Cost-efficient Design of Future Broadband Fixed Wireless Access Systems

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Abstract.

In future broadband fixed wireless access systems the overall design procedure is critical for their successful commercial deployment as well as their efficient operation and management. The problem addressed in this paper is twofold. Specifically, at a first phase the radio access network planning problem is addressed, which aims at finding the minimum-cost configuration of *Access Point Transceivers* (APTs) given the geographical layout of the area to be covered. At the second phase, the interconnecting planning problem is addressed and aims at finding the minimum-cost configuration of the *Access Point Controllers* (APCs) and *Inter-Working Units* (IWUs) given the *Access Point Transceivers* layout. Both problems are formally defined, optimally formulated, and solved by computationally efficient heuristics. Finally, results are provided and subsequent conclusions are drawn.

KEY WORDS: BFWA systems; planning tools; 0-1 linear programming; simulated annealing

1. INTRODUCTION

In telecommunication networks fixed radio technologies traditionally play an important role, especially if right of way constraints, adverse terrain conditions and

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speed of deployment are the driving forces. Nowadays, Broadband Fixed Wireless Access (BFWA) systems have been expected to contribute successfully to the last mile problem. In the frame of liberalisation and deregulation of the telecommunication sector, BWFA systems offer new operators unlimited access to a customer database, which up to now has been fully in the hand of the incumbent [1,2,3,4,5,6]. From the viewpoint of the users, the success of these systems will depend on the service spectrum they offer, as well as on the QoS they will provide and especially, on whether it will be comparable to the quality levels offered by fixed wired systems. From the providers' perspective, the aim will be to provide QoS in the most cost efficient manner. In this context, planning tools are expected to play a significant role in meeting these challenges, enabling operators to design from scratch or to expand and modify their systems by providing solutions to difficult combinatorial problems [7,8,9,10].

Future broadband communications systems have been conceived as consisting of the following two segments: (a) the *core network* segment that provides the switching and transmission functions, and (b), the *access network* segment that enables inter-working between the customer premises and the fixed network. A detailed description of the multilevel, star one architecture of fixed wireless access systems is illustrated in figure 1. Figure 1 depicts also the network elements that appear in each segment. In brief, the role of the elements in the access segment may be summarised in the following. The APTs provide radio link management, the APCs provide switching functionality, as well as connection and call control, while the IWUs enable the inter-working among the access network segment (and consequently, the customer premises) with the fixed network. Therefore, the IWUs complement the switching infrastructure by being points of interface with the core segment. An assumption may be that IWUs are owned, administered, and offered for rent by the backbone network operator.

The subject of this paper falls into the overall design procedure. In the context of the overall access segment design a number of problems may be addressed. In brief, the first aims at finding the minimum cost APT configuration which guarantees radio coverage and traffic performance over the service area beyond a certain level, thus providing the required QoS, given the layout of the geographical area to be covered.

The second is targeted to the efficient utilisation of the (scarcely) available radio spectrum. At the final stages of the overall access network design problem, the interconnecting network planning problem is addressed, which aims at finding the minimum cost APC and IWU configuration given the APT layout. In general, accomplishment of the aforementioned tasks involves definition of the cost functions and specification of the respective problem constraints (related primarily to system performance requirements and equipment capabilities).

In this paper, two of the aforementioned problems are addressed. The aim of the first problem is to find the minimum cost configuration of the APTs given the layout of the sub-areas (henceforth called grids) constituting the geographical area to be covered, while the second is targeted to the minimum cost configuration of the candidate APCs and IWUs, given the APT configuration obtained in a previous phase. Inputs from the previous phase are the APT layout and the pertinent traffic requirements. Consequently, the aim is to obtain the minimum cost configuration of the network segment i.e., best allocation of grids to APTs, APTs to APCs and APCs to IWUs that satisfies the problem constraints.

The work of this paper is related to pertinent previous work in the literature, since software tools for cellular or broadband system design is a topic that attracts attention of the researchers. While most BFWA systems use a cellular structure they are far from cellular in their operation and characteristics. At this point we should present the main features of BFWA systems, which differentiate the overall design procedure with respect to mobile communication systems. Without being exhaustive, the focal points are the following. First, as a consequence of users' fixed locations, the initial deployment of BFWA systems aims at covering areas with high demand for innovating and traffic consuming services. Accordingly, BFWA systems have a modular structure and they are developed gradually and progressively following the market demand curve. However, this is not the case in mobile communication systems, which aim at an initial wide area coverage. Second, there is no requirement for handover procedure between neighboring APTs, since the users do not move while a connection is in use. Third, BFWA systems use narrow-beam, high gain antennas for consumer units, thus a careful and precise pointing is required. The benefit of narrow beam angle is clearly that it enables interference from other stations or from reflected signals to be eliminated by careful pointing. Fourth, the usage of sectorised antennas at APTs with the employment of different polarisation schemes, lead to an increased capacity, which in conjunction with the static nature of the paths that make QoS calculations more predictable, enables the BFWA systems to meet the higher bandwidth requirements for business connections. Fifth, the line-of-sight nature of BFWA systems mandated by the usage of microwave frequencies means that adequate coverage (one of the major prerequisites for successful commercial deployment) is dependent upon terrain features and environmental conditions. In this context, the cell overlapping notion constitutes a desirable feature of BFWA systems, as it forms a means of reliable coverage provision over the service area.

Our approach for addressing this problem is the following. In section 2, the radio access network segment design is addressed. Specifically, the high level definition of the radio access design problem is provided, the formal problem statement is described and the problem is optimally formulated as a 0-1 linear planning problem [11,12]. A computationally efficient solution based on simulated annealing algorithm [13,14] is provided in order to acquire the optimal solution [15]. In a similar manner, in section 3, the interconnecting network planning problem is addressed. Specifically, the problem is described, formally defined, optimally formulated and computationally efficient solved following again the simulated annealing technique. Finally, indicative results are presented in section 4 and concluding remarks are drawn in Section 5.

The contribution of this paper lies in the following areas. First, the definition and mathematical formulation of (one possible version) of the radio access network planning problem as well as the interconnecting planning problem. Through this work it is shown that the problems can be reduced to well-known optimisation problems, which can be solved by relevant standard algorithms. Second, the presentation of two novel, computationally efficient algorithms based on simulated annealing technique, which are adopted for the solution of the problems. Third, the provision of indicative evidence on the performance of the algorithms by applying them to a different set of experimental cases, with alternate coverage and/or capacity constraints.

2. PROBLEM 1 : RADIO ACCESS NETWORK DESIGN

2.1 High Level Problem Description

This section provides a high level definition of the version of the radio-access network segment planning problem addressed in the first part of this paper. The radio access network design may be decomposed in the following sub-phases (depicted also in figure 2). In brief, the first aims at identifying and determining the candidate sites for APTs given the geographical layout. To this end, a *Business Model Analysis* should be conducted in order to evaluate the business potential of the network. Without being exhaustive, this task involves evaluation of customer coverage with respect to the revenue potential taking into account environment type (i.e., business, residential), service packages, service penetrations etc. The second phase involves *Environmental Analysis*, which aims at capturing and evaluating the service area requirements. This task comprises the following aspects. First, radio-coverage area estimation with respect to each pre-defined candidate APT site. Second, load evaluation denoting the traffic requirement associated with each grid.

The third phase is targeted to the construction of an optimisation module in order to find the minimum cost APT configuration provided that the system performance will be within acceptable range. In this respect, an APT deployment is determined that satisfies the service area requirements identified in the previous phase. The final phase of the radio access network design comprises many subtasks such as adjustment of the APTs transmitting power with respect to the APT configuration obtained during the previous phase, further adjustment of the aforementioned values in order to account for terrain irregularities and conduction of interference analysis, required for an efficient frequency planning scheme at a latter stage. At this phase, one may also elaborate on the cell-overlapping notion, as it constitutes a means of reliable coverage provision over the service area. In the scope of our paper, grids with potential coverage limitation due i.e., to terrain irregularities or special environmental conditions are identified and given the capability to be served by two distinct APTs.

Based on the above description we may provide the high level definition of the pertinent design problem. Our focus is laid on phase 3, while specific inputs to this phase are the pertinent results of phases 1 and 2. Specifically, our aim is to find the minimum cost APT configuration given the geographical layout, while the system performance is guaranteed (within acceptable limits). Accomplishment of this task involves definition of the cost function and specification of the constraints that derive primarily from service area requirements and the APTs respective capabilities. Finally, following the principle of cell overlapping, for a given set of grids attributed with coverage limitations, two distinct APTs ensure adequate coverage.

The cost function of the radio access network design problem may consist of the following factors. First, the cost of the equipment (namely, APTs) that need to be deployed (involved in the solution) in order to adequately cover the geographical area. Second, the cost of assigning grids to APTs. This factor is strongly related to the distance between the location of the grid and the site of the deployed APT and is introduced in order to model the fact that neighboring to an APT site grids are covered by the candidate APT more economically than the rest of them. The constraints of the problem derive primarily from the capabilities of the relative equipment, namely APTs. These may be expressed in terms of their capacity (maximum bandwidth they can handle as well as maximum number of CPEs they may serve), while coverage and traffic performance related factors need to be within the pre-defined thresholds suggesting that system performance will be kept within acceptable range.

Taking into account the aspects outlined above, a general problem statement may be the following. Given the grid layout representing the geographical area to be covered, the bandwidth requirement (aggregate traffic load) corresponding to each grid, a set of candidate APT sites, the coverage area of each candidate APT, the cost of each APT and the cost of assigning a grid to an APT, find the minimum cost assignment of grids to APTs (in terms of the number of APTs that need to be deployed and the cost of assigning a grid to an APT), subject to a set of constraints, associated with system performance and respective capabilities of the APTs.

