Design of the ATM-based interconnecting network of the access segment of future cellular systems

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Summary. An important issue in future cellular communication systems is the design of the interconnecting network of their access segment. This problem aims at finding the minimum-cost configuration of *Cell Site Switches* (CSSs) and *Local Exchanges* (LEs) given the *Base Transceiver Station* (BTS) layout. An extended version of the problem may also comprise the deployment of *Mobility and Service Control Points - Access* (MSCPs-A), based on the assumption that CSSs and LEs are not fully capable of handling the logic of the cellular system. In this paper we solve the extended problem, under the additional assumption that the communication among the network elements is based on the ATM technique. The problem is formally defined, optimally formulated, and solved by computationally efficient heuristics. Finally, results are provided and subsequent conclusions are drawn.

1. INTRODUCTION

Future cellular communications systems, e.g., the Universal Mobile Telecommunications System (UMTS) [1,2], the future versions of the Global System for Mobile communications (GSM) [3], or others [4], will have to provide a wide variety of sophisticated services, over the widest possible service area. From the viewpoint of the users, the success of these systems will depend on the Quality of Service (QoS) that they will provide, and especially, on whether it will be comparable to the quality levels provided by fixed systems. From the providers perspective, the aim will be to provide QoS in the most cost efficient manner. Another design objective is gradual introduction by minimally impacting the existing fixed communication infrastructures. In this respect, future cellular communications systems have been conceived as consisting of the following three segments: (a) the *core network* segment that provides the switching and transmission functions, (b) the *intelligent network* segment that comprises the logic and data that enable service provision to mobile users, and (c), the *access network* segment that enables interworking between the mobile unit and the fixed network. This concept, along with the network elements that appear in each segment, is illustrated in figure 1. In the rest of this paper (as may also be observed in figure 1) the reference system will be UMTS. However, the practices proposed hereafter may be equally applicable to other, future or legacy, cellular systems.

The subject of this paper falls into the overall access segment design. In particular, our aim is to find the minimum cost configuration of the interconnecting network, under the additional assumption that the underlying communication (among the elements therein) is based on the ATM (Asynchronous Transfer Mode) technique [5]. The motivation is the potential gradual integration among UMTS (or in general, any other future cellular system) and the ATM-based B-ISDN. More specifically, the problem addressed in this paper aims at finding the minimum-cost *Cell Site Switch* (CSS), *Mobility and Service Control Point* (MSCP-A) and *Local Exchange* (LE) configuration given the *Base Transceiver Station* (BTS) layout. The inclusion of the deployment of the MSCPs-A is a new feature. In brief, the role of the elements in the access segment may be summarised in the following. The BTSs provide radio link management, the CSSs provide switching functionality, as well as connection and call control [1,2], while the LEs enable the interworking among the access network segment with the fixed network. Therefore, the LEs complement the switching infrastructure by being points of interface with the core segment. An assumption may be that LEs are owned, administered, and offered for rent by the backbone network operator. The presence of MSCPs-A may be justified in the (general) case, in which CSSs and LEs are assumed incapable of (fully) handling the logic of the cellular system. Therefore, the MSCPs-A may be seen as specialised entities that comprise all the additional functionality required for supporting mobility (e.g., location update), service access (e.g., call set-up), and service continuity (e.g., handover). In UMTS these procedures are called, *UMTS operations and procedures* [1,2]. This term will be adopted for the rest of this paper.

In the context of the overall access segment design a number of topics arise (figure 2). In brief, these are the problem of finding the minimum cost BTS layout [6], the problem of efficiently utilising the (scarcely) available radio spectrum [7,8], and the grouping of cells into location and paging areas [9]. The interconnecting network planning problem comes at the final stages of the overall access segment design. Inputs from the previous phases are the BTS layout and the pertinent traffic and signalling requirements. Inputs, specific to this phase, are the candidate CSS, MSCP-A and LE sites, the cost factors, and the problem constraints (related to performance requirements and equipment capabilities). The aim is the minimum cost configuration of the network segment, i.e., the best allocation of BTSs to CSSs, and CSSs to MSCPs-A and LEs, that satisfies the problem constraints.

Our approach for addressing this problem is the following. In section 2, we describe in more detail the architecture of the interconnecting network and give the high level definition and formal statement of design problem. In section 3 we discuss about the evaluation of the service area requirements and give the optimal formulation as a 0-1 linear programming problem [10]. Since the optimal formulation falls within the *NP*-complex [11] category, section 4 provides two computationally efficient solutions. One is based on a greedy technique [12], while the other follows the simulated annealing paradigm [13]. Finally, results are comprised in section 4 and concluding remarks are made in section 5. Comparisons with other works in the literature are given in the next section.

2. PROBLEM STATEMENT

2.1 High Level Problem Description and Relation with Previous Work

A more detailed view of the architecture of the ATM-based interconnecting network is depicted in figure 3. The protocol stacks that may support this communication are depicted in figure 4. Even though not specifically addressed in this paper, our practices include the wireless-ATM case [14,15] (i.e., systems in which ATM is used also over the radio link). The CSSs and LEs are assumed to be ATM switches. The methodology of this paper is applicable in an increasingly IP world. For space limitations this aspect will not be further addressed in this paper.

Based on the described architecture we may provide the high level definition of the pertinent design problem. This means that we should define the cost function and specify the constraints that derive from the requirements of (primarily) the BTSs and the capabilities of the CSSs, MSCPs-A, and LEs. The solution in our case should provide the minimum cost allocations of BTSs to CSSs, CSSs to MSCPs-A and CSSs to LEs.

The BTS requirements derive from the behaviour of the users in the respective cell. User behaviour may be characterised in terms of service preferences and mobility. Service preferences yield the traffic load that will originate from each BTS, which may be expressed in terms of an associated with each BTS ATM-level, bandwidth value. In essence, this value corresponds to the bandwidth required by the BTS, so as to adequately provide the services preferred by the users in the cell. The combination of service preferences and mobility behaviour yields the signalling load and the volume of UMTS operations and procedures associated with each BTS.

The cost function of the interconnecting network design problem may consist of the following factors. First, the cost of the equipment (namely, CSSs, MSCPs-A and LEs) that needs to be deployed (involved in the solution). Second, the cost of connecting (cabling) BTSs to CSSs, and CSSs to MSCPs-A and LEs. Third, the cost of handovers that occur among BTSs that are connected to different CSSs, and CSSs that are connected to different MSCPs-A and LEs (this factor is considered also in [16]). The constraints of the problem derive from the capabilities of the CSSs, MSCPs-A, and LEs. These may be expressed in terms of their capacity, and probably, the maximum number of BTSs and CSSs they can control. For the CSSs and LEs the capacity notion refers to the maximum bandwidth that they can handle, while for the MSCPs-A it refers to the volume of UMTS operations and procedures that may be handled, while keeping the performance within the acceptable range.

Taking into account the aspects outlined above, a general problem statement may be the following. Given the BTS layout, the bandwidth requirement (aggregating traffic and signalling load) and the volume of UMTS operations and procedures corresponding to each BTS, the handover rates among neighboring BTSs, a set of candidate CSS, MSCP-A and LE sites, the cost of each CSS, MSCP-A and LE, and the cost of inter-connecting BTSs to CSSs, and CSSs to MSCPs-A and LEs, find the minimum cost allocation of BTSs to CSSs and of CSSs to MSCPs-A and LEs (in terms of the number of CSSs, MSCPs-A and LEs that need to be deployed, the cost of inter-connecting BTSs to CSSs and CSSs to MSCPs-A and LEs, and of the signaling imposed by the arrangement), subject to a set of constraints, associated with the capabilities of the CSSs, MSCPs-A and LEs.

The work of this paper is related to pertinent previous works in the literature. In general, several articles have dealt with the integration of future cellular systems with B-ISDN, or addressed specific features that will make this integration feasible (e.g., [17,18,19] are early samples of relevant work). Another topic that attracts attention in the recent literature is that of software tools for cellular or broadband system design (e.g., see [20,21,22]). Such tools enable the design from scratch (“green-field” scenario), or the expansion and modification of a communication system, by offering to the operator the ability to solve hard optimisation problems. One such problem is the one addressed in this paper. Relevant work is its GSM (or second generation Code Division Multiple Access-CDMA) version that is addressed in [23]. Another advanced version of the problem is addressed in [24,25]. The cost function therein consists of the cost of interconnecting BTSs to CSSs and CSSs to LEs and the cost of the equipment that need to be deployed. The communication among the network elements is based on PCM (Pulse Come Modulation) modules. Reference [16] introduces the cost factor that penalises handovers.

The focal points in our work, and in a sense the difference from pertinent works in the literature, are the following. First, a more general problem version is considered, since it spans over the information transfer part of the problem (CSS and LE deployment) and the service logic deployment part of the problem (MSCP-A deployment). Second, an extended cost function is introduced, combining factors like the cost of the equipment, the cost of interconnecting (cabling) and the cost of signalling (handovers). Third, an extended set of constraints, related to performance requirements and equipment (CSS, LE and MSCP-A) capabilities, is incorporated. Fourth, the ATM feature is taken into account. Finally, an optimal formulation comprising all the desired features and two novel computationally efficient algorithms are presented.

