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Methods for Planning of Next Generation Mobile and Data Networks

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1 Introduction

Nowadays, there is a significant change in the telecommunication society, which effects the planning of the networks. The classical circuit switching seems to be lost its dominance within some years. Similarly, the voice based services, which today generate more than two–third of the total traffic will be less important and their share will reduce by about 50% within the next years, while the data traffic will be more and more important. Numerous new applications (like Multimedia Message Service (MMS), Web based applications and other value added services, as well as Mobile Internet Access) come into the picture, and growing the importance of an *integrated, multi–service* network technology.

The changes of the mobile market illustrate the above processes very clearly. Apart from the continuous and enormous growth of GSM subscribers, the third generation (3G) mobile systems (like Universal Mobile Telecommunication System /UMTS/) are almost ready for the operation. Because the 3G systems will be able to incorporate a multitude of services, they will play an important role in near future telecommunication world. Their penetration is expected to be high, because the 3G mobile terminals can fulfill the user requirements of looking forward a device for all the available services. According to the rapidly increasing volume of data traffic, the 3G core networks will be so-called *all–IP* networks, fitted to data transferring. From the viewpoint of network planning, the 3G networks raise numerous *new* network planning problems to be solved both in the access and core networks.

The increasing importance of IP based networks results that the Open Shortest Path First (OSPF) routing protocol also comes into the focus. OSPF is a link–state dependent routing protocol and uses so–called administrative link weights as metrics in the routing process. Obtaining suitable network performance it is important to find the adequate setting of these weights.

For providing Quality of Service guarantees and introducing traffic engineering functionalities into the IP based 3G mobile networks, the Multi–Protocol Label Switching (MPLS) technology will be applied. The introduction of MPLS also influenced the long–haul networks, where the Wavelength Division Multiplexing (WDM) is used as the most important technology in traffic forwarding. There are some efforts of European Telecommunications Standards Institute (ETSI) and Optical Internetworking Forum (OIF) to take the MPLS principle into the WDM networks that resulted the so–called Multi–Protocol Lambda Switching (MPλS) solution. An important question of this topic is to design a resource allocation strategy that fits to the bursty characteristic of data traffic in an adequate way.

The above tendencies of introducing new technologies and systems raises numerous open *network planning and optimization* problems to be solved.

In case of introducing 3G networks it is required to solve the *green–field topological* planning (determining the position of transmission nodes and links) of both the terrestrial access and the core networks. On the on hand the topology planning determines the investment cost of the network, on the other hand it has a great effect on the long–term network performance, consequently the near–optimal design is a critical issue here. In addition to topology planning, calculation of the routes of traffic flows is also a significant design problem, especially in the IP/MPLS based 3G core networks. Because the 3G networks have several specific topology constraints and traffic features, the available design methods cannot be applied here, so new planning methods need to be developed.

The continuous and fast spreading of IP based networks raises the problem that the commonly accepted, simple OSPF administrative weight adjustment solutions do not give proper network utilization, consequently there is a demand for such techniques that help to set OSPF administrative weights in a better way, in order to achieve adequate network utilization. This is a new research area, and very few considerable solutions were proposed.

In case of bursty data traffic, the demand of obtaining higher network utilization in WDM/MPλS networks caused that the emphasis on different dynamic wavelength and route allocation techniques increases continuously. Several methods are proposed in this area, but none of them give near–optimal solutions and it is expected that more complex methods are able to obtain measurable better solution.

In case of all the above tasks, the complexity of the problems, as well as the increasing size of networks, the complicated architectures and the great magnitude of traffic requires the use of *heuristic algorithmic based* optimization for the efficient network design.

2 Research Objectives

In the introduction I have mentioned the most important areas of today's info-communication world that raise open, currently unsolved network planning questions. That is why the motivation of my dissertation is to develop and propose some new, efficient network planning *methods* and *algorithms*, that can be used in case of planning 3G mobile networks, as well as IP/OSPF and WDM/MPλS networks. I give solution for the following tasks:

- Cost–based UMTS access network planning: Here my goal was to propose and evaluate a two–phase heuristic planning method that can solve this design problem more effectively than the existing methods, within reasonable running time.
- Cost–based UMTS core (backbone) network planning: My goal was to propose algorithms and a local improvement method that are able to solve the task jointly in a better way (resulting lower cost) than the known heuristics.
- Optimization of OSPF administrative weights: My goal was to develop different algorithmic strategies that can help to set such link weights that result in better network utilization than the existing solutions.