2.2 Formal Problem Statement

This section provides the formal statement of the version of the radio access network planning problem addressed in this paper. A_T represents the set of candidate APT sites. Given is the set of grids representing the geographical layout, denoted by G, the coverage area CA_j ($j \in A_T$) of each candidate APT-j, and for each grid-i ($i \in G$), the capacity (bandwidth) requirement bw_i. The assumption in the previous notations is that the coverage area CA_j ($j \in A_T$) comprises a set of grids that could be potentially assigned to APT-j i.e., APT-j satisfies coverage constraints of each grid-i ($i \in CA_j$).

Let T_j denote the set of grids that will be assigned to APT-j ($j \in A_T$). The objective is to find the assignment A_{APT}, where $A_{APT} = \{T_j \mid j \in A_T\}$ ($T_j \subseteq G$). This assignment should minimise a cost function that may be represented as $f(A_{APT})$.

The following factors contribute to the cost of the assignment. First, the cost of the APTs, that will need to be deployed. This cost is denoted as c_{APT}. This factor comprises hardware as well as installation cost. For notation simplicity it is assumed that the cost of deploying an APT is the same in all sites. As an alternative this cost could be taken variant (depending on the cost of acquiring and/or maintaining the site etc.). Notation may readily be extended. The second cost factor is that of assigning grids to APTs. We assume that set $P_{APT} = \{p_{GT}(i, j) \mid i \in G, j \in A_T\}$ provides the cost of assigning grid-i to the APT that may be located at the candidate site j. This cost is strongly related to the distance between location of grid-i and the APT-j site and is introduced in order to account for dependencies between cost and equipment specific properties dependent on distance (i.e., antennas with respect to gain, transmitters/receivers with respect to peak transmitting power).

The constraints of our problem are the following. First, each grid should be assigned to one APT. Therefore, $T_{j_1} \cap T_{j_2} = \varnothing$ for all $(j_1, j_2) \in A_T^2$. Second, all grids should be assigned to an APT. Hence, $\bigcup_{j \in A_T} T_j = G$. Third, the coverage constraint with respect to each APT should be satisfied. Accordingly, $T_j \subseteq CA_j$. Fourth, the capacity constraints of each APT should be preserved. Lets assume that $\varphi_{APT}^{\max}$ and k_{APT} represent the maximum load (bandwidth) and the maximum number of grids that an APT may handle. The constraints are $\varphi_T(T_j) \le \varphi_{APT}^{\max}$, $|T_j| \le k_{APT}$. The assumption in the previous constraints is that function $\varphi_T(T_j)$ provides the bandwidth requirements of the grids assigned to APT j. It is noted that k_{APT} may be easily derived by dividing the maximum number of CPEs that an APT can handle with the potential number of CPEs installed per grid.

For notation simplicity is assumed that set G comprises grids belonging to the same environment type (i.e., urban, suburban, rural). Notation may readily be extended. In the general case, a new constraint will be introduced which concerns the assignment of grids belonging to only one environment type to an APT.

The general problem version is open to various solution methods. Its generality partly lies in the fact that the objective and the constraint functions are open to alternate implementations. The problem statement can be distinguished from the specific solution approach adopted in the next subsection. In the sequel, we discuss about optimal and computationally efficient solutions.

2.3 Optimal Formulation

This section provides the optimal formulation of the version of the radio access network planning problem addressed in this paper as a 0-1 linear programming problem. The experimentation and comparison with important alternate formulation approaches is a stand-alone issue for future study. In order to describe the allocation A_{APT} of grids to APTs we introduce the decision variables $x_{GT}(i,j)$ ($i \in G$, $j \in A_T$) that take the value 1(0) depending on whether grid-i is (is not) connected to APT-j.

The decision variable $y_{APT}(j)$ assume the value 1(0) depending on whether candidate APT j ($j \in A_T$) is (is not) deployed. In addition, we define the variable $b(i,j)$ ($i \in G$, $j \in A_T$) that take the value 1(0) depending on whether the grid-i belongs to the coverage area of the APT-j. Finally, the set of variables $z_G(i,i')$ ($\forall (i,i') \in G^2$) is defined that take the value 1(0) depending on whether the grids i and i' belong (do not) to the same environment type.

Allocation A_{APT} may be obtained by reduction to the following 0-1 linear programming problem.

Problem 1 [Radio Access Network Design]: Minimise

$$c_{APT} \sum_{j=1}^{|A_T|} y_{APT}(j) + \sum_{i=1}^{|T|} \sum_{j=1}^{|A_T|} p_{GT}(i,j) \cdot x_{GT}(i,j) \qquad (1)$$

subject to,

$$\sum_{j=1}^{|A_T|} x_{GT}(i,j) = 1 \qquad , \forall i \in G , \qquad (2)$$

$$x_{GT}(i,j) \le b(i,j) \cdot y_{APT}(j) \qquad , \forall (i \in G, j \in A_T) , \qquad (3)$$

$$x_{GT}(i,j) \cdot x_{GT}(i', j) \le z_G(i,i') \cdot y_{APT}(j) \qquad , \forall ((i,i') \in G^2 , j \in A_T) \qquad (4)$$

$$\sum_{i=1}^{|G|} x_{GT}(i,j) \le k_{APT} \cdot y_{APT}(j) \qquad , \forall j \in A_T , \qquad (5)$$

$$\sum_{i=1}^{|G|} x_{GT}(i,j) \cdot bw_i = \varphi_T(j) \le \varphi_{APT}^{\max} \cdot y_{APT}(j) \qquad , \forall j \in A_T , \qquad (6)$$

Cost function (1) penalises the aspects identified in section 2.1-2.2 (i.e., cost of the equipment deployed and cost of assigning a grid to an APT). Constraint (2) guarantees that each grid will be assigned to one APT. Constraint (3) guarantees that a grid will not be assigned to an APT if it does not belong to the respective radio coverage area. Constraint (4) ensures that all grids assigned to an APT will belong to the same environmental type. Finally constraints (5) and (6) express the traffic requirements to be satisfied. Specifically, constraint (5) guarantees that APTs will not be assigned more grids than allowed according to their capacity constraints, while constraint (6) guarantees that each APT will not have to cope with more load than that dictated by its pertinent capacity constraint.

2.4 Computationally Efficient Solution

The optimal formulation presented in the previous section yields that the solution of the radio access network planning problem in general could be a computationally intensive task. This means that an optimal algorithm, especially in case the problem instance is prohibitively large, may not be able to provide a solution in reasonable time. Furthermore, the optimal formulation comprises many variables. The usual next step for solving such difficult problems is to devise computationally efficient algorithms that may provide good solutions in reasonable time. Classical methods in this respect are simulated annealing [13,14] taboo search [16,17], genetic algorithms [18,19,20,21], greedy algorithms, etc. Hybrid or user defined heuristic techniques may also be devised.

As already stated, in this sub-section we present an algorithm that follows the simulated annealing paradigm.

Annealing is the physical process in which a crystal is cooled from the liquid to the solid state. Careful cooling brings the crystal in the minimum energy state. In analogy, a simulated annealing algorithm considers each solution of the optimisation problem as a state, the cost of each solution as the energy of the state, and the optimal solution as the minimum energy state. During each phase of the algorithm a new solution is generated by minimally altering the currently best solution (in other words, the new solution is chosen among those that are “neighbouring” to the currently best one). If the cost value that corresponds to the new solution is smaller (i.e., the difference among the cost of the old and the new solution, Δc, is positive) the new solution becomes the currently best solution. Solutions that increase the cost may also be accepted with probability $e^{-(\Delta c/CT)}$ (Metropolis criterion). This is a mechanism that assists in escaping from local optima. CT is a control parameter, which may be perceived as the physical analogous of the temperature in the physical process. The algorithm ends when either $CT=0$ (temperature reaches 0) or when a significant number of moves have been made without improving the cost function.

As also stated in [22] 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 $\{x_{GT}(i,j), y_{APT}(j)\}$, that satisfy the constraints (2)-(6). The cost function is the one introduced by relation (1). The neighbourhood structure of a solution is produced by moving a grid i from its present APT-j to a neighbouring APT-j'. This new assignment guarantees the satisfaction of the constraints (2)-(6). 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-Initial APT Assignment.

Step 0. Initialisation. Get an initial solution, IS, and an initial temperature value T.

The currently best solution (CBS) is IS, i.e., $CBS = IS$, 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.

By means of the algorithm described above, an initial good assignment of grids to APTs $\tilde{A}_{init}$ has been found. The algorithm, however, may overestimate the required number of APTs. Assuming that there are no radio coverage limitations, the minimum number of APTs may be estimated by dividing the total load that originates from the grids with the capacity constraint of the APTs. However, this number may be larger in order to account for the radio coverage constraints. The number of APTs included in the solution is assumed to be the main factor contributing to the cost function. In this sense, the second phase is targeted to the elimination of some APTs. This procedure works as follows. The least loaded APTs (APTs that are assigned with few grids) are candidates for elimination. The grids assigned to the eliminated APTs need to be assigned to the APTs that remain in the solution, provided that the coverage and traffic constraints are preserved. In the context of this procedure, it is possible to deploy the remaining APTs in different sites, so as to be able to acquire the new grids. Moreover, the APTs that remain in the solution may have to release grids (so as to acquire the new ones). For brevity, the formal description of the algorithm is not provided. Finally, we obtain a new, improved assignment $\tilde{A}_{APT}$. These two phases are depicted in figure 3.

As a final phase to the design problem addressed in section 2, we elaborate on the overlapping notion. Specifically, in the context of our analysis, grids with potential coverage constraints are identified and allowed to have access to services through two APTs. In this sense, this phase is targeted to the determination of the second potential APT that could provide services to each of the identified grids. This procedure works as follows. Attempts to assign each grid to an APT already deployed in the solution are conducted. It is possible to adjust the transmitting power of an APT, so as to satisfy the related coverage constraints of our problem when the new grid is assigned to it, or even to relocate APTs at different sites. More than one APT may be satisfying the respective radio coverage and traffic constraints and therefore form a solution to our problem. However, in our study, the closest APT deployed to each grid is considered for the provision of services. That is adopted so as to minimise the interference introduced in our system due to the increase of the transmitting power required. In any case the new assignment satisfies the constraints (2)-(6) of our problem. The formal description of the algorithm may be readily provided.