2.2 Formal Statement

The set of BTSs is denoted by V, and for each BTS-i ($i \in V$), the capacity (bandwidth) requirement is bw_i, and the volume of UMTS operation and procedure requests is u_i. The calculations of bw_i and u_i are discussed in the following section. C represents the set of candidate CSS sites, M_a the set of candidate MSCP-A sites and L represents the set of candidate LE sites.

Let C_j denote the set of BTSs that will be connected to CSS-j ($j \in C$), M_k denote the set of CSSs that will be connected to the k-th MSCP-A ($k \in M_a$), and L_l denote the set of CSSs that will be connected to LE-l ($l \in L$). The objective is to find the allocations A_C, A_{M_a}, and A_L, where $A_C = \left\{C_j \middle| j \in C\right\}$ ($C_j \subseteq V$), $A_{M_a} = \left\{M_k \middle| k \in M_a\right\}$ ($M_k \subseteq C$), and $A_L = \left\{L_l \middle| l \in L\right\}$ ($L_l \subseteq C$). These should minimise a cost function $f\left(A_C, A_{M_a}, A_L\right)$ that is associated with the cost of the equipment, the cost of interconnecting the equipment and the signaling cost.

The costs of the CSSs, MSCPs-A, and LEs that will need to be deployed are denoted as c_C, c_{M_a}, and c_L, respectively. Set $P_C = \left\{p_{BC}(i,j) \middle| i \in V, j \in C\right\}$ provides the cost of connecting BTS-i to the CSS that may be located at the candidate site j. Set $P_{M_a} = \left\{p_{CM}(j,k) \middle| j \in C, k \in M_a\right\}$ provides the cost of connecting the CSS that may be located at candidate site j to the MSCP-A that may be located at candidate site k. Set $P_L = \left\{p_{CL}(j,l) \middle| j \in C, l \in L\right\}$ provides the cost of connecting the CSS that may be located at candidate site j to the LE (that may be) located at candidate site l. The cost factor associated with the handovers among BTSs that are controlled by different CSSs is provided by the set $H_b = \left\{h_B\left(i,i'\right) \middle| \forall \left(i,i'\right) \in V^2\right\}$.

The constraints of our problem are the following. First, each BTS should be assigned to one CSS, and each CSS should be assigned to exactly one MSCP-A and one LE. Therefore, $C_{j_1} \cap C_{j_2} = \varnothing$ for all $\left(j_1, j_2\right) \in C^2$, $M_{k_1} \cap M_{k_2} = \varnothing$ for all $\left(k_1, k_2\right) \in M_a^2$, and $L_{l_1} \cap L_{l_2} = \varnothing$ for all $\left(l_1, l_2\right) \in L^2$. Second, all BTSs should be assigned to a CSS, and all CSSs should be assigned to an MSCP-A and an LE. Hence, $\bigcup_{j \in C} C_j = V$, $\bigcup_{k \in M_a} M_k = C$, and $\bigcup_{l \in L} L_l = C$. Third, the capacity constraints of each CSS, MSCP-A and LE should be preserved. Lets assume that $\varphi_{CSS}^{\max}$, and k_C represent the maximum load (bandwidth) and the maximum number of BTSs that a CSS may handle, $\varphi_{M_a}^{\max}$ and k_{M_a} represent the maximum load and the maximum number of CSSs that an MSCP-A may handle, and that $\varphi_{LE}^{\max}$ and k_L represent the maximum load (bandwidth) and the maximum number of CSSs that an LE may handle. The constraints are $\varphi_C(C_j) \le \varphi_{CSS}^{\max}$, $\left|C_j\right| \le k_C$, $\varphi_{M_a}(M_k) \le \varphi_{M_a}^{\max}$, $\left|M_k\right| \le k_{M_a}$, $\varphi_L(L_l) \le \varphi_{LE}^{\max}$, $\left|L_l\right| \le k_L$. The assumption in the previous constraints is that function $\varphi_C\left(C_j\right)$ provides the bandwidth requirements of the BTSs assigned to CSS j, function $\varphi_{M_a}\left(M_k\right)$ provides the volume of UMTS operations and procedures of the CSSs assigned to MSCP-A k and that function $\varphi_L\left(L_l\right)$ provides the bandwidth requirements of the CSSs assigned to LE l.

3. Optimal Formulation

The aim of this section is to provide a sample model for the evaluation of the service area requirements and to give the optimal formulation of the problem.

3.1 Load evaluation

Our aim in this subsection is to evaluate the bandwidth (bw_i) and the volume of UMTS operations and procedures (u_i) associated with each BTS i ($i \in V$). A set of alternate approaches will be identified and a sample model will be given. However, the formal statement of the planning problem (given in the previous section) and the solutions (provided in the next sections) are generic with respect to the specific calculation scheme selected.

Figure 5 illustrates a general approach for evaluating the service area requirements, along with the factors that play a role in this process. In this paper it is assumed that the user related information, within a time-zone in the day, consists of the density of users in each cell d_i ($user/km^2$), their average velocity v, and their service preferences. Service preferences may be expressed by the call rate per user, λ_s (calls per time unit per user), where $s \in S$ is one of the services offered by the system.

The service area characteristics may be assumed to comprise the area A_i (km^2) and the perimeter L_i (km) of each cell i ($i \in V$). Finally, the service characteristics are assumed to comprise for each service s, the average duration of a call, $1/\mu_s$, QoS requirements, for example, maximum tolerable blocking probability bl_s, cell loss ratio and delay, and the source characteristics, for example, the source rate for constant bit rate (CBR) services, or the peak rate, mean rate and burst length, for variable bit rate (VBR) services. An assumption adopted is that the blocking probability threshold should be preserved by all the cells of the system (based on the argument that it is important to provide uniform QoS in all the cells of the system).

3.1.1 Bandwidth estimation

The method for evaluating the bandwidth requirement bw_i may be summarised in the following (figure 6). The average number of users expected in cell i, may readily be estimated through the formula, $N_i = A_i \cdot d_i$. Based on these figures and the population model of [26], the steady state probabilities $\pi_n(N_i)$ that there will be n users in cell i may be obtained. In parallel, the load $\rho_s = (\lambda_s/\mu_s) \cdot penetration(s)$, caused by each user that requests service s, may be obtained where $penetration(s)$ is the proportion of users that makes use of service s. Based on this information we may compute the load $\varphi_s(i)$ due to the invocations of service s by the users in cell i, using the formula $\varphi_s(i) = \rho_s \cdot \sum_{n=0}^{\infty} \pi_n(N_i)$. Given this load and the maximum tolerable blocking probability for the calls of service s, we may obtain the maximum number of calls $b_s(i)$ that should be simultaneously supported in the cell, so as to guarantee that the blocking probability will be within the acceptable range. This phase may be based on the Erlang-B formula [27].

The final stage (*bandwidth requirement per cell* estimation phase in figure 6) is targeted to the computation of the bandwidth required by each cell, bw_i, given the $b_s(i)$ quantity. Two alternate approaches may be adopted in this respect, essentially, motivated by the existence of VBR services. The first aims at high network efficiency (in other words, at high statistical multiplexing gain) by allowing full sharing of resources among different service classes (which may be CBR or VBR). The drawback of this approach is the difficulty that is incurred in preserving the QoS requirements of the distinct service classes. The second approach adheres to the *service separation* paradigm [28,29]. The resources are structured in a manner that service classes (i.e., set of services with homogeneous requirements) have, conceptually, their own dedicated resources. Hence, statistical multiplexing is limited within each class, but the task of guaranteeing the requirements of each class is facilitated. The determination of the bandwidth requirements in this case (given the $b_s(i)$ quantity) may be based on the equivalent bandwidth notion [30,31,32,33] (which may be estimated by the characteristics of a single or multiplexed connections through analysis, simulation or measurements) or any other advanced technique (e.g., see [34,35]). The equivalent bandwidth approach is often articulated as a popular notion [36] that is suitable for (at least) the current versions of planning tools [37]. In this perspective, and since the exact method of determining the bandwidth requirements is not crucial for the rest of this paper, we will assume that bw_i is obtained either as a function of $b_s(i)$, or by the straightforward formula bw_i = $\sum_{s \in S} C_s \cdot b_s(i)$, wherein C_s is assumed as the equivalent bandwidth required by each connection of service s.

3.1.2 *Volume of UMTS operations and procedures estimation*

The calculations of this sub-section may be based in models as those in [38,39]. In this paper we use a simpler (subset) model (in order to concentrate on the overall design problem). The load originating from each BTS is assumed to be a function of the *call set-up*, *handover* and *location update* rates. Based on the input measures defined so far, the rate of call requests that correspond to the users in cell i may be obtained by the following formula,

$$r_c(i) = \sum_{s=1}^{|S|} \lambda_s \cdot \sum_{n=0}^{\infty} n \cdot \pi_n(N_i) \tag{1}$$

The rate of handover operations that are caused by the users of cell i may be obtained by the following formula,

$$r_h(i) = \left(1/\pi\right) \cdot L_i \cdot d_i \cdot \left(\sum_{s=1}^{|S|} \rho_s\right) \cdot v \tag{2}$$

In the formula above, the fluid model [40] has been used for conceptualising the user mobility. Other models could have been used instead. Moreover, the probability that a user is involved in a call has been taken into account. Finally, the rate of location update operations that are caused by the users of cell i may be obtained by the following formula,

$$r_l(i) = (1/\pi)\cdot L_i \cdot d_i \cdot \left(1-\sum_{s=1}^{|S|}\rho_s\right)\cdot v \cdot \delta_i \tag{3}$$

In the formula above δ_i is the percentage of the cell border that is at the same time a location area border. Similarly to relation (2), the probability that a user is not involved in a call has been taken into account. Finally, lets denote by $1/x_c$, $1/x_h$ and $1/x_l$ the cost of serving a call request, a handover and a location update by an MSCP-A. Then, the load that originates from BTS i is,

$$u_i = r_c(i)\cdot(1/x_c) + r_h(i)\cdot(1/x_h) + r_l(i)\cdot(1/x_l) \tag{4}$$

3.2 Optimal Formulation

In order to describe the allocation A_C of BTSs to CSSs we introduce the decision variables $x_{BC}(i,j)$ ($i \in V$, $j \in C$) that take the value 1(0) depending on whether BTS-i is (is not) connected to CSS-j. In a similar manner, allocations A_{M_a} and A_L are described by the decision variables $x_{CM}(j,k)$ and $x_{CL}(j,l)$, that take the value 1(0) depending on whether CSS j is (is not) connected to MSCP$_a$ k and LE l, respectively.