- Dynamic routing and wavelength assignment in WDM networks: My goal was to propose several strategies that can solve the problem of dynamic (by other words: on–line) path establishment (wavelength and route selection) in optical networks with different kind of protection modes, obtaining smaller blocking probability than the existing ones.

During the development of my methods and algorithms I had the following aims and took the following conditions and requirements into account:
- I have proposed planning methods that are *faster* or/and *able to obtain better* results than the existing algorithms.
- In case of the off–line planning methods I assumed that the quality of results obtained is more important than the running time of the methods.
- In case of the on–line configuration tasks the running time is also a critical factor in addition to the requirement for a reasonable solution.
- It was a basic requirement that the algorithms give better results during longer running time (scalability).

Although all algorithms are developed using a well-defined network technology environment, they are capable to handle similar kind of optimization tasks in other types of networks, i.e. they are technology independent.

3 Methodology

I have modeled the telecommunication networks by graphs, which is widely accepted approach. Then in case of all the above cited problems I have applied some basic, well–known algorithms of graph theory. The most important ones are the following:
- Methods of Dijkstra and Suurballe for finding the minimum cost shortest path, and the minimum cost pair of disjoint shortest paths in a graph.
- Minimum cost spanning tree construction algorithms (Prim's and Kruskal's method).

Using the above methods as basic building blocks, I developed some heuristic algorithms for solving the problems mentioned in Section 2.

Some of the appeared tasks are such kind of *optimization problems*, which can be formulated as linear programming (LP) or integer linear programming (ILP) tasks, and they can be solved by using any of LP– or ILP–solver programme packets (CPLEX, LP_solve). Using this technique we can obtain *optimal* solution, but due to the great size of the state space, the practical network sizes cannot be handled and solved this way in reasonable running time.

Therefore, I concentrate to development of *heuristic* methods that are usable in case of practical planning problems. On the one hand I have used some *general heuristic methods* that available in the literature, as *Simulated Annealing (Thesis 1,2), Simulated*

Allocation (Thesis 2) and Genetic Algorithm (Thesis 1) and adapted them for the specific design tasks, furthermore, I have improved them to obtain better solution. One the other hand I have also developed some *problem specific heuristics (Thesis 2,3,4)*, which consider the special properties of the given design problem and obtain better solution than the general methods.

To evaluate the performance of the design algorithms the most frequently used technique is the *simulation*. This is the basic method I have also used in my theses, because the complexity of the design problems and the size of real networks cause that *analytical methods* can be used only in a very limited way. In case of some problems it was possible to calculate the lower bounds, which is a good measure of the quality of the proposed algorithms.

4 New Results

Thesis 1 : Cost–based Planning of UMTS Terrestrial Radio Access Networks (UTRAN) [C1, C4, C8, J6]

UMTS design problem in UTRAN level raises the questions of how the Radio Network Controllers (RNC) must be placed (task 1), furthermore how the Radio Base Stations (RBS) are connected to each other (in a so–called *RBS tree*) and to the RNCs in a multi–constrained tree topology (task 2), resulting a cost–optimal network. One difficulty in the problem is the complex cost structure, because the total cost of the network consists of the sum of two cost functions (the cost depends on the number of RNCs and cost of RBS trees) and these two functions depend on each others. Another problem is that, due to some technological reasons the RBS trees have to fulfill two constraints, namely degree and cascading ones. In [5] it is proved that the construction of multi–constrained spanning trees is already an $\mathcal{NP}$–hard task. Further difficulty is that the cost of the links depends on both the distance and the capacity, furthermore each RBS has also a capacity dependent step–like cost function. In [9] the authors propose an algorithm for mobile network planning, but without any constraint on the tree subnetworks. In [C1] a two-layer algorithm is proposed, which solves the two above tasks in an integrated way.

The essence of my proposed method is if I solve the RNC localization and the tree–building tasks separately using different algorithms, and then their results are combined, better solution is obtained.