3. PROBLEM 2 : INTERCONNECTING NETWORK DESIGN

3.1 Problem statement and formulation

This section provides the optimal formulation of the version of the interconnecting network planning problem addressed in this paper. Given is the set of APTs, denoted by T, and for each APT-i ($i \in T$), the capacity (bandwidth) requirement $\varphi_T(i)$. C represents the set of candidate APC sites and I the set of candidate IWU sites.

Let C_j denote the set of APTs that will be connected to APC-j ($j \in C$), and I_k denote the set of APCs that will be connected to the k-th IWU ($k \in I$). The objective is to find the allocations A_{APC} and A_{IWU} where $A_{APC} = \{C_j | j \in C\}$ ($C_j \subseteq T$), and $A_{IWU} = \{I_k | k \in I\}$ ($I_k \subseteq C$). These should minimise a cost function that may be represented as $f(A_{APC}, A_{IWU})$.

The following factors contribute to the cost of the allocations. First, the cost of the APCs, and IWUs that will need to be deployed. These costs are denoted as c_{APC} and c_{IWU} respectively. For notation simplicity it is assumed that the cost of deploying a network element (of a certain type) is the same in all sites. As an alternative this cost could be taken variant (depending on the cost of acquiring and/or maintaining the site, etc.). Notation may readily be extended. The second cost factor is that of inter-connecting APTs to APCs, and APCs to IWUs. We assume that the set $P_{APC} = \{p_{TC}(i, j) | i \in T, j \in C\}$ provides the cost of connecting APT-i to the APC that may be located at the candidate site j. In a similar manner, the cost of connecting the APC that may be located at candidate site j, to the IWU that may be located at candidate site k, is provided by set $P_{IWU} = \{p_{CI}(j,k) | j \in C, k \in I\}$.

The constraints of our problem are the following. First, each APT should be assigned to one APC, and each APC should be assigned to exactly one IWU. Therefore, $C_{j_1} \cap C_{j_2} = \varnothing$ for all $(j_1, j_2) \in C^2$ and $I_{k_1} \cap I_{k_2} = \varnothing$ for all $(k_1, k_2) \in I^2$. Second, all APTs should be assigned to an APC, and all APCs should be assigned to an IWU. Hence, $\bigcup_{j \in C} C_j = T$ and $\bigcup_{k \in I} I_k = C$. Third, the capacity constraints of each APC and IWU should be preserved. Lets assume that $\varphi_{APC}^{\max}$, and k_{APC} represent the maximum load (bandwidth) and the maximum number of APTs that an APC may handle, $\varphi_{IWU}^{\max}$ and k_{IWU} represent the maximum load (bandwidth) and the maximum number of APCs that an IWU may handle. The constraints are $\varphi_C(C_j) \le \varphi_{APC}^{\max}$, $|C_j| \le k_{APC}$, $\varphi_I(I_k) \le \varphi_{IWU}^{\max}$, $|I_k| \le k_{IWU}$. The assumption in the previous constraints is that function $\varphi_C(C_j)$ provides the bandwidth requirements of the APTs assigned to APC j and function $\varphi_I(I_k)$ provides the bandwidth requirements of the APCs assigned to IWU k.

In order to describe the allocation A_{APC} of APTs to APCs we introduce the decision variables $x_{TC}(i, j)$ ($i \in T$, $j \in C$) that take the value 1(0) depending on whether APT-i is (is not) connected to APC-j. In a similar manner, allocation A_{IWU} is described by the decision variables $x_{CI}(j,k)$ that take the value 1(0) depending on whether APC j is (is not) connected to IWU k.

The decision variables $y_{APC}(j)$ and $y_{IWU}(k)$ assume the value 1(0) depending on whether candidate APC j ($j \in C$) and IWU k ($k \in I$) is (is not) deployed. Allocations A_{APC}, and A_{IWU} may be obtained by reduction to the following 0-1 linear programming problem.

Problem 2 [Interconnecting Network Design]: Minimise

$$c_{APC} \sum_{j=1}^{|C|} y_{APC}(j) + \sum_{i=1}^{|T|} \sum_{j=1}^{|C|} p_{TC}(i, j) \cdot x_{TC}(i, j) + c_{IWU} \sum_{k=1}^{|I|} y_{IWU}(k) +$$
$$\sum_{j=1}^{|C|} \sum_{k=1}^{|I|} p_{CI}(j,k) \cdot x_{CI}(j,k) \qquad (7)$$

subject to,

$$\sum_{j=1}^{|C|} x_{TC}(i,j)=1 \qquad , \ \forall i \in T , \qquad (8)$$

$$\sum_{i=1}^{|T|} x_{TC}(i,j) \le k_{APC} \cdot y_{APC}(j) \qquad , \ \forall j \in C , \qquad (9)$$

$$\sum_{i=1}^{|T|} x_{TC}(i,j) \cdot \varphi_T(i) = \varphi_C(j) \le \varphi_{APC}^{\max} \cdot y_{APC}(j) \qquad , \ \forall j \in C , \qquad (10)$$

$$\sum_{k=1}^{|I|} x_{CI}(j,k)=1 \qquad , \ \forall j \in C , \qquad (11)$$

$$\sum_{j=1}^{|C|} x_{CI}(j,k) \le k_{IWU} \cdot y_{IWU}(k) \qquad , \ \forall k \in I , \qquad (12)$$

$$\sum_{j=1}^{|C|} x_{CI}(j,k) \cdot \varphi_C(j) \le \varphi_I^{\max} \cdot y_{IWU}(k) \qquad , \ \forall k \in I , \qquad (13)$$

Cost function (7) penalises the aspects identified in section 3.1 (i.e., cost of the equipment deployed, and cost of interconnecting the network elements deployed). Constraints (8) and (11) guarantee that each APT will be assigned to one APC, and each APC will be controlled by one IWU respectively. Constraints (9) and (12) guarantee that APCs and IWUs will not be assigned more APTs and APCs than allowed by their capacity constraints. Constraints (10) and (13) guarantee that each APC and IWU will not have to cope with more load than that dictated by its pertinent capacity constraint.

3.2 Computationally Efficient Solution

As already stated the algorithm presented in this subsection follows as well the simulated annealing paradigm. A step further for reducing the complexity of *problem 2* (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 two phases, which are targeted to the computation of the allocations A_{APC} (APTs to APCs) and A_{IWU} (APCs to IWUs), respectively. The simulated annealing algorithm may follow both approaches, i.e., divide and conquer or one-phase solution to *problem 2*. In the sequel, we choose to present the second (and more general) version of the algorithm.

The configuration space in our case is the set of feasible solutions $\{x_{TC}(i, j), x_{CI}(j,k), y_{APC}(j), y_{IWU}(k)\}$, that satisfy the constraints (8)-(13). The cost function is the one introduced by relation (7). The neighbourhood structure of a solution is produced by moving an APT i from its present APC j to a neighbouring APC $j^{'}$. This new assignment guarantees the satisfaction of the constraints (8)-(13). The cooling schedule, the stop criterion and the neighbouring solutions are implemented in line with the algorithm presented in subsection 2.4.

4. RESULTS AND DISCUSSION

The previous sections addressed two problems involved in the overall design of the access segment of future broadband fixed wireless communication systems, the radio access and the interconnecting network planning problem. These problems were formally stated, formulated as 0-1 linear programming problems and solved by means of computationally efficient heuristic algorithms. Specifically, the simulated annealing based algorithm was considered for the provision of a near-optimal solution for both problems within reasonable time.

This section provides numerical results. The aim is to provide indicative evidence on the performance of the algorithms, by applying them to a set of experiments. Each experiment may generally be described as follows. The input consists of the service area characteristics (so as to compute the traffic requirements and the radio coverage area of each APT), the capabilities of the APTs, APCs and IWUs, the cost related factors (e.g., equipment and interconnection costs, etc.) and the set of candidate sites, wherein APTs, APCs and IWUs may be deployed. The aim of each experiment will be the following. First, to build the configuration of the radio access network, that is the allocation of grids to APTs given the geographical area to be covered. For brevity, in this section the attention is limited to a unique environmental type (urban, since it is the most demanding one). Second, to build the configuration of the interconnecting network in an hierarchical manner, i.e., starting with the allocation of APTs to APCs, and continuing with the allocation of APCs to IWUs (hence, the simulated annealing-based algorithm will be applied in the divide and conquer mode).

The geographical layouts (respectively, the grid structures) used in our experiments are square (Manhattan) grid networks. This choice does not simplify the computational effort. Other topologies of the same size and connectivity degree could have been chosen instead. At the first experiment a 5x5 square (Manhattan) grid network (figure 4a) is used, while in the second experiment the network is a 7x7 square (Manhattan) grid (figure 4b). The grids constituting the geographical area to be covered are assumed identical, square-like, with dimension $D = 1\ Km$.

At this point it should be noted that the dimension of the grids could vary in the range of a few hundred meters to few kilometers, depending on the environmental type (urban, suburban, or rural), the specific technology adopted (i.e., FWA systems operating in the frequency band of 3GHz, 26GHz or 45GHz) and the traffic demand originating from the service area. Considering urban geographical area and Local Multipoint Distribution Service Technology (LMDS) [4], which results in potential coverage range of 3-5Km, grid dimension equal to $1\ Km$ seems adequate for the scope of our experimentation. Additionally, the grid structure adopted could be similar to a real situation (i.e., small city). However, our main goal is to realise different sets of experiments and provide comments on the obtained results in order to exhibit the performance of the algorithms adopted under different situations (i.e., alternate coverage and capacity constraints).