The decision variables $y_C(j)$, $y_M(k)$, and $y_L(l)$ assume the value 1(0) depending on whether candidate CSS j ($j \in C$), MSCP$_a$ k ($k \in M_a$) or LE l ($l \in L$) is (is not) deployed. In addition, we define the set of variables $z_B(i,i')$ ($\forall(i,i') \in V^2$) that take the value 1(0) depending on whether the BTSs i and i' are (are not) connected to the same CSS node. The variables $z_B(i,i')$ are related to variables $x_{BC}(i,j)$, $x_{BC}(i',j)$, through the relation $z_{BC}(i,i') = \sum_{j=1}^{|C|} x_{BC}(i,j)\cdot x_{BC}(i',j)$, which may be turned into a set of linear constraints through the technique of [16]. In a similar manner we can define variables $z_{CM}(j,j')$ and $z_{CL}(j,j')$ indicating whether CSSs j and j' are controlled by the same MSCP$_a$ or LE respectively. Allocations A_c, A_{M_a} and A_L may be obtained by reduction to the following 0-1 linear programming problem.

Problem 1 [Interconnecting Network Design]: Minimise

$$c_C \sum_{j=1}^{|C|} y_C(j) + \sum_{i=1}^{|V|}\sum_{j=1}^{|C|} p_{BC}(i,j)\cdot x_{BC}(i,j) + c_{M_a}\sum_{k=1}^{|M_a|} y_M(k) + \sum_{j=1}^{|C|}\sum_{k=1}^{|M_a|} p_{CM}(j,k)\cdot x_{CM}(j,k) +$$

$$c_L \sum_{l=1}^{|L|} y_L(l) + \sum_{j=1}^{C}\sum_{l=1}^{|L|} p_{CL}(j,l)\cdot x_{CL}(j,l) +$$

$$\sum_{i=1}^{|V|}\sum_{i'=1}^{|V|} h_B(i,i')\cdot\left(1 - z_{BC}(i,i')\right) + \sum_{j=1}^{|C|}\sum_{j'=1}^{|C|} h_C(j,j')\cdot\left(1 - z_{CM}(j,j')\right)$$

$$+\sum_{j=1}^{|C|}\sum_{j'=1}^{|C|} h_C(j,j')\cdot\left(1 - z_{CL}(j,j')\right) \qquad (5)$$

subject to,

$$\sum_{j=1}^{|C|} x_{BC}(i,j) = 1 \qquad , \forall i \in V, \qquad (6)$$

$$\sum_{i=1}^{|V|} x_{BC}(i,j) \le k_C \cdot y_C(j) \qquad , \forall j \in C, \qquad (7)$$

$$\sum_{i=1}^{|V|} x_{BC}(i,j)\cdot u_i = u_C(j) \qquad , \forall j \in C, \qquad (8)$$

$$\sum_{i=1}^{|V|} x_{BC}(i,j)\cdot bw_i = \varphi_C(j) \le \varphi_{CSS}^{\max} \cdot y_C(j) \qquad , \forall j \in C, \qquad (9)$$

$$\sum_{k=1}^{|M_a|} x_{CM}(j,k) = 1 \qquad , \forall j \in C, \qquad (10)$$

$$\sum_{j=1}^{|C|} x_{CM}(j,k) \le k_M \cdot y_M(k) \qquad , \forall k \in M_a, \qquad (11)$$

$$\sum_{j=1}^{|C|} x_{CM}(j,k)\cdot u_C(j) \le \varphi_{M_a}^{\max} \cdot y_M(k) \qquad , \forall k \in M_a, \qquad (12)$$

$$\sum_{l=1}^{|L|} x_{CL}(j,l) = 1 \qquad , \forall k \in M_a, \qquad (13)$$

$$\sum_{j=1}^{|C|} x_{CL}(j,l) \le k_L \cdot y_L(l) \qquad , \forall l \in L, \qquad (14)$$

$$\sum_{j=1}^{|C|} x_{CL}(j,l) \cdot \varphi_C(j) \le \varphi_{LE}^{\max} \cdot y_l(l) \qquad , \forall l \in L, \qquad (15)$$

Cost function (5) penalises the aspects identified in section 2 (i.e., cost of the equipment deployed, cost of interconnecting the network elements deployed, and cost of handovers among BTSs and CSSs controlled by different CSSs, MSCPs-A and LEs respectively). Constraints (6), (10), and (13) guarantee that each BTS will be assigned to one CSS, and each CSS will be controlled by one MSCP-A and one LE, respectively. Constraints (7), (11) and (14) guarantee that CSSs, MSCPs-A and LEs will not be assigned more BTSs and CSSs than allowed by their capacity constraints. Constraints (8), (12) and (15) guarantee that each CSS, MSCP-A and LE will not have to cope with more load than that dictated by its pertinent capacity constraint.

4. COMPUTATIONALLY EFFICIENT SOLUTIONS

This section provides two computationally efficient solutions for the version of the interconnecting network planning problem addressed in this paper. The optimal formulation presented in the previous section yields that the interconnecting network planning problem falls within the *NP*-complete category. This means that an optimal algorithm may not be able to provide a solution in reasonable time.

The usual next step for solving such difficult problems is to devise computationally efficient algorithms that may provide good solutions in reasonable time. As already stated in this section we present two such methods. The first follows a greedy strategy, while the second is influenced by the simulated annealing technique. A step further for reducing the complexity of *problem 1* (any complex problem in general) is to solve it in a divide and conquer manner. This approach is facilitated by the fact that the architecture of the interconnecting network is a multilevel, star one. Hence, the problem may be solved in phases. Each phase may be targeted to one level of the architecture, and the output of each phase may be input to the next. In our case this idea yields that an algorithm should have three phases, which are targeted to the computation of the allocations A_C (BTSs to CSSs), A_{M_a} (CSSs to MSCPs-A), and A_L (CSSs to LEs) respectively.

The greedy algorithm presented in the sequel follows the divide and conquer approach. The simulated annealing algorithm is more general since it may follow both approaches, i.e., divide and conquer or one-phase solution to *problem 1*. In the sequel, we choose to present the second (and more general) version of the algorithm.

4.1 Greedy based solution

As already stated this algorithm solves *problem 1* in three phases. As these are methodologically similar, we will limit our attention to finding allocation A_C (BTSs to CSSs). The algorithm of two main phases. At the first main phase, an initial feasible assignment of BTSs to CSSs is found, which will be called A_C^1. Allocation A_C^1 satisfies all the constraints designated by the definition of *problem 1* (i.e., all BTSs are assigned to exactly one CSS and the capacity restrictions of each CSS are respected). At the second main step, an improved assignment is searched, and hence, A_C is obtained.

A greedy strategy is followed for building the initial allocation of BTSs to CSSs, A_C^1. Greedy algorithms provide solutions by making a series of choices. In each step the solution that is best at that particular step is selected. Each step in our algorithm is targeted to the assignment of a BTS to a CSS. The assignment that is selected results to the smaller increase on the cost function value. If no feasible assignment can be found a new CSS is deployed.

By means of the first phase described above an initial good assignment of BTSs to CSSs has been found. This algorithm, however, may overestimate the required number of CSSs. The number of CSSs included in the solution is assumed to be the main factor contributing to the cost function. The minimum number of CSSs in any solution may be estimated by dividing the total load that originates from the BTSs with the capacity of the CSSs. In this sense, the second phase is targeted to the elimination of some CSSs. This procedure works as follows. The least loaded CSSs (or CSSs that control few BTSs) are candidates for elimination. Attempts to assign the BTSs that were controlled by the eliminated CSSs, to CSSs that remain in the solution are conducted, through an appropriate instance of the maximum flow problem. In turn, the CSSs that remain in the solution may have to release BTSs (so as to be able to acquire the new ones). For brevity the formal description of the algorithm is not provided.

The output of the two-phase algorithm above is allocation A_C. Similarly, we may obtain allocations A_{M_a} and A_L.

4.2 Simulated annealing based solution

In this section we present an algorithm that follows the simulated annealing paradigm.