According to the mentioned task separation I proposed in Thesis 1.1 and 1.2 two algorithms that solve the following tasks, respectively:

- Task 1.: Finding the optimal number and placement of Radio Network Controllers. A part of this task is to determine the home RNC of each RBS. In other words this is the RBS clustering task. (Thesis 1.1)

- Task 2.: Constructing the constrained–tree topology subnetworks of Radio Base

Stations that connects them to each others and the RNCs. (Thesis 1.2)

Furthermore, I present a brief performance analysis of my proposed algorithms, comparing them to existing other methods.

Thesis 1.1 : Solving Task 1. – RNC Localization Algorithm (RLA)

I proposed a new algorithm based on the application of an improved genetic algorithm that is able to determine the cost–optimal number and location of the RNCs, furthermore it can solve the clustering problem of RBSs.

The planning method is based on the problem specific application of the genetic algorithm. The genetic algorithm uses the genetic processes of biological entity. Over many generations, natural populations evolve according to the principles of natural selection. Modeling this process, genetic algorithm is able to "evolve" solutions to real world problems, if they have been suitably encoded. A simple genetic algorithm has the following operators: recombination, crossover and mutation.

The most important steps of my algorithm as follows:

Initial state generation. In my adaptation an entity is a vector x, and the length of the vector is equal to the possible RNC positions. If the ith position of the vector $x_i = 1$, then RNC is installed there, else not. After the number of entities is set, some RNCs are placed into randomly chosen locations in each entity of the population.

Step 1. **Recombination.** I used the so–called "elitism" here: always the two best entities are selected from the previous population (as parents) and the new population is created from them using the crossover operation.

Step 2. **Crossover.** I have improved the classical method of crossover, using a so-called *best* entity, which is independent of the population and stores collected information about the past of the optimization, and it is considered in case of each crossover. In any position of *best* entity there is a number of how many times an RNC was installed into the current position during the foregoing optimization. In my adaptation the crossover operator compares the two parents, and in those position in which the values are different the *best* entity is used to decide which value will be used in the new entity, according to the following process: We have a probability $P_{inherit\_the\_better}$ (adjusted by the user) and a random generated number $0 \leq R \leq 1$. If we denote the current step by j and the number in the ith position in *best* entity by c, then the decision happens in the following way:

- If $R \leq P_{inherit\_the\_better}$ and if $c > (j - c)$ then in the new entity $x_i = 1$, else $x_i = 0$.
- If $R > P_{inherit\_the\_better}$ and if $c > (j - c)$ then in the new entity $x_i = 0$, else $x_i = 1$.

Using extended simulations I have shown that this technique gives 2-5% better results than the classical crossover technique.

Step 3. **Mutation.** In this algorithm I have proposed three ways to apply the mutation operator, namely:

- Simple mutation: Random alternation of the value x_i at a randomly chosen position i

of an entity; $x_i = 1 - x_i$.
- Double mutation: In this case two positions are searched in a randomly selected entity, such that $x_i = 1$ in the one position, while $x_k = 0$ in the other position, then both values are altered.
- Strong mutation: In this case an entity is selected randomly and in some positions $x_i := 1 - x_i$.

The ratio between the mutations can be fixed or their probability can be adjusted adaptively on the basis of their effectiveness. I have shown that in case of smaller networks and simpler cost structures, the fixed probabilities are preferable, but in case of larger networks or complex cost functions the adaptive probability setting results better solution.

Step 4. **Cost calculation for all entities.** It is required to determine the goodness of the current RNC locations, and for the cost calculation we should connect the RBSs to their home RNC in some way. In my algorithm three ways are possible to build the whole access network:
1. connect each RBS directly to the closest RNC.
2. apply a simple greedy RBS tree construction method (presented in [C1]).
3. apply the proposed Tree Construction Algorithm for building up the RBS tree (see Thesis 1.2).

Step 5. Continue the optimization at Step 1 until a prescribed number of iterations is reached or the algorithm will stop automatically, using an adaptive way, which depends on the number of iteration while the algorithm did not obtain better solution. Simulations show that application of the adaptive stopping criteria can reduce the running time by about 20-25% comparing the classical genetic algorithm without performance degradation.

Thesis 1.2 : Solving Task 2. – RBS Tree Construction Algorithm (TCA)

I proposed an algorithm that is able to determine the near–optimal interconnection of RBSs within a cluster of an RNC in a better way than the known methods.

This method starts out from the output of previous process (positions of RNCs and clusters of RBSs) and builds up the final transmission network between the RBSs and RNCs. It is required to run this method cluster by cluster to obtain the whole transmission network. The algorithm is based on simulated annealing method, which is a widely used optimization technique, known to be able to find a solution close to the global optimum even in cases of large state spaces. The method works in an analogous fashion to the physical annealing of solids to attain minimum internal energy states (see [10, 11] for a general overview). My proposed algorithm tries to optimize the number and locations of those RBSs that are connected directly to their home RNC (these are RBSs on $level_1$ in the following). The optimization works in the following way:

Initial state generation. Random appointment of some RBS to be on $level_1$.

Step 1. The algorithm selects one of the next alternates to achieve a new configuration:
- Select an RBS randomly and assign it to $level_1$.
- Remove an RBS selected randomly from $level_1$.
- Swap an RBS on $level_1$ and another one from another $level$.

The classical simulated annealing works with fixed ratio between the alternates, but I propose a strategy, where the probabilities of the alternates change in each step according to their success or unsuccess. I have shown that this method results faster convergation and smaller running time.

Step 2. After the modification of the network structure, build up the access network tree using a greedy method presented in [C1] and [C4].

Step 3. Calculate the cost difference between the original and the new network. On the basis of the following stochastic acceptance criteria, the simulated annealing decides to accept or refuse the new network structure:

$$P_{accept} = \min\left\{1, \exp\left(-\frac{Cost_{new} - Cost_{orig}}{T}\right)\right\} \tag{1}$$

where $Cost_{new}$ and $Cost_{orig}$ are the total cost of the network after and before the modification and T is the temperature parameter of simulated annealing, which decreases exponentially during the optimization. Then the process continues from *Step 1* until RBS distribution optimization has finished.

Final Step. Network will be further optimized by local improvement methods, namely:
- Try to connect an RBS and the subnetwork what is connected to it to another RBS.
- Try to swap two links.
- Compute the global optimum inside all such subtrees that connect to $level_1$ RBSs.

I have analyzed the performance of TCA comparing the results of TCA and the greedy tree construction method [C1] using different networks. Table 1 shows the results.

It can be seen that TCA can obtain results about 8.25% lower than the Greedy. It is also important to note that TCA works well even in case of great network sizes. On the basis of 100 runnings, we may say that the variance values of TCA are also favourable, the very small variance values prove that the method works stable.

Performance analysis of the algorithms

Beside my proposed methods several known algorithms are usable to solve the above two planning tasks. It is not clear what kind of combination of these methods results the best final solution, therefore I have developed a frame where most of the methods can be compared to each other. I considered the following ways to solve the green–field planning of UMTS networks:
- Method 1: Using the Integrated Planning Algorithm (IPA) proposed in [C1].
- Method 2: Using any kind of known distance–based clustering technique [2] for RNC

Table 1: Performance of TCA compared to Greedy tree construction method

#Nodes	Greedy	TCA	Improvm.	Variance of TCA
50	10587,3	9340,77	11.8%	0.147%
70	13930,6	12365,4	11,2%	0.383%
100	18252,8	16742,5	8,3%	0.405%
120	21901,9	19883,4	9,2%	0.672%
150	26362	24300,8	7,8%	0.715%
200	33657,4	31434,8	6,6%	1.086%
300	48341,1	45245.4	6,4%	0.972%
500	77144,9	73627	4,6%	1.135%

localization problem, then greedy algorithm [C1] is used for tree construction.
- Method 3: Using any kind of known distance–based clustering technique, then TCA is used.
- Method 4: Using RLA with cost–calculation version 1, then TCA is used.
- Method 5: Using RLA with cost–calculation version 2, then TCA is used.
- Method 6: Using RLA with cost–calculation version 3.

Using different networks the cost of the final solutions of the above methods were calculated, then the relative cost values were compared (the best solution was 100%, all the other results were compared to this value). The results are summarized in Table 2. The

Table 2: Comparison of different planning methods

#Nodes	Method 1	Method 2	Method 3	Method 4	Method 5	Method 6
100	108.82%	109.76%	107.43%	100.36%	102.54%	100%
200	109.23%	109.92%	106.87%	100.45%	103.34%	100%
300	110.23%	110.54%	107.67%	100.98%	103.45%	100%
500	110.76%	110.57%	107.74%	100.78%	104.12%	100%

best solution can be obtained by method "6", but this is very time-consuming, since the TCA must be ran in all clusters in each step of RLA. A good quality solution is obtained if we use method "4", during reasonable running time, since the difference between the results of method "4" and "6" is less than one percent even in cases of great networks. These results prove that the proposed algorithms are able to solve the planning task in a better way than the existing methods.

Thesis 2 : Cost–based Planning of UMTS Core (Backbone) Networks [C9, C10, C13]

Planning UMTS core networks also raises new design tasks, and currently only several methods exist that can be used for solving them. This is because, this planning task contains classical mesh-like topology optimization as well as traffic engineering and dimensioning problems, too. Furthermore, the significant volume of traffic means that a node or link failure can cause critical traffic loss, therefore, we also have to take some protection capability into account during the design. Figure 1 shows the structure of a UMTS core network.

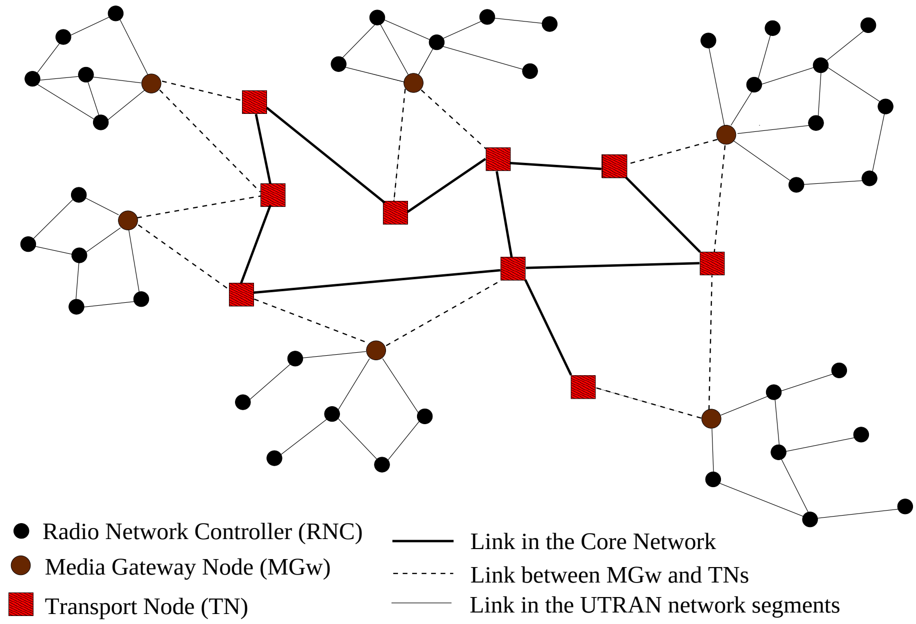

Figure 1: UMTS network architecture

The planning task that appears here is to connect the RNCs, which belong to a common UTRAN and select one or two RNCs where a so-called Media Gateway (MGw) equipment is placed, which provides the connection between the core and access network. Furthermore, these UTRANs must be connected to each other, which means that the topology between the transport nodes (TN) of the core network, which connects MGws with a two–connected network structure also have to be designed. In parallel with the topology planning (which is a type of the classical *node and link localization problem*) all the demands must be routed using step–like capacity dependent cost functions for each link and equipment in the nodes.

Since the aforementioned problem is $\mathcal{NP}$–hard (it can be traced back to the well known Steiner tree problem), it is necessary to use heuristic methods. Furthermore the state space of the problem is great, therefore I decomposed the original task into smaller, but well–defined subproblems, and I solved the original problem in two different phases. Here I defined the subproblems to be solved in the consequent phases.

- Phase 1: The task is to find a near–optimal placement of MGws and find reasonable network topology using linear cost function instead of the step–like one. Because the linear function has an $A_e + B_e * C_e$ form for each link e, it is required to calculate A_e, which is related to the installation cost of a link, and B_e is the gradient of the function, which is related to the capacity and cost steps of the original link cost function, while C_e is the sum of traffic passed on the link currently. I proposed a Simulated Annealing based heuristic algorithm for solving the task of Phase 1. (Thesis 2.1)

- Phase 2: In Phase 2, the original (step–like) link cost function is used. The network topology has not yet been modified, but heuristic methods are used to re-route some demands, due to reduce the original network cost according to the step–like cost function. (Thesis 2.2)

For further improvement of the results I proposed a post-process algorithm, which consists of some local improvement methods (Thesis 2.3).

The problem decomposition can cause some running time increasing, but the two–phase optimization can result better solution (cheaper networks) than those methods that try to solve the original problem, because the subproblems can be handled better with my proposed two–phase approach.

Thesis 2.1 : Solving Phase 1. – An algorithm for topology planning of UMTS core (backbone) networks

I proposed a Simulated Annealing based algorithm that is able to plan the topology of the UMTS core networks and route the traffic on this topology in a near–optimal way.

In this planning case a state of the Simulated Annealing method is a network topology, which is the set of established links (σ_e denotes the state of a link; if $\sigma_e = 1$ the link is established, otherwise $\sigma_e = 0$), as well as the positions of the MGws. This state space provides that the algorithm is able to find optimal solution, since it is the optimal position of the links and MGws.

Initialization step. Calculation of A_e and B_e values for each link e. Some links are installed into the network and the demands are routed on the distance–based shortest paths.

Step 1. A new network topology can be obtained using the following steps:

- Link switch off/on in the UTRAN level (LSU): In this step a UTRAN network and a link e within this UTRAN is selected randomly and its status will be inverted.

- Link switch off/on in the core level (LSC): A link e is selected randomly from the core network (the end point of the selected link must be TN) and its status will be inverted.

- MGw movement (MGM): A UTRAN network is selected and the MGw will be moved to a new node inside the UTRAN area. In this case all the traffic demands that originate or terminate in the UTRAN must use the new MGw.

The simulated annealing works on an adaptive way: the probability of the modifications (one of from LSU, LSC, MGM) depends on their effect on the network cost.

Step 2. After each modification all demands must be routed using Dijkstra's method with the following weight functions, where ($M \approx (2...5) \cdot A_e$):

$$w_e = \begin{cases} B_e * C_e & \text{if} \quad \sigma_e = 1 \\ M & \text{if} \quad \sigma_e = 0 \end{cases}$$

Step 3. After the routing of demands, the network cost is calculated, which is the sum of link initialization costs (A_e) and of the traffic dependent cost of the links ($B_e * C_e$). After it is decided whether the new network topology is acceptable or not, the optimization is continued at *Step 1* until pre–described number of iterations.

Comparing with lower bound it is shown that difference between the cost of the network resulted by my proposed method and the lower bound is about 11.3%, which is more favourable than the results of existing methods.

Thesis 2.2 : Solving Phase 2. – Two algorithms for configuration of the routing in UMTS core networks

I proposed a simulated annealing and an improved simulated allocation based algorithm for routing traffic demands with 1+1 protection.

These algorithms start out the output of the previous one and tries to optimize the paths of traffic demands using step–like cost function. The network topology has not been modified any more (except when a link is not used; this link will be deleted from the network) the goal is to search the optimal routing of demands.

The SAN algorithm

In this method a pre-defined set of possible different explicit working and protection paths is searched for each demand. Firstly, all (or some of) the shortest paths are searched, measured in hops (their length is denoted by L_{sp}), then the paths of length $L_{sp} + 1$ are searched, and so on. The results have shown that paths of length $L_{sp} + 3$ are enough to obtain a near–optimal solution, since longer paths than $L_{sp} + 3$ increase the load of the current demand in the network significantly.

The kth path of demand d is denoted by p_k^d, $k = 1...K$, where K is the number of different paths. The state of the optimization is which path is selected to carry the demand. The neighbour states can be obtained by selecting a demand d randomly and moving it from p_k^d to p_l^d, where $l \neq k$. To evaluate the new state the stochastic acceptation criteria of simulated annealing is used. The algorithm finishes its operation after pre-defined iterations.

Because the paths of demands are determined in advance the sequence of demand allocation does not influence the goodness of the final solution. Further important feature of this method is that the working and protection paths are handled independently during the optimization. Independently means that the working and protection paths need not to be established at the same step; they are handled as individual paths, but of course they will be disjoint in the network.

The improved SAAL algorithm

This method is an improved version of the Simulated Allocation (SAAL) strategy proposed by Michal Pióro in [13]. I improved the Simulated Allocation method in the following ways:

- I have proposed such kind of adaptive link weight function for demand allocation, which uses the increasing of network cost caused by the demand allocation as basic factor:

$$w^d(e) = \begin{cases} \epsilon + (1 - \frac{(c_e^l - C_e + cap^d)}{c_e^l}) & \text{if} \quad C_e + cap^d \leq c_e^l \\ Cost_{link}(C_e + cap^d) - Cost_{link}(C_e) & \text{if} \quad C_e + cap^d > c_e^l \end{cases}$$

  where ϵ is a small number, cap^d is the bandwidth of demand d, and c_e^l is the current capacity of link e (the lth step according to the step–like link capacity function).

- In the classical SAAL only one demand is allocated or de–allocated in one iteration step. In my version there are two states. In the allocation state several demands are selected and allocated one by one. The demands to be routed can be selected randomly or sorted in a decreasing order according to their bandwidth, their capacity requirement or to the cost increasing caused by their allocation in the current network state. In the de–allocation state several random selected demands are deleted from the network in the following ways:

  – one demand is deleted that contains a random selected link
  – several demands are deleted from the most–loaded links
  – about 50 percent of the demands are deleted from the most–loaded link
  – those demands are deleted that result the largest cost reduction

  The repeating setup and tear down of the demands provides that great part of the state space will be examined. In case of protection, the primary and backup paths are handled together (if a demand is selected to be routed both primary and backup paths must be allocated for it).

- The classical SAAL finishes its operation when all the demands are allocated. I have proposed an iterative more–phase process, which consists of more than one classical SAAL process. After each phase, when all demands are allocated some of them are deleted from the critical part (bottleneck links, underloaded or overloaded parts) of the network. The percent of deleted demands and the probability of allocation decreases phase by phase. This iterative process is more time–consuming than classical SAAL, but provides about 4-6% better results.

- In case of classical SAAL the probability of demand allocation is fixed during the optimization. I proposed a possible way for adaptive probability adjustment:

  – when the demand allocations are successful the probability is increasing for faster convergence
  – when some demand allocations have failed (it requires the installation of a greater capacity link), the allocation probability is decreasing in order to delete more demands from the network to leave the current network state

  Using this adaptive allocation probability adjustment further 2-3% cost reduction can be obtained comparing to the classical SAAL.

Thesis 2.3 : A PostProcess method to improve the configuration of core networks

I propose a collection of local improvement methods that try to modify the paths of some demands in order to find a better (cost–economical) network configuration.

The motivation of this algorithm is that although the outlined basic algorithms usually obtain favorable results, by using simple local subprocesses the solution can often further improved. For this reason I proposed the following four methods:

1. The idea behind this method is that by re-routing some demands the capacities of low utilized links can be reduced. Some links will be selected on which the relative load is small and as many demands are deleted from them as required to install a link with smaller capacity (and smaller cost according to the step–like cost function). Then the deleted demands are routed again using a special weight function that provides the minimal additional network cost.

2. Often the routing of some demands is not optimal. This process is able to check it and tries to re-route all demands one by one, so that it results smaller cost. This process helps to re–route especially the too long paths to a shorter one, and helps to balance the load in the network.

3. The idea behind this process is that increasing the capacity of a link (installing a larger capacity link) can cause link capacity reduction on other link(s), resulting smaller network cost. In this case a larger capacity link is installed into the network

(for example 622Mbps instead of 155 Mbps) link by link without larger cost. All the demands are re–routed, then the marginal cost of the increased link is added to the final network cost. This method helps to install large capacity links in the "centre" (core) of the network, which carry most of the traffic demands that appear between the "edge" nodes of the network.

4. The network cost can be drastically decreased if some unnecessary links are found and deleted from the network. This method examine all the links, whether it is deleted from the network and those are deleted that results in the much significant cost reduction.

I have to note that although PostProcess method is fitted to work on a previously optimized network, it can be used to handle the green-field planning task as well; of course in this case the final solution will be far from the optimal one.

Using simulations I have shown that using the Postprocess algorithm