The rest of this section is organised as follows. Initially, the service area characteristics are exploited in order to compute the problem requirements (bandwidth associated with each grid and potential radio coverage area of each candidate APT). Thus, a load evaluation and radio coverage estimation phase is conducted. Next, the derivation of the appropriate radio access and interconnecting network configurations that may serve the 5x5 and the 7x7 grid layouts (given their requirements) is studied.

The load evaluation phase computes the bandwidth requirement of each grid, which is a requirement that will be posed to the $(grid, APT)$ connection. This quantity in conjunction to the potential radio coverage area of each APT constitutes our problem constraints so as to determine the allocation, since they enable the APT to satisfactorily provide the services in its service area, which is composed of several grids. In our experiments, the methodology proposed in [23] is followed and the same assumptions are adopted. Specifically, it is assumed that Load Evaluation Module input consists of User Related Information, Service Area Characteristics, and Service Characteristics. User Related Information, within a time-zone in the day, consists of the density of users in each grid d_i $(user / km^2)$, and their service preferences, which 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) of each grid 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, grid 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 grids of the system (based on the argument that it is important to provide uniform QoS in all the grids of the system).

Table 1 comprises the set of services offered by the system, 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 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. 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.

The method for evaluating the bandwidth requirement bw_i may be summarised in the following. The average number of users expected in grid i, may readily be estimated through the formula, $N_i = A_i \cdot d_i$. Based on these figures and the population model of [24], the steady state probabilities $\pi_n(N_i)$ that there will be n users in grid 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 grid 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 grid, so as to guarantee that the blocking probability will be within the acceptable range. This phase may be based on the Erlang-B formula [25].

The value assumed for the density of users is $d_i =$ 1.000 $users/Km^2$ ($\forall i \in V$), and hence, $N_i =$ 1000 users is the mean number of users expected per grid. 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), $\rho_3 =$ 1/60 (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 grid is $\varphi_1(i) \cong$ 75, $\varphi_2(i) \cong$ 8.3, $\varphi_3(i) \cong$ 0.83, $\varphi_4(i) \cong$ 12.5 and $\varphi_5(i) \cong$ 1.04 ($\forall i \in V$). The corresponding maximum number of calls of each service that should be supported in each grid, so as to preserve the blocking probability below the predefined levels is, $b_1(i) \cong$ 91, $b_2(i) \cong$ 16, $b_3(i) \cong$ 4, $b_4(i) \cong$ 21, and $b_5(i) \cong$ 5 ($\forall i \in V$).

The final stage (*bandwidth requirement per grid* estimation phase) is targeted to the computation of the bandwidth required by each grid, 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 [26,27]. 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 [28,29,30,31] (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 [32,33]). The equivalent bandwidth approach is often articulated as a popular notion [34] that is suitable for (at least) the current versions of planning tools [35]. 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. Thus, given the (constant and equivalent) bandwidth requirement of each call we obtain that the bandwidth requirement of each BTS is less than 25.500 cells per second (cps), or equivalently, 11 Megabits per second (Mbps).

Regarding the estimation of the coverage area of each candidate APT, we realised two different experiments each time by altering the maximum distance $d_{\max}$ between the APT considered and the grids adequately covered. During the first experiment, $d_{\max}$ is taken equal to 3 Km. For the second experiment, $d_{\max}$ is taken equal to 1.5 Km. Although these values were arbitrary taken, they are quite logical to assume in the case of BFWA systems operating in the band of 26-30 GHz (i.e., LMDS [4]). However, in any practical planning, realistic link calculations have to confirm their feasibility, taking into account three dimensional model of the area, terrain specific features (i.e., local obstructions, foliage) and environmental conditions (i.e., rainfall rate), as Line of Sight propagation conditions may be affected and temporal or permanent unavailability effects may be introduced. Thus, the potential coverage area CA_j of each candidate APT j is found.

Having obtained the bandwidth requirements of the grids and the potential radio coverage area of each candidate APT, we proceed with the first experiment that aims at the derivation of the configuration of the radio access network and of the interconnecting network, for the case of the 5x5 network (figure 4a). As already stated the configuration will be constructed following the simulated annealing based approach. As a first phase, we consider the derivation of the allocation of grids to APTs. Figure 5 depicts the allocation of grids to APTs when the grid network structure and the pertinent requirements are known. A number of experiments is realised, each time by altering the APT capacity. The grid structure is the square (Manhattan) grid structure of figure 4a, the load that originates from each grid area is at most 11 Mbps and the maximum distance $d_{\max}$ between the APT and the most distant grid adequately covered is taken equal to $3\,Km$. The APT capacity is taken equal to 50Mbps in the experiment in figure 5(a), and 100Mbps in the experiment in figure 5(b). The results of figure 5 are obtained by applying the simulated annealing-based algorithm, and after the APT elimination sub-phase is conducted. From the obtained results we observe that the number of APTs that are deployed equals to the minimum number of APTs required, so as to satisfy the capacity constraints of the APTs. Since the load originating from each grid is 11 Mbps and the capacity constraint of each APT is taken equal to 50Mbps, 4 grids at the maximum may be assigned to each APT. Therefore, the minimum number of APTs in the solution is 7, as is also the case in our experiment. Furthermore, as expected due to the looser capacity constraint introduced in figure 5(b), the number of APTs deployed in figure 5(b) is smaller than the one in figure 5(a) (only 3), since each APT may be assigned at the maximum 9 grids.

In the second phase of the first experiment the aim is to find the allocation of *APTs* to *APCs*. The APT requirements according to the arrangements of figures 5(a)-(b) are those depicted in table 2. Figure 6 depicts the allocation of APTs to APCs when the APT network structure, the APT requirements, and the APC capacity are known. The results of figures 6(a)-(b) are obtained by applying the simulated annealing-based algorithm, when the APT layout is the one depicted in Figure 5(c), each time by altering the capacity of the APCs. In a similar manner, figure 6(c) depicts the APC layout, when the APT layout is the one presented in figure 5(d). As expected, the number of APCs deployed in figure 6(b) is smaller than the one in figure 6(a), attributed again to the looser APC capacity constraint introduced in the experiment of figure 6(b).

In the third phase of the first experiment the aim is to find the allocation of *APCs* to *IWUs*. The APC requirements according to the arrangements of figure 6 are those depicted in table 3. Figure 7(a)-(b) depicts the allocation of APCs to IWUs when the APC network structure, the APC requirements, and the IWU capacity are known. The results of figures 7(a)-(b) are obtained by applying the simulated annealing-based algorithm, for the APC network structure in figures 6(a) and 6(c) respectively.

The second experiment aims also at the derivation of the configuration of the radio access network and of the interconnecting network, for the case of the 5x5 network (figure 4a). As a first phase, we consider the derivation of the allocation of grids to APT layout. Figure 8 depicts the allocation of grids to APTs when the grid network structure and the pertinent requirements are known. A number of experiments is realised, each time by altering the APT capacity. The grid structure is the square

(Manhattan) grid structure of figure 4a, the load that originates from each grid area is at most 11 Mbps and the maximum distance $d_{\max}$ between the APT and the most distant grid adequately covered is taken equal to $1{,}5\,Km$. For comparison reasons, the capacity constraints introduced in figures 8(a) and 8(b) are the same with the ones of figures 5(a)-(b). Thus, the APT capacity is taken equal to 50Mbps in the experiment in figure 8(a) and 100Mbps in the experiment in figure 8(b). The results of figure 8 are obtained by applying the simulated annealing-based algorithm, and after the APT elimination sub-phase is conducted. From the obtained results we observe that for the allocation depicted in figure 8(a) the number of APTs deployed equals to the minimum number of APTs required, so as to satisfy the capacity constraints of the APTs. However, for the allocation depicted in figure 8(b) an additional APT is deployed. This is owed to the stricter coverage constraints introduced as $d_{\max}$ is set equal to $1{,}5\,Km$. When comparing the allocation depicted in figure 5(a) with the allocation of figure 8(a), a differentiation in the assignment of grids to APTs could be observed. This is attributed to the stricter coverage constraint introduced in the experiment of figure 8(a).

In the second phase of the second experiment the aim is to find the allocation of *APTs* to *APCs*. The APT requirements according to the arrangements of figures 8(a)-(b) are those depicted in table 4. Figure 9 depict the allocation of APTs to APCs when the APT network structure, the APT requirements, and the APC capacity are known. The results of figures 9(a)-(b) are obtained by applying the simulated annealing-based algorithm, when the APT layout is the one depicted in Figure 8(c), each time by altering the capacity of the APCs. In a similar manner, figure 9(c) depicts the APC layout, when the APT layout is the one presented in figure 8(d). As expected, the number of APCs deployed in Figure 9(b) is smaller than the one in figure 9(a). This is attributed to the looser capacity constraint introduced in the experiment of figure 9(b).

In the third phase of the second experiment the aim is to find the allocation of *APCs* to *IWUs*. The APC requirements according to the arrangements of figure 9 are those depicted in table 5. Figures 10(a)-(b) depict the allocation of APCs to IWUs when the APC network structure, the APC requirements, and the IWU capacity are known. The results of figures 10(a)-(b) are obtained by applying the simulated annealing-based algorithm, for the APC network structure in figures 9(a) and 9(c), respectively.

The third experiment aims at the derivation of the configuration of the radio access and the interconnecting network for the case of the 7x7 network (figure 4b). 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. The maximum distance $d_{\max}$ is taken equal to $3\,Km$.

Figure 11 depicts the allocation of grids to APTs when the grid network structure and the pertinent requirements are known. The APT capacity is taken equal to 70Mbps and 100Mbps, respectively. The results are obtained by applying the simulated annealing-based algorithm and after having conducted the APT elimination sub-phase. From the obtained results we observe that the number of APTs deployed equals to the minimum number of APTs required, so as to satisfy the capacity constraints of the APTs. Furthermore, as expected due to the looser capacity constraint introduced in figure 11(b), the number of APTs deployed in figure 11(b) is smaller than the one in figure 11(a).

In the second phase of the experiment the objective is to find an allocation of *APTs* to *APCs*. The APT requirements based on the arrangements of figure 11 are presented in table 6. The derived allocation of APTs to APCs is given in figure 12. The results of figures 12(a)-(b) are obtained by applying the simulated annealing-based algorithm, when the APT layout is the one depicted in Figure 11(c), each time by altering the capacity of the APCs. In a similar manner, figures 12(c)-(d) depict the APC layout, when the APT layout is the one presented in figure 11(d), each time by altering the capacity of the APCs. As expected, the number of APCs deployed in figures 12(b) and 12(d) is smaller than the one introduced in figures 12(a) and 12(c) respectively, attributed to the looser capacity constraint in the experiments of figures 12(b) and 12(d).

In the last phase of this experiment the allocation of *APCs* to *IWUs* is found. The APC requirements according to the arrangements of figure 12 are those depicted in table 7. Figure 13 depicts the allocation of APCs to IWUs when the APC network structure, the APC requirements, and the IWU capacity are known. The results of figures 13(a)-(c) are obtained by applying the simulated annealing-based algorithm, for the APC network structure in figures 12(a)-(c), respectively.

As a last experiment we consider the derivation of the configuration of the radio access and the interconnecting network for the case of the 7x7 network (figure 4b), where the maximum distance $d_{\max}$ is taken equal to $1{,}5\,Km$.

Figure 14 depicts the allocation of grids to APTs when the grid network structure and the pertinent requirements are known. The APT capacity is taken equal to 70Mbps and 100Mbps, respectively. The results are obtained by applying the simulated annealing-based algorithm and after having conducted the APT elimination sub-phase. From the obtained results we observe that the number of APTs that are deployed is increased compared to the minimum number of APTs required in order to satisfy the APT capacity constraints. Again, this is attributed to the stricter coverage constraints introduced, as $d_{\max}$ is set equal to $1{,}5\,Km$. Furthermore, it is observed that the number of APTs deployed in figure 14(b) is smaller than the one in figure 14(a). This is expected and attributed to the looser capacity constraint introduced in figure 14(b).

In the second phase of the experiment the objective is to find an allocation of *APTs* to *APCs*. The APT requirements based on the arrangements of figure 14 are presented in table 8. The derived allocation of APTs to APCs is given in figure 15. The results of figures 15(a)-(b) are obtained by applying the simulated annealing-based algorithm, when the APT layout is the one depicted in Figure 14(c), each time by altering the capacity of the APCs. In a similar manner, figure 15(c)-(d), depicts the APC layout, when the APT layout is the one presented in figure 14(d), each time by altering the capacity of the APCs. As expected, the number of APCs deployed in figures 15(b) and 15(d) is smaller than the one introduced in figures 15(a) and 15(c) respectively, attributed to the looser capacity constraint introduced in the experiments of figures 15(b) and 15(d).

In the last phase of this experiment the allocation of APCs to IWUs is found. The APC requirements according to the arrangements of figure 16 are those depicted in table 9. Figure 16(a)-(b) depict the allocation of APCs to IWUs when the APC network structure, the APC requirements, and the IWU capacity are known. The results of figure 16(a)-(b) are obtained by applying the simulated annealing-based algorithm, for the APC network structure in figures 15(a) and 15(c), respectively.

5. Conclusions

This paper addressed the problem of designing the radio access network and the interconnecting network of a future broadband fixed wireless communications system. The architecture of the overall access segment was presented. Subsequently, the problems were formally stated, optimally formulated, and solved in a computationally efficient manner by means of a heuristic algorithm based on the simulated annealing approach. Finally, results were presented. Issues for further study include the following. First, the expansion of the set of heuristics that may solve the problem. Second, the fine-tuning of heuristics and the integration in an overall broadband fixed wireless access planning tool. Third, the realisation of more general experiments.

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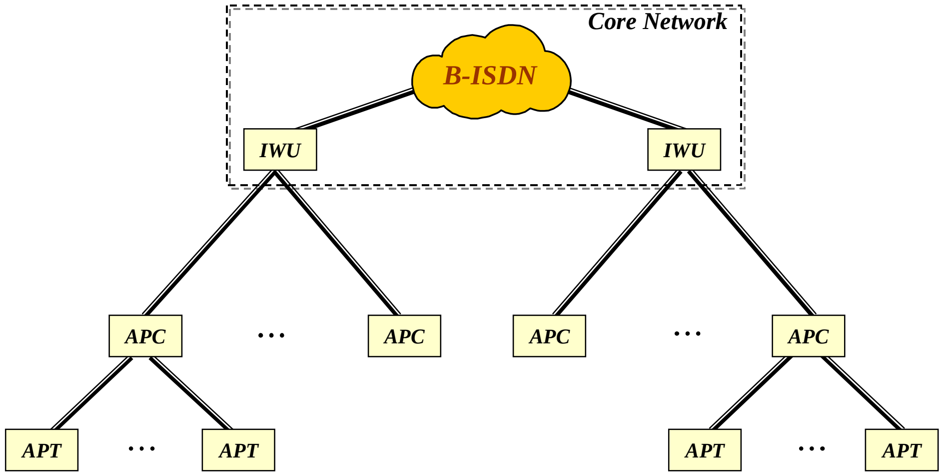


Figure** Σφάλμα! Μόνο κύριο έγγραφο.**: Architecture of the Broadband Fixed Wireless Access Systems

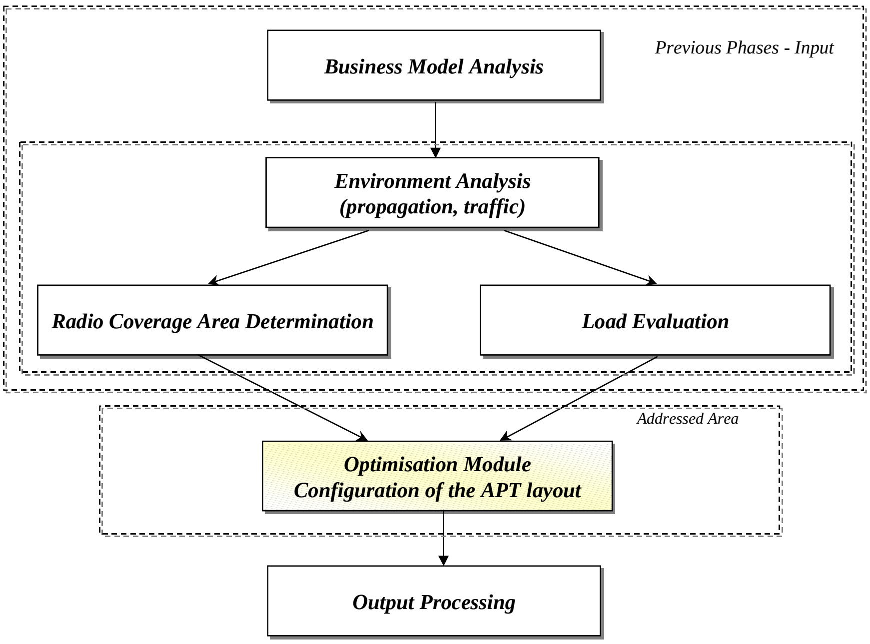


Figure** Σφάλμα! Μόνο κύριο έγγραφο.**: Radio Access Network Design

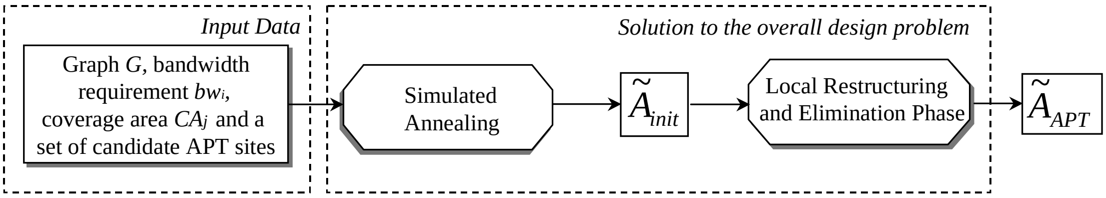


Figure** Σφάλμα! Μόνο κύριο έγγραφο.**:Solution of the radio access design problem

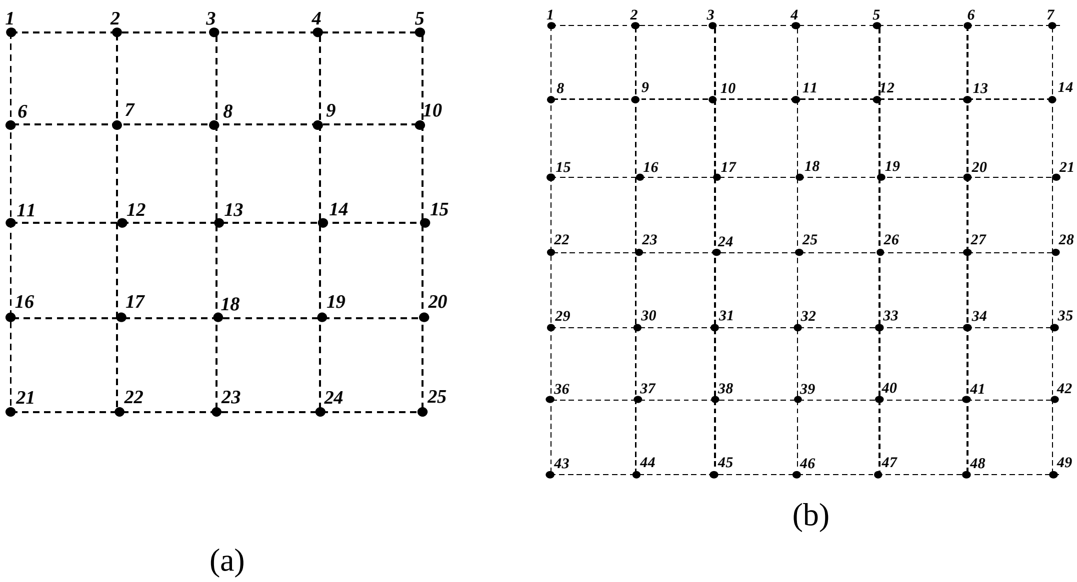


Figure 4: Square grid structure (Manhattan) representing the topology layout

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

Table 1: Service Related Characteristics

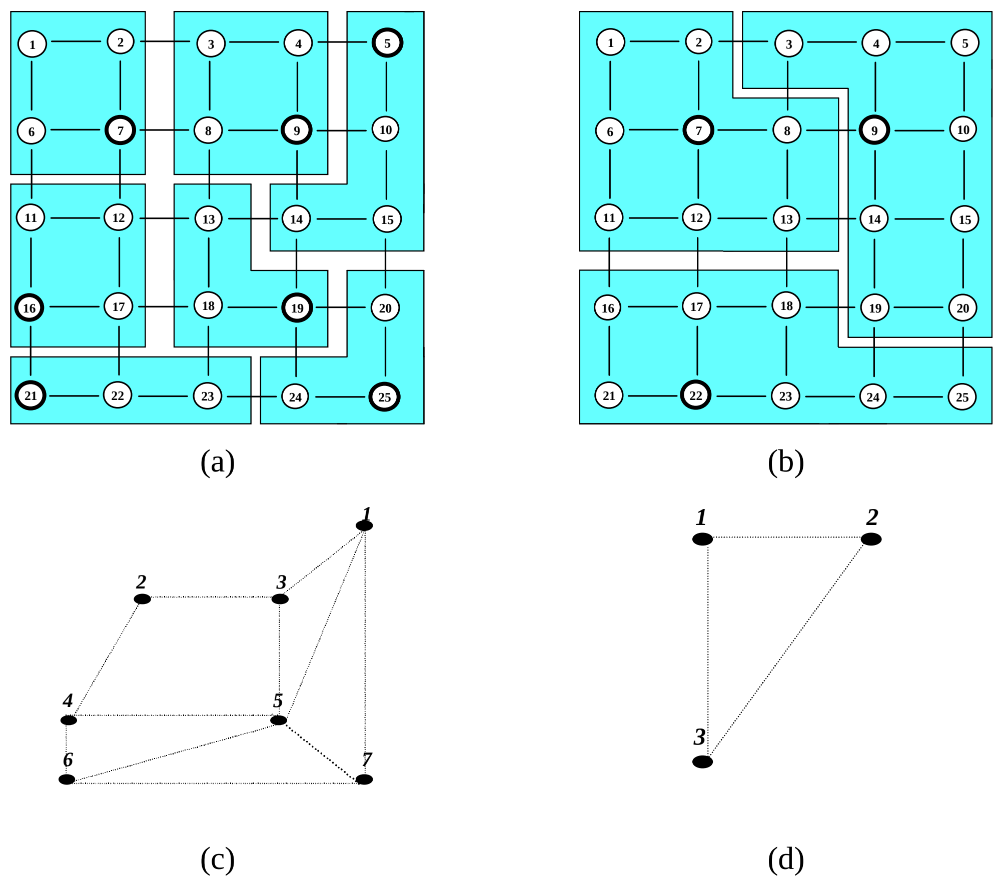


Figure 5(a)-(d): Allocation of grids to APTs and the resulting APT structure, when the grid structure is the one depicted in Figure 4a, the maximum distance is taken equal to 3Km and the APT capacity is in the order of 50Mbps and 100Mbps, respectively. The simulated annealing algorithm is applied.

APT Number	APT Location		APT Load (Mbps)	
	a	***b***	***a***	***b***
1	5	7	44	88
2	7	9	44	99
3	9	22	44	88
4	16		44	
5	19		33	
6	21		33	
7	25		33	

Table 2: APT requirements for the structure of figures 5(a)-(d)

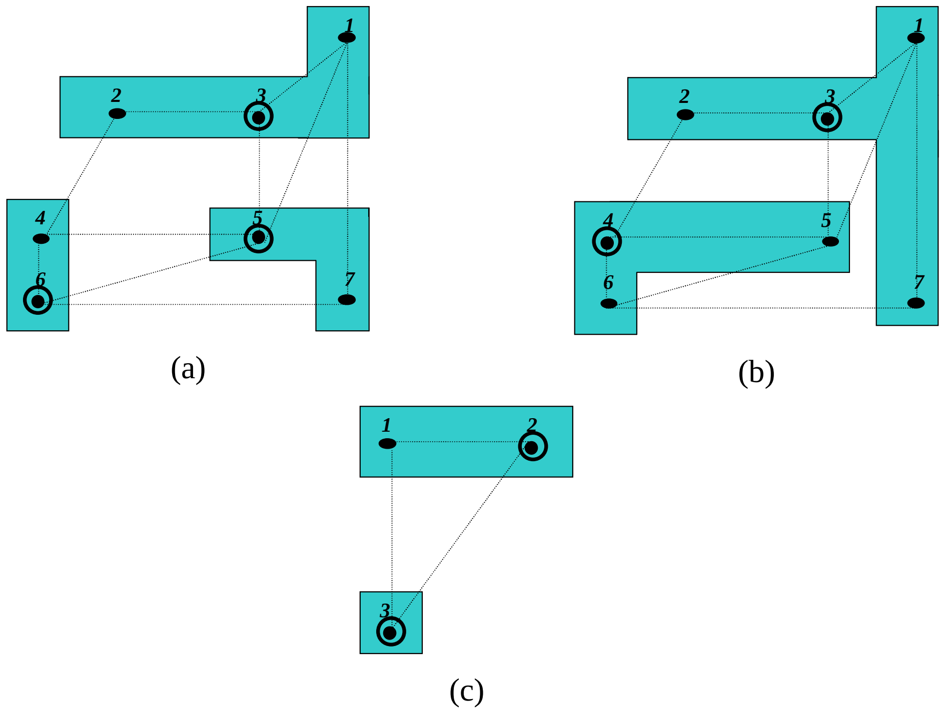
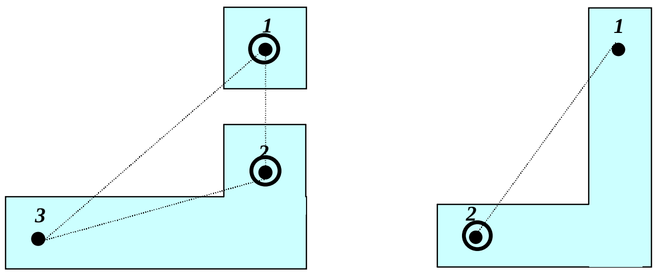


Figure 6(a-b)-(c): APC coverage in our experiments when the APTs layout is the one in Figure 5c and 5d, the respective APTs requirements are presented in Table 2 and the APC capacity is in the order of 150Mbps, 170Mbps and 190Mbps, respectively

APC Number	APC Location			APC Load (Mbps)		
	7a	***7b***	***7c***	***7a***	***7b***	***7c***
1	9	9	9	132	165	187
2	19	16	22	66	110	88
3	21			77		

Table 3: APC requirements for the structure of figures 6(a-b)-(c)



(a) (b)

Figure 7(a)-(b): IWU coverage in our experiments, when the APC structure is the one in figures 6(a) and 6(c) and the respective APC requirements are presented in table 3. The IWU capacity is in the order of 150Mbps and 300Mbps, respectively.

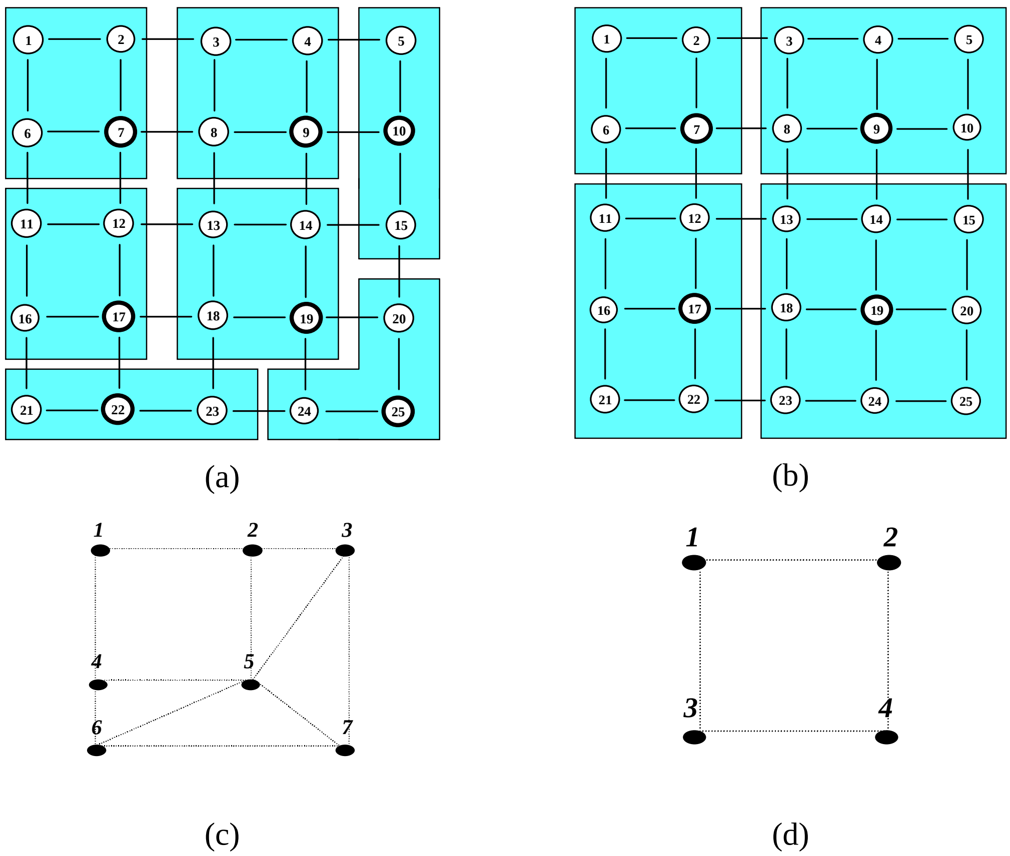


Figure 8(a)-(d): Allocation of grids to APTs and the resulting APT structure, when the grid structure is the one depicted in Figure 4a, the maximum distance is taken equal to 1,5 Km and the APT capacity is in the order of 50Mbps and 100Mbps, respectively. The simulated annealing algorithm is applied.

APT Number	**APT Location**		**APT Load (Mbps)**	
	a	***b***	***a***	***b***
1	7	7	44	44
2	9	9	44	66
3	10	17	33	66
4	17	19	44	99
5	19		44	
6	22		33	
7	25		33	

Table 4: APT requirements for the structure of figures 8(a)-(b)

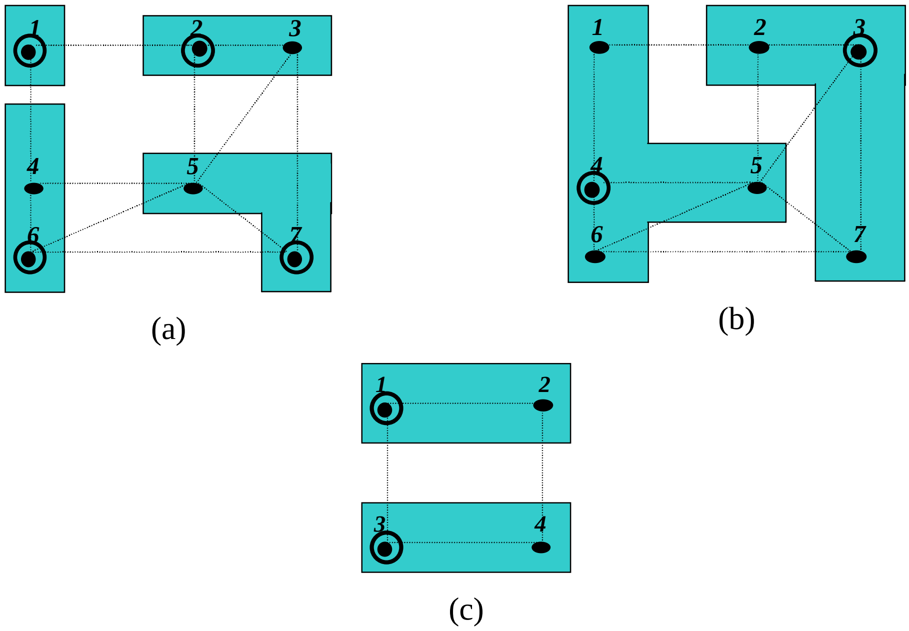


Figure 9(a-b)-(c): APC coverage in our experiments when the APTs layout is the one in Figure 8a and 8b, the respective APTs requirements are presented in Table 4 and the APC capacity is in the order of 80Mbps, 170Mbps and 170Mbps, respectively.

APC Number	**APC Location**			**APC Load (Mbps)**		
	10a	***10b***	***10c***	***10a***	***10b***	***10c***
1	7	10	7	44	110	110
2	9	17	17	77	165	165
3	22			77		
4	25			77		

Table 5: APC requirements for the structure of figures 9(a-b) and 9(c).

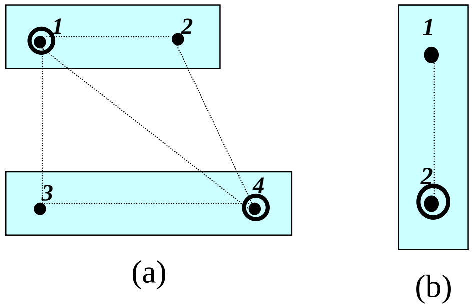


Figure 10(a)-(b): IWU coverage in our experiments, when the APC structure is the one in figures 9(a) and 9(c) and the respective APC requirements are presented in table 5. The IWU capacity is taken equal to 170Mbps and 280Mbps, respectively.

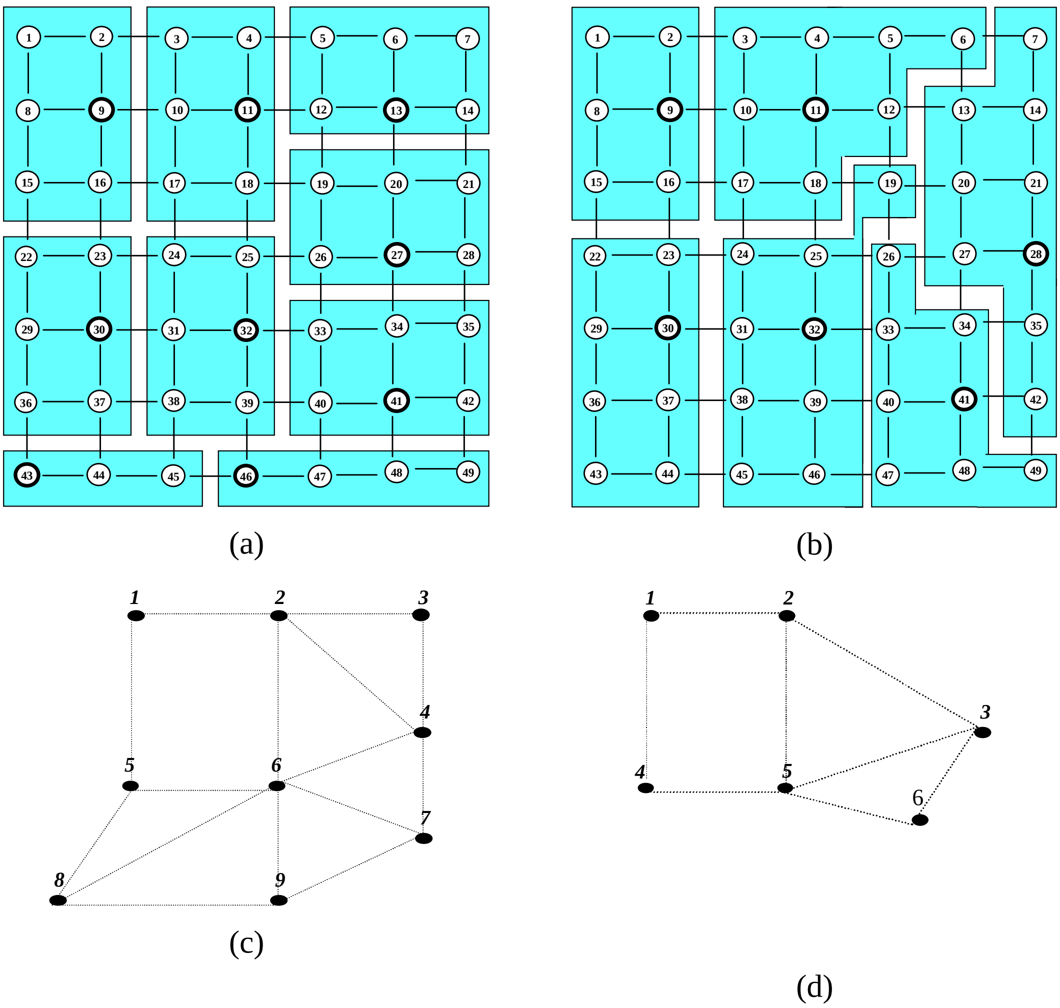


Figure 11(a)-(d): Allocation of grids to APTs and the resulting APT structure, when the grid structure is the one depicted in Figure 4b, the maximum distance is taken equal to 3Km and the APT capacity is in the order of 70Mbps and 100Mbps, respectively. The simulated annealing algorithm is applied.

APT Number	APT Location		APT Load (Mbps)	
	a	***b***	***a***	***b***
1	9	9	66	66
2	11	11	66	99
3	13	28	66	99
4	27	30	66	88
5	30	32	66	99
6	32	41	66	88
7	41		66	
8	43		33	
9	46		44	

Table 6: APT requirements for the structure of figures 11(a)-(b)

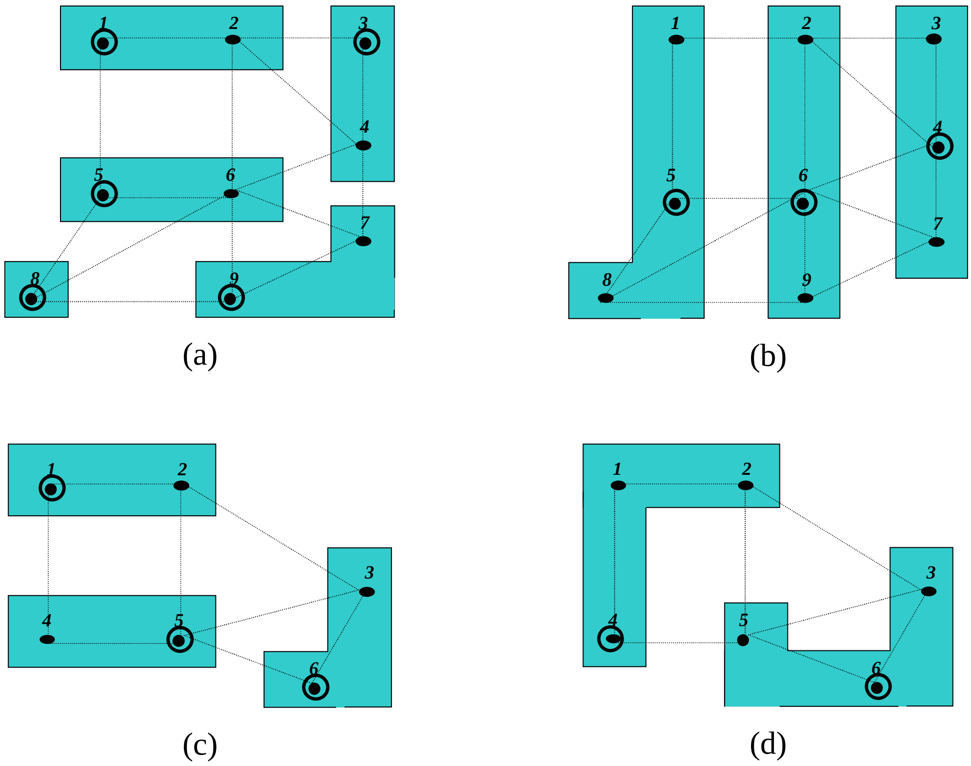
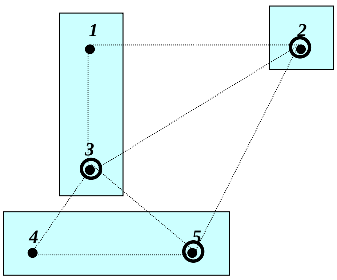


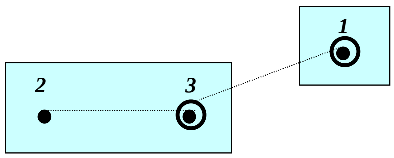
Figure 12(a-b)-(c-d): APC coverage in our experiments when the APTs layout is the one in Figure 11c and 11d, the respective APT requirements are presented in Table 6 and the APC capacity is in the order of 140Mbps, 210Mbps, 190Mbps and 300Mbps, respectively.

APC Number	APC Location				APC Load (Mbps)			
	13a	***13b***	***13c***	***13d***	***13a***	***13b***	***13c***	***13d***
1	9	27	9	30	132	198	165	253
2	13	30	32	41	132	165	187	286
3	30	32	41		132	176	187	
4	43				33			
5	46				110			

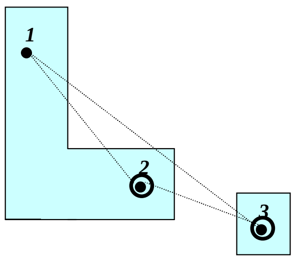
Table 7: APC requirements for the structure of figures 12(a)-(d)



(a)

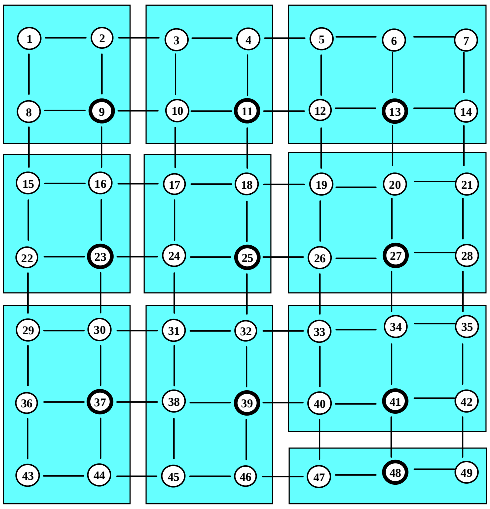


(b)

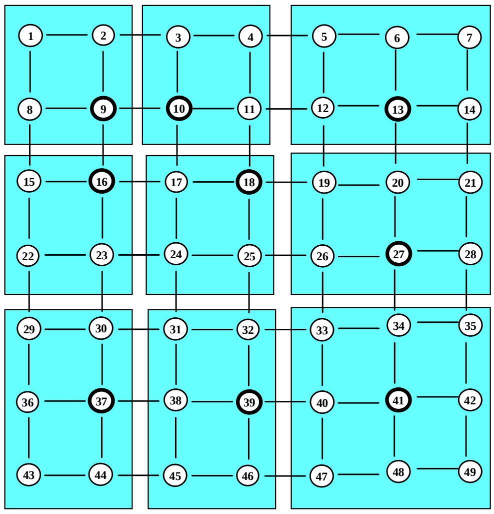


(c)

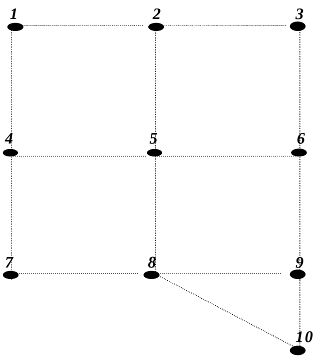
Figure 13(a-b)-(c): IWU coverage in our experiments, when the APC structure is the one in figures 12(a)-(c) and the respective APC requirements are presented in table 7. The IWU capacity is in the order of 280Mbps, 350Mbps and 360Mbps, respectively



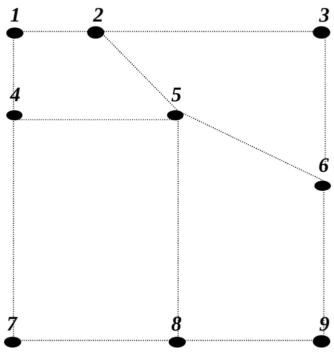
(a)



(b)



(a)



(b)

Figure 14(a)-(d): Allocation of grids to APTs and the resulting APT structure, when the grid structure is the one depicted in Figure 4b, the maximum distance is taken equal to 1,5Km and the APT capacity is in the order of 70Mbps and 100Mbps, respectively. The simulated annealing algorithm is applied.

APT Number	**APT Location**		**APT Load (Mbps)**	
	a	***b***	***a***	***b***
1	9	9	44	44
2	11	10	44	44
3	13	13	66	66
4	23	16	44	44
5	25	18	44	44
6	27	27	66	66
7	37	37	66	66
8	39	39	66	66
9	41	41	66	99
10	48		33	

Table 8: APT requirements for the structure of figures 14(a)-(b)

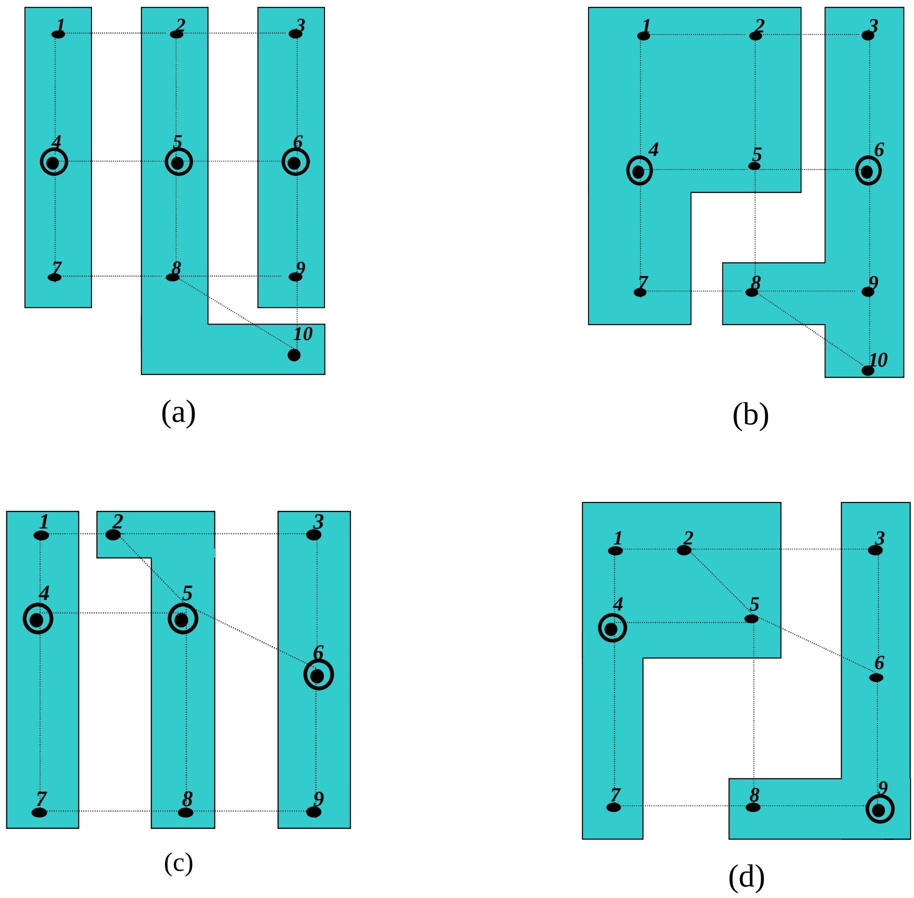


Figure 15(a-b)-(c-d): APC coverage in our experiments when the APTs layout is the one in Figure 14c and 14d, the respective APTs requirements are presented in Table 8 and the APC capacity is in the order of 210Mbps, 300Mbps, 240Mbps and 300Mbps, respectively.

APC Number	**APC Location**				**APC Load (Mbps)**			
	16a	***16b***	***16c***	***16d***	***16a***	***16b***	***16c***	***16d***
1	9	16	16	16	154	242	154	242
2	25	41	18	41	187	297	154	297
3	27		27		198		231	

Table 9: APC requirements for the structure of figures 15(a)-(d)

(a) (b)

Figure 16(a)-(b): IWU coverage in our experiments, when the APC structure is the one in figures 15(a) and 15(c) and the respective APC requirements are presented in table 9. The IWU capacity is in the order of 350Mbps and 310Mbps, respectively.