As also stated in [6] the development of a simulated annealing-based procedure means that the following aspects have to be addressed: configuration space, cost function "neighbourhood" structure and cooling schedule (i.e., manner in which the temperature will be reduced). The configuration space is the set of feasible solutions $\{x_{BC}(i,j),\ x_{CM}(j,k),\ x_{CL}(j,l),\ y_C(j),\ y_M(k),\ y_L(l)\}$ that satisfy the constraints (6)-(15). The cost function is the one introduced by relation (5). The neighbourhood structure of a solution is produced by moving a BTS (CSS) i (j) from its present CSS (LE or MSCP-A) j (k or l) to a neighbouring CSS (LE or MSCP-A) j' (k' or l'). The cooling schedule may be calculated according to $T' = r \cdot T$, where T is the temperature and r is usually a number that ranges from 0.95 to 0.99. Other techniques may also be applied.

The simulated annealing-based algorithm may be described as follows.

Basic Simulated Annealing Algorithm.

Step 0. Initialisation. Get an initial solution, IS, and an initial temperature value T. The currently best solution (CBS) is IS, i.e., $NBS = IS$, and the current temperature value (CT) is T, i.e., $CT = T$.

Step 1. If $CT = 0$ or if the stop criterion is satisfied, the procedure ends and a transition to *step 6* is performed.

Step 2. A new solution (NS) that is *neighbouring* to CBS is found.

Step 3. The difference of the costs of the two solutions, CBS and NS is found, i.e., the quantity $\Delta c = C(CBS) - C(NS)$ is computed.

Step 4. If $\Delta c \geq 0$ then the new solution becomes the currently best solution, i.e., $CBS = NS$. Otherwise, if $\Delta c < 0$, then if $e^{-(\Delta c/CT)} > rand[0,1)$, the new solution becomes the currently best solution, i.e., $CBS = NS$.

Step 5. The cooling schedule is applied, in order to calculate the new current temperature value CT, and a transition to *step 1* is performed.

Step 6. End.

There are various alternatives for realising the stop criterion mentioned in *step 1*. In our version, the algorithm stops when no improvement has been made after a given number of temperature decreases (in other words consecutive moves or alterations of the currently best solution). Neighbouring solutions (*step 2*) are selected randomly among all the neighbouring ones of the currently best solution, with the same probability for all neighbours.

5. Results and Discussion

The aim of this section is to provide indicative evidence on the performance of the algorithms, by applying them to a set of experiments. The aim of each experiment will be the following. First, to exploit the service area characteristics so as to compute the requirements (bandwidth and volume of UMTS operations and procedures) of each BTS (load evaluation phase). Second, to built the configuration of the interconnecting network in an hierarchical manner, i.e., starting with the allocation of BTSs to CSSs, and continuing with the allocation of CSSs to MSCPs-A and of CSSs to LEs (hence, the simulated annealing-based algorithm will be applied in the divide and conquer mode). Traffic and mobility pattern fluctuations may be incorporated in the focus of the experiments, through the time-zone based approach that was explained in section 2. For brevity, in this section the attention is limited to a unique time-zone. This particular time-zone is assumed to be the most demanding one, in terms of the installation cost.

The networks used in our experiments are square (Manhattan) grid structures. At the first experiment a 5x5 square (Manhattan) grid network (figure 7a) is used, while in the second experiment the network is a 9x9 square (Manhattan) grid (figure 7b). Cells are assumed identical, circular-like, with radius $R = 1\ Km$. The density of users is counted in terms of the number of users per square kilometer ($users/Km^2$). The value assumed is $d_i = 1.000\ users/Km^2$ ($\forall i \in V$), and hence, $N_i = 3.140$ users is the mean number of users expected per cell.

The load evaluation phase starts with the computation of the bandwidth requirement of each BTS, which is a requirement that will be posed to the (BTS, CSS) connection. This quantity enables the BTS to satisfactorily provide the services in its service area. In our experiments, it is assumed that the set of services offered by the system is the ones presented in table 1, namely, basic telephony, telefax, video conference, database browsing and database downloading. Table 1 comprises also the service-related characteristics. More specifically, we assume that the acceptable blocking probability for all five kind of services is 1%. The duration of each call type (i.e., call of a certain service type) is a random variable that is assumed exponentially distributed with mean $1/\mu_1 =$ 90 seconds, $1/\mu_2 =$ 30 seconds, $1/\mu_3 = 1/\mu_4 =$ 180 seconds and $1/\mu_5 =$ 30 seconds. Basic telephony and telefax are assumed CBR, while, video conference, database browsing and downloading are assumed VBR. Hence, the bandwidth requirements listed in table 1 correspond to the source rate for the CBR and the equivalent rate for the VBR services. As stated in section 4 more complex traffic models may also be considered by the design process. However, as this is not essential to our presentation, a simplifying assumption is made. Specifically, it is assumed that the equivalent rate of each VBR source is a-priori known.

The preferences of the users in the service area are modeled as follows. Each user requests basic telephony at a rate $\lambda_1 =$ 3 calls per hour per user, telefax $\lambda_2 =$ 1 call per hour per user, video-conference $\lambda_3 =$ 0.333 (one call every three hours) calls per hour for only 5% of the users in the service area (i.e., a 5% penetration is assumed for this service), database browsing $\lambda_4 =$ 1 call per hour for only 25% of the users in the service area, and database downloading $\lambda_5 =$ 0.5 (one call every two hours) calls per hour for only 25% of the users in the service area. Based on the service preferences and the call duration characteristics (see table 1), we obtain that the load per service per user is $\rho_1 =$ 0.075 (load per user, or in other words probability that a user is involved in a basic telephony call), $\rho_2 =$ 1/120 (probability that a user is using the telefax service), $\rho_3 =$ 1/30 (probability that a user, among the 5% that are interested in the service, is involved in a video-conference call), $\rho_4 =$ 0.05 (probability that a user, among the 25% that are interested in the database browsing, uses the service) and $\rho_5 =$ 1/240 (probability that a user, among the 25% that are interested in database downloading, uses the service). Consequently, the mean aggregate load per service that originates from each cell is $\varphi_1(i) \cong$ 240, $\varphi_2(i) \cong$ 27, $\varphi_3(i) \cong$ 2.7, $\varphi_4(i) \cong$ 40 and $\varphi_5(i) \cong$ 3.3 ($\forall i \in V$). The corresponding maximum number of calls of each service that should be supported in each cell, so as to preserve the blocking probability below the predefined levels is, $b_1(i) \cong$ 260, $b_2(i) \cong$ 35, $b_3(i) \cong$ 7, $b_4(i) \cong$ 52, and $b_5(i) \cong$ 8 ($\forall i \in V$). Given the (constant and equivalent) bandwidth requirement of each call we obtain that the bandwidth requirement of each BTS is less than 57.500 cells per second (cps), or equivalently, 25 Megabits per second (Mbps). This may be an optimistic value for current (or classical future) cellular systems, however, it is an assumption that is inline with the observations in [14,15].

The second aspect in the BTS characterisation phase is the computation of the volume of UMTS operations and procedures which is associated with each BTS. The rate of call set-up requests that originate from each BTS i is $r_c(i) \cong$ 13800 requests per hour (based on relation (1)), and the corresponding rate of handovers is $r_h(i) \cong$ 4.000 operations per hour (provided by relation (2)), assuming that the average user speed is 20 km/h. The rate of location updates is $r_l(i) =$ 36.000 operations per hour (based on relation (3) and assuming that every crossing of a mobile that is not involved in a call leads to a location update, i.e., no location area planning has been performed and δ_i defined in section 4 is equal to one). Furthermore, it is assumed that the cost of serving a handover ($1/x_h$) is greater than the cost of serving a call set-up request ($1/x_c$), and then, that the cost of serving an outgoing call request is greater than serving a location update ($1/x_l$). Hence, an arbitrary value assignment that is adopted is, $1/x_h =$ 3, $1/x_c =$ 2, and $1/x_l =$ 1. Based on the distribution of users per BTS area, the activity of the users and the cost of the operations, it is deduced that the mean volume of UMTS operations and procedures per BTS is approximately 84.000 (normalised) invocations per hour (based on relation (4)).

Having obtained the requirements of the BTSs we proceed with the first experiment that aims at the derivation of the configuration of the interconnecting network, for the case of the 5x5 network (figure 7a). As already stated the configuration will be constructed following the divide and conquer approach (which is inherent to the greedy-based algorithm, while, for the simulated annealing-based algorithm it is a selection that is made). The first phase is targeted to the derivation of the BTS to CSS layout. Figure 8 depicts the allocation of BTSs to CSSs when the BTS network structure and the pertinent requirements are known. A number of experiments are realised, each time by altering the CSS capacity. The BTS structure is the square (Manhattan) grid BTS structure of figure 7a and the load that originates from each BTS area is at most 57.500 cps (25 Mbps). Another assumption made is that terminals that are in a certain cell i move to one of the neighbouring cells with the same routing probability which is taken equal to 0.25. The CSS capacity is taken equal to 350.000 cps (i.e., in the order of 150 Mbps) in the experiment in figure 8(a)-(b) and 450.000 (approximately, 200 Mbps) in the experiment in figure 8(c)-(d). The results of figures 8(a), 8(c) are obtained by applying the greedy-based algorithm. The results of figures 8(b), 8(d) are obtained by applying the simulated annealing-based algorithm. From the obtained results we observe that the number of *CSS*s that are deployed when we apply the greedy-based algorithm is the same with the one that we obtain when we apply the simulated annealing-based algorithm. However, the simulated annealing algorithm shows an improved behaviour since the overall cost of the derived *CSS* structure is improved (lower) by 1.5% in case CSS capacity is equal to 350000cps and by 1.2% in case CSS capacity is equal to 450000cps. The outcome of this first phase of our experiment is depicted in figures 9(a)-(b) and figures 9(c)-(d) in case the *CSS* capacity is equal to 350000 cps and 450000 cps respectively.

In the second phase of the first experiment the aim is to find the allocation of *CSS*s to *LE*s. The CSS requirements according to the arrangements of figures 8(a)-(b) and figures 8(c)-(d) are those depicted in table 2 and table 3 respectively. Figure 10 depicts the allocation of CSSs to LEs when the CSS network structure, the CSS requirements, and the LE capacity are known. The results of figures 10(a), 10(c) are obtained by applying the greedy-based algorithm. The results of figures 10(b), 10(d) are obtained by applying the simulated annealing-based algorithm. From the obtained results it is obvious that the simulated annealing-based algorithm shows an improved behaviour since less *LE*s are deployed when we apply the respective algorithm.

In the third phase of the experiment the aim is to find the allocation of *CSS*s to *MSCP*s-A. As already explained the mean volume of UMTS operations and procedures per BTS is approximately 84.000 (normalised) invocations per hour. Consequently, the CSS requirements according to the arrangements of figures 8(a)-(b) and figures 8(c)-(d) are those depicted in table 2 and table 3 respectively. Figure 11 depicts the allocation of CSSs to MSCPs-A when the CSS network structure, the CSS requirements and the MSCP-A capacity are known. The results of figures 11(a), 11(c) are obtained by applying the greedy-based algorithm. The results of figures 11(b), 11(d) are obtained by applying the simulated annealing-based algorithm. Again, the results show that the application of the simulating annealing algorithm yields an improved behaviour in terms of the number of *MSCP*s-A that are deployed and the overall cost that the respective results involve.

The second experiment aims at the derivation of the configuration of the interconnecting network for the case of the 9x9 network (figure 7b). The assumptions that we made in this set of experiments, regarding service characteristics and user preferences, are similar to those that were mentioned in the first experiment.

Figure 12 depicts the allocation of BTSs to CSSs when the BTS network structure and the pertinent requirements are known. The CSS capacity is taken equal to 450.000 cps (approximately, 200 Mbps). The results of figure 12(a) are obtained by applying the greedy-based algorithm whereas the results of figure 12(b) are obtained by applying the simulated annealing-based algorithm. From the obtained results we observe that the number of *CSS*s that are deployed when we apply the greedy-based algorithm is the same with the one we obtain when we apply the simulated annealing-based algorithm. However, the simulated annealing algorithm shows an improved performance since the overall cost is improved (lower) by 5%. Figures 13(a)-(b) depict the derived CSS structure in our experiment.

In the second phase of the experiment the objective is to find an allocation of *CSS*s to *LE*s. The CSS requirements based on the arrangements of figure 12 are presented in table 4. The derived allocation of CSSs to LEs is given in figure 14. Again, the results of figure 14(a) are obtained by applying the greedy-based algorithm whereas the results of figure 14(b) are obtained by applying the simulated annealing-based algorithm. Furthermore, the simulated annealing-based algorithm shows an improved performance comparing to the respective greedy algorithm since the overall cost is improved by 3%.

In the last phase of this experiment the allocation of *CSS*s to *MSCP*s-A is found. As already explained the mean volume of UMTS operations and procedures per BTS is approximately 84.000 (normalised) invocations per hour. Consequently, the CSS requirements based on the structure of figure 12 are depicted in table 4. The derived allocation of CSSs to MSCPs-A is presented in figure 15. Similarly to the previous results, figure 15(a) depicts the results that are obtained by the greedy-based algorithm and figure 15(b) the respective results of the simulated annealing-based algorithm. Again, the results show that the application of the simulating annealing algorithm yields an improved behaviour in terms the overall cost that the respective results involve.

6. CONCLUSIONS

This paper addressed the problem of designing the interconnecting network of the access segment of a cellular communications system, under the assumption that the underlying communication is based on ATM. The architecture of the interconnecting network was presented. Subsequently, the problem was formally stated, optimally formulated, and solved in a computationally efficient manner by means of two heuristic algorithms. Finally, results were presented. Issues for further study include the following. First, the experimentation with alternate load evaluation models. Second, the expansion of the set of heuristics that may solve the problem. Third, the fine-tuning of heuristics and the integration in an overall cellular network planning tool, and the realisation of more general experiments. This last feature requires a platform as the one specified in [41,42].

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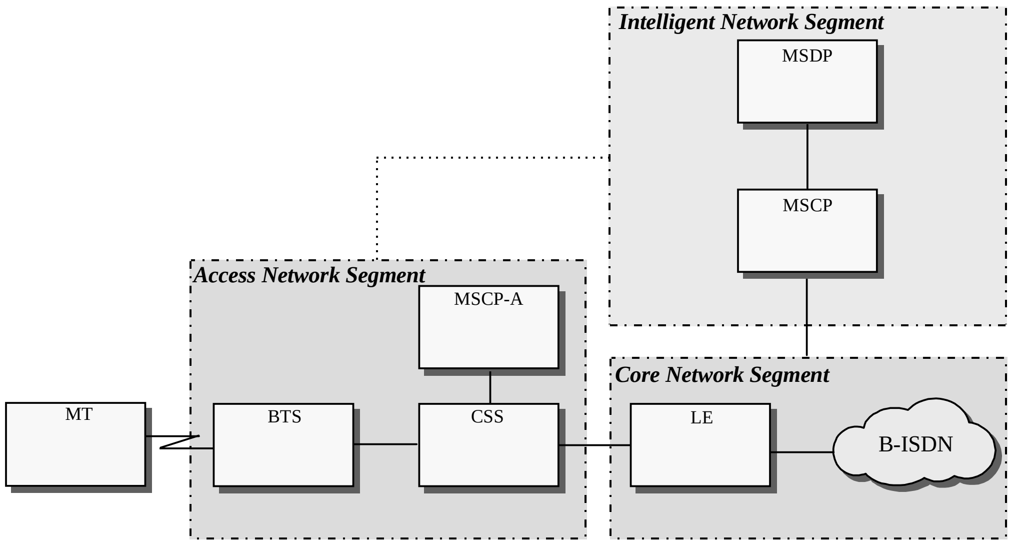


Figure 1. UMTS system architecture - Reference configuration

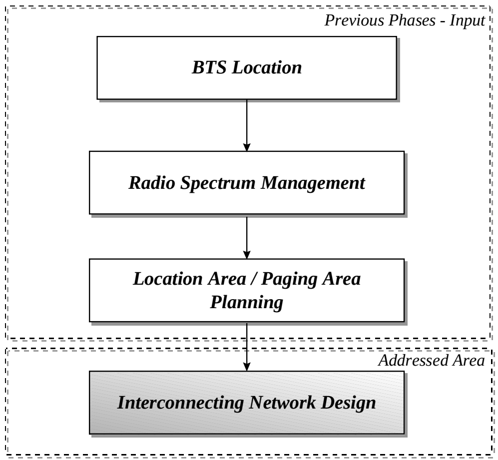


Figure 2. Problem areas in the overall access segment design

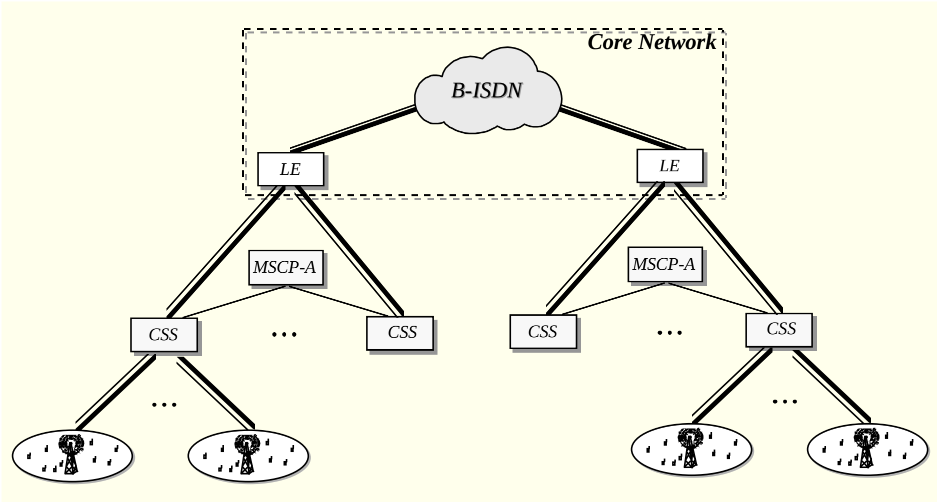


Figure 3. Architecture of the interconnecting network of the access segment of future cellular networks

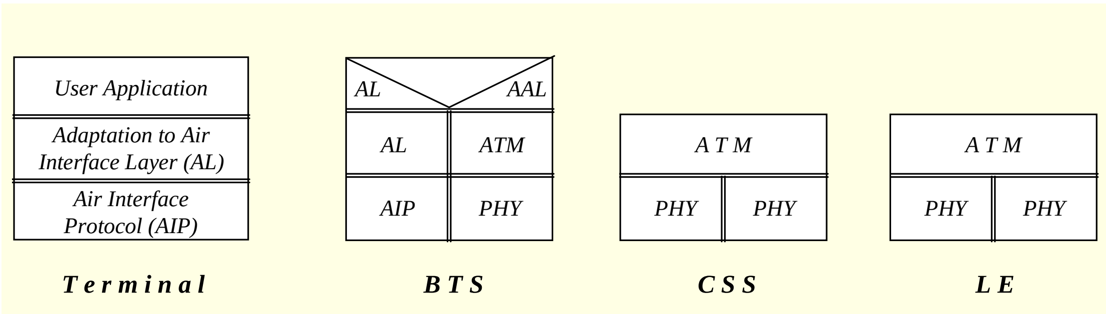


Figure 4. Protocol stacks supporting the ATM-based interconnecting network

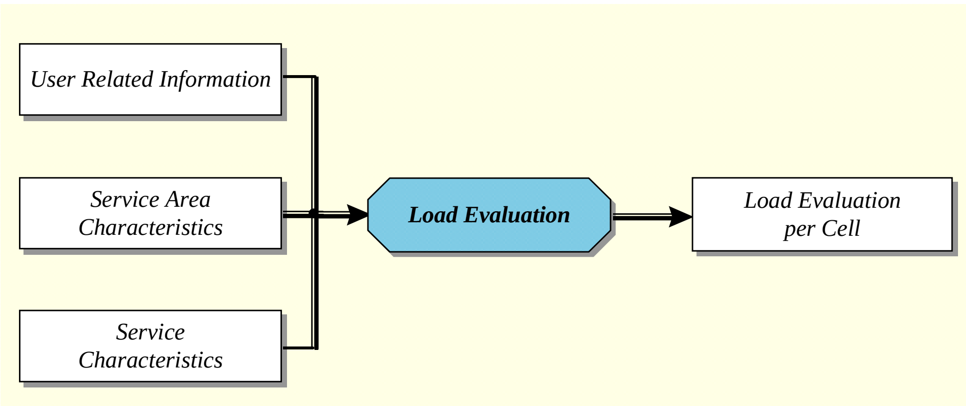


Figure 5. Load evaluation process

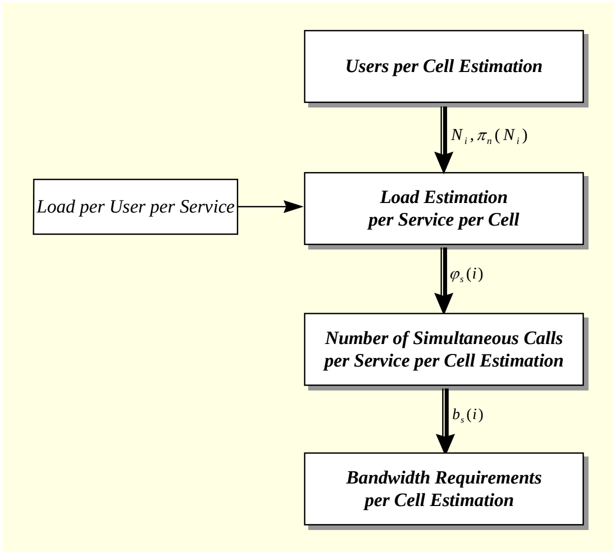


Figure 6. Bandwidth estimation process

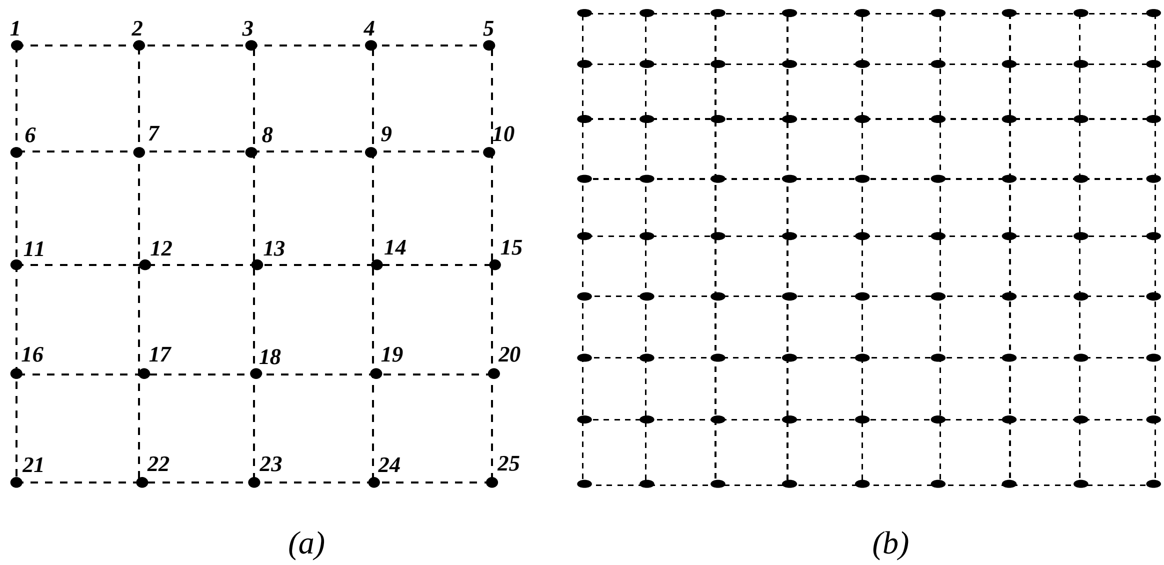
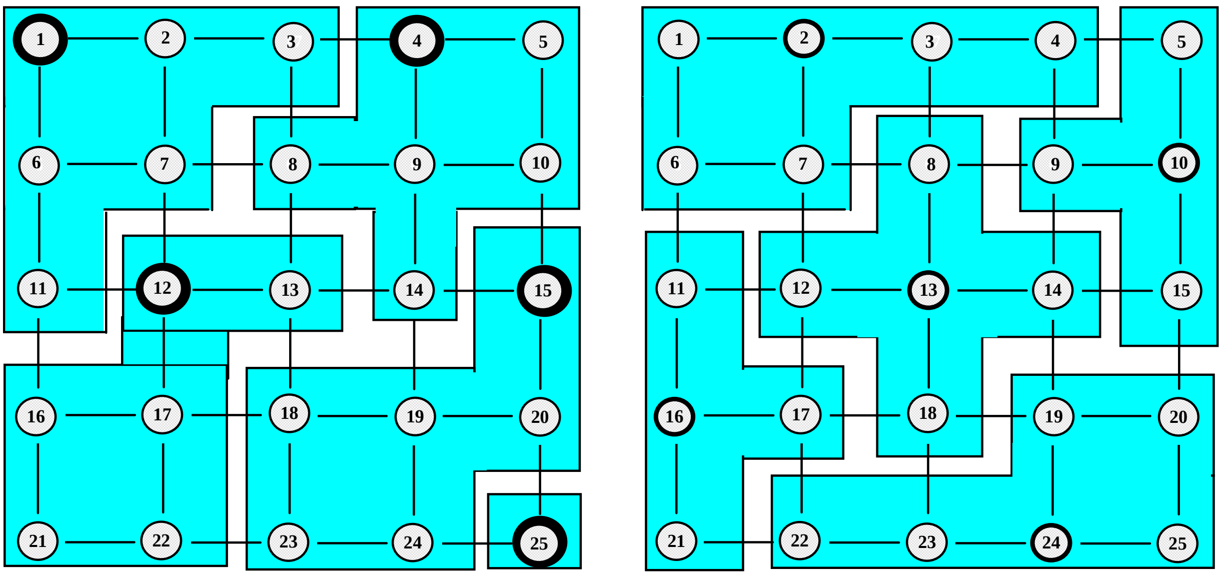


Figure 7(a) - (b): Square grid cell structure

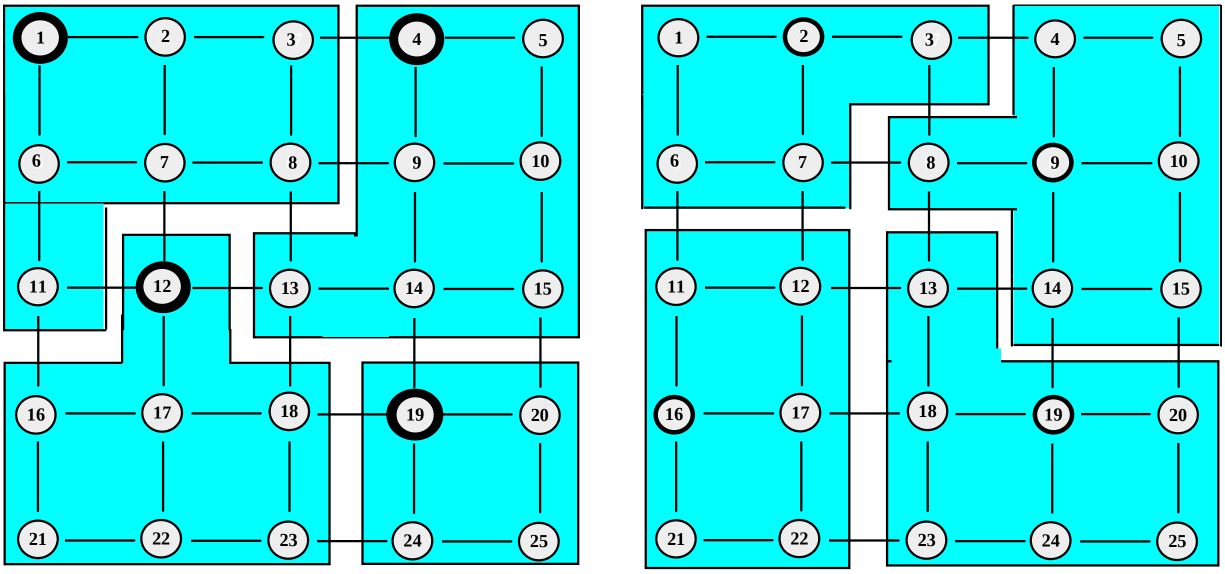
Table 1: Service related characteristics

s	***Service Type***	$1/\mu_s$	C_s	***Blocking Probability***
1	Basic Telephony	90	85	0.01
2	Telefax	30	170	0.01
3	Video Conference	180	1000	0.01
4	D.B Browsing	180	85	0.01
5	D.B Access	30	1850	0.01



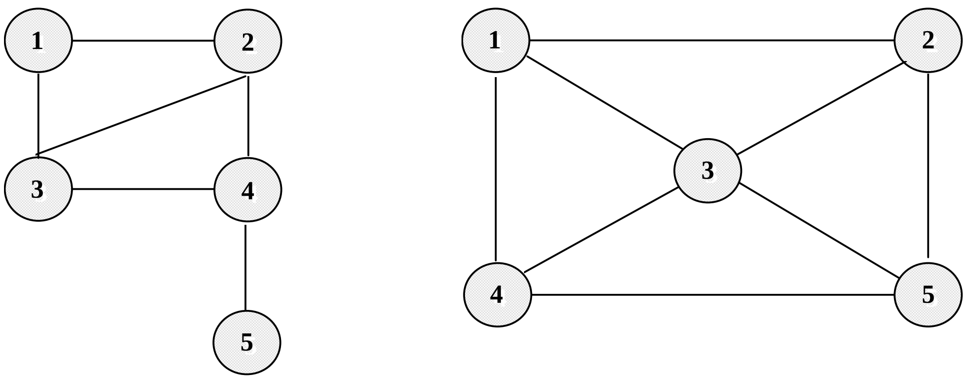
(a) (b)

Figure 8(a)-(b). Allocation of BTSs to CSSs, when the BTS structure is the one depicted in Figure 7(a) and the CSS capacity is taken equal to 350000 cps and (a) the greedy algorithm is applied and (b) the simulated annealing algorithm is applied



(c) (d)

Figure 8(c)-(d). Allocation of BTSs to CSSs, when the BTS structure is the one depicted in Figure 7(a) and the CSS capacity is taken equal to 450000 cps and (c) the greedy algorithm is applied (d) the simulated annealing algorithm is applied



(a) (b)

Figure 9(a)-(b). CSS structure in our experiments when the CSS capacity is taken equal to 350000 cps and (a) the greedy algorithm is applied (b) the simulated annealing algorithm is applied

(c) (d)

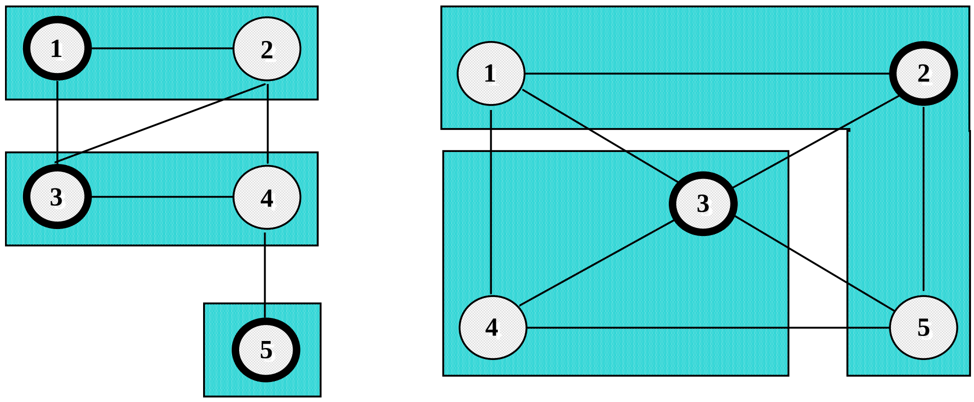
Figure 9(c)-(d). CSS structure in our experiments when the CSS capacity is taken equal to 450000 cps and (a) the greedy algorithm is applied (b) the simulated annealing algorithm is applied

Table 2: CSS requirements for the structure of figure 9(a)-(b)

CSS Number	**CSS Location for the Greedy (Simulated Annealing) algorithm**	**CSS Load (invocations per hour)**	**CSS Load (cells per second)**
1	1 (2)	503808 (503808)	343740 (343740)
2	4 (10)	503808 (335872)	343740 (229160)
3	12 (13)	503808 (419840)	343740 (286450)
4	15 (16)	503808 (335872)	343740 (229160)
5	25 (24)	83968 (503808)	57290 (343740)

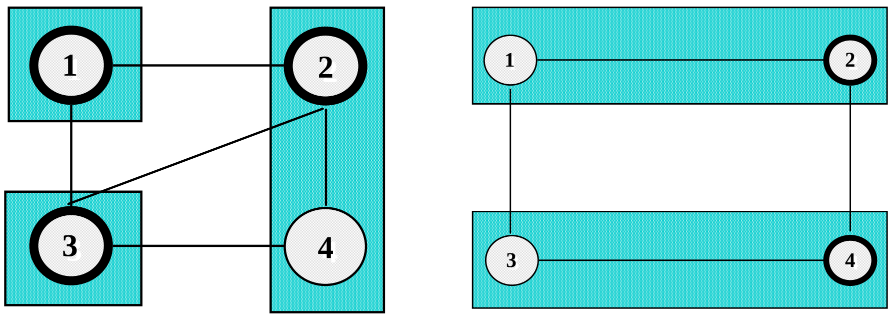
Table 3: CSS requirements for the structure of figure 9(c)-(d)

CSS Number	**CSS Location for the Greedy (Simulated-Annealing) algorithm**	**CSS Load (invocations per hour)**	**CSS Load (cells per second)**
1	1 (2)	587776 (419840)	401030 (286450)
2	4 (9)	587776 (587776)	401030 (401030)
3	12 (16)	587776 (503808)	401030 (343740)
4	19 (19)	335808 (587776)	229160 (401030)



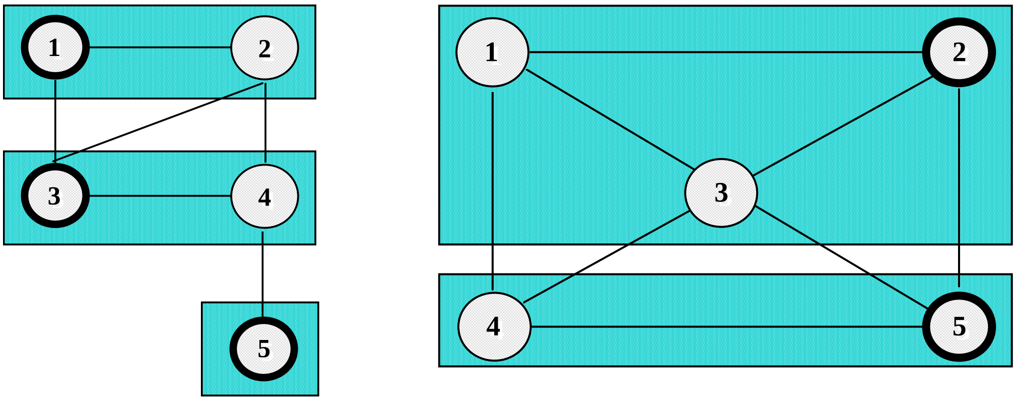
(a) (b)

Figure 10(a)-(b). LE coverage in our experiments when the LE capacity is taken equal to 1000000 cps, the CSS structure is the one in figure 9(a)-(b) and the respective CSS requirements are presented in Table 2



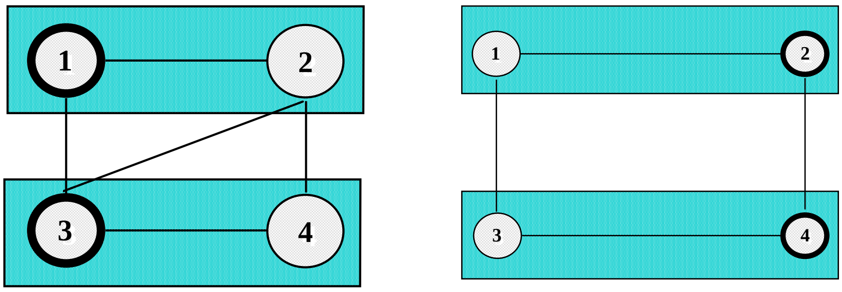
(c) (d)

Figure 10(c)-(d). LE coverage in our experiments when the LE capacity is taken equal to 750000 cps, the CSS structure is the one in figure 9(c)-(d) and the respective CSS requirements are presented in Table 3



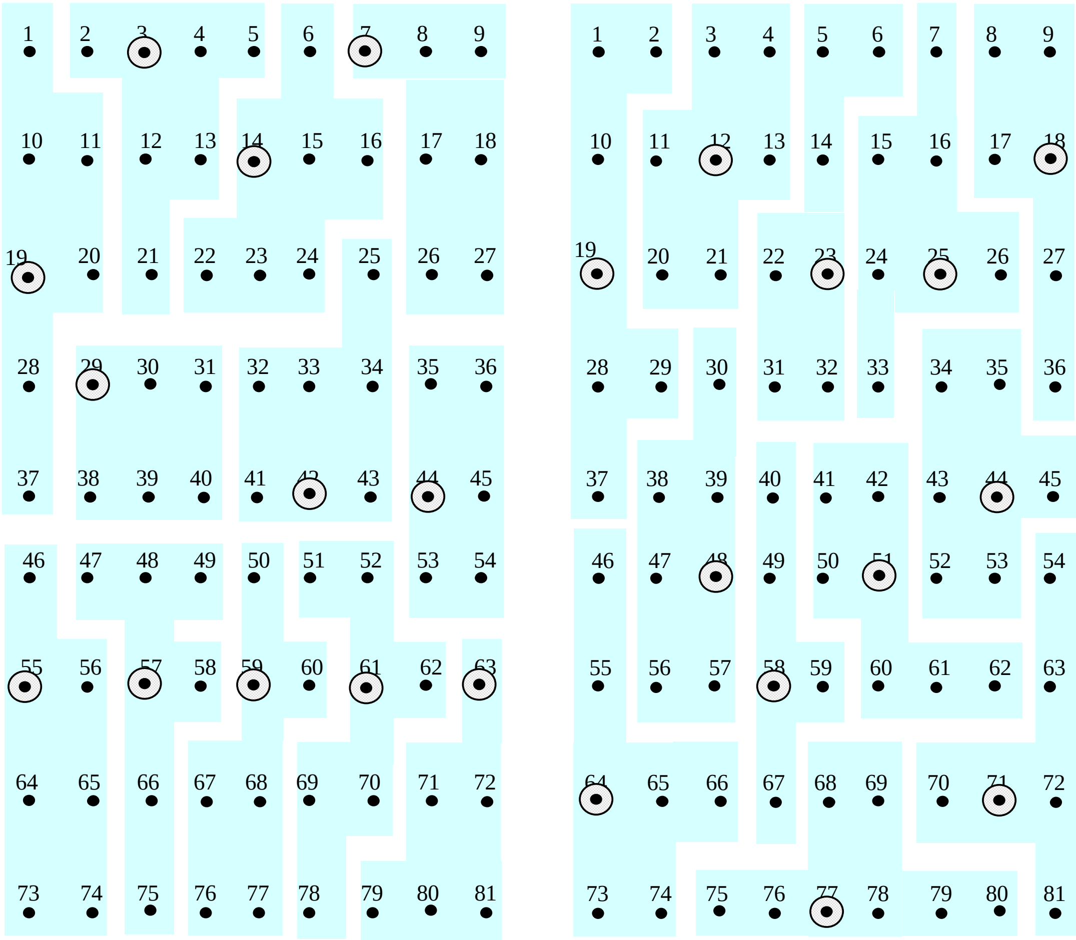
(a) *(b)*

Figure 11(a)-(b). MSCP-A coverage in our experiments when the MSCP capacity is taken equal to 1300000 oph, the CSS structure is the one in figure 9(a)-(b) and the respective CSS requirements are presented in Table 2



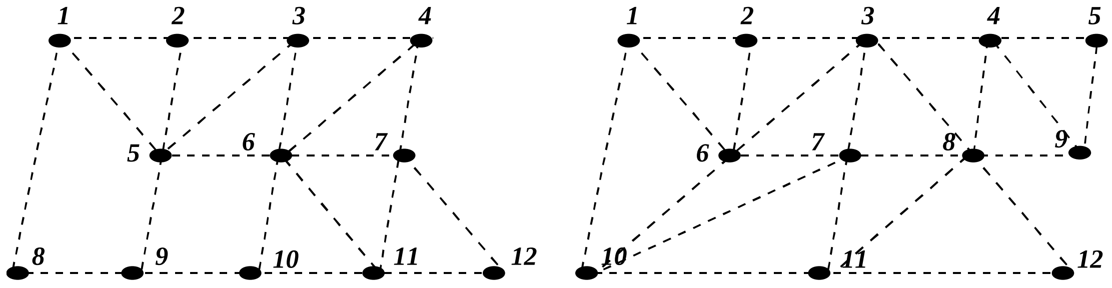
(c) (d)

Figure 11(c)-(d). MSCP-A structure in our experiments when the MSCP capacity is taken equal to 1300000 oph, , the CSS structure is the one in figure 9(c)-(d) and the respective CSS requirements are presented in Table 3



(a) *(b)*

Figure 12(a)-(b). Allocation of BTSs to CSSs, when the BTS structure is the one depicted in Figure 7(b) and the CSS capacity is taken equal to 450000 cps and (a) the greedy algorithm is applied and (b) the simulated annealing algorithm is applied

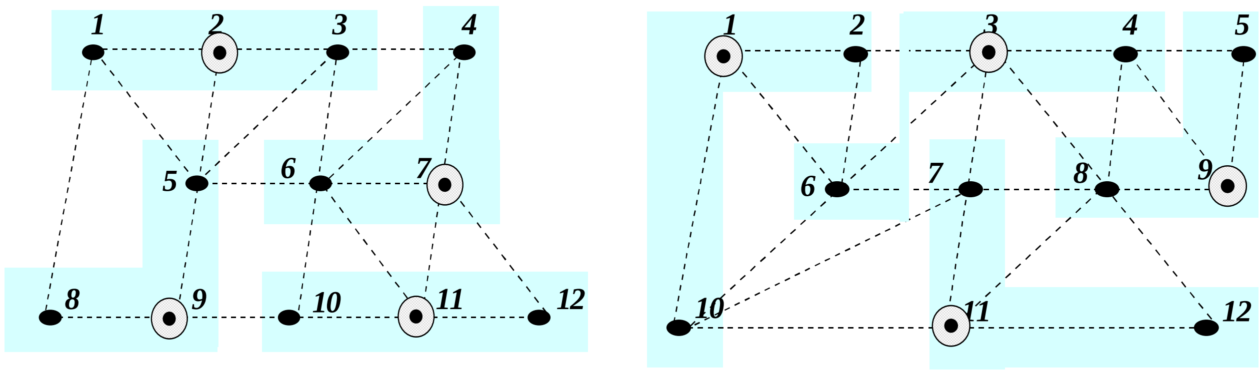


(a) (b)

Figure 13(a)-(b). CSS structure in our experiments when the CSS capacity is taken equal to 450000 cps and (a) the greedy algorithm is applied (b) the simulated annealing algorithm is applied

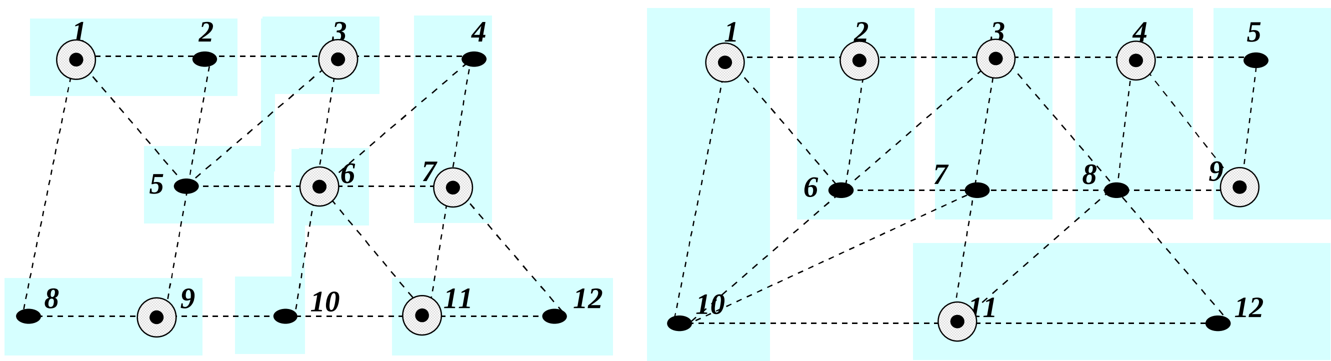
Table 4: CSS requirements for the structure of figure 12(a)-(b)

CSS Number	**CSS Location for the Greedy (Simulated Annealing) algorithm**	**CSS Load (invocations per hour)**	**CSS Load (cells per second)**
1	19 (19)	587776 (587776)	401030 (401030)
2	3 (12)	587776 (587776)	401030 (401030)
3	14 (23)	587776 (587776)	401030 (401030)
4	7 (25)	587776 (587776)	401030 (401030)
5	29 (18)	503808 (503808)	343740 (343740)
6	42 (48)	587776 (587776)	401030 (401030)
7	44 (58)	503808 (419840)	343740 (286450)
8	55 (51)	587776 (587776)	401030 (401030)
9	57 (44)	587776 (587776)	401030 (401030)
10	59 (64)	587776 (587776)	401030 (401030)
11	61 (77)	587776 (587776)	401030 (401030)
12	63 (71)	503808 (587776)	343740 (401030)



(a) (b)

Figure 14(a)-(b). LE coverage in our experiments when the LE capacity is taken equal to 1250000 cps, the CSS structure is the one in figure12(a)-(b) and the respective CSS requirements are presented in Table 4



(a) *(b)*

Figure 15(a)-(b). MSCP coverage in our experiments when the LE capacity is taken equal to 1500000 cps, the CSS structure is the one in figure12(a)-(b) and the respective CSS requirements are presented in Table 4