	64.7	60.6	969962	1156696	1.20	11.96
C3	100	800	10	10	8.7	86.0	81.1	1297650	1506095	1.16	26.17
C4	100	1000	10	13	10.5	107.7	101	1603348	1916708	1.20	45.43

5. Conclusions

In this paper, we studied the access network design in UMTS mobile communication networks and formulated the problem of minimizing the total cost of constructing the access network. We show that the problem is NP-complete, making it difficult to solve optimally even for small problem instances. Thus, we developed a heuristic algorithm based on simple add/drop and move/exchange procedures, along with a lower bounding method. In particular, we devised two initial solution methods to strengthen the solution quality. We test the heuristics on a number of randomly generated problems and demonstrate that our solution heuristics perform extremely well and are computationally efficient. An interesting extension to this problem would be to consider the case where there is reliability built into the network using dual homing techniques.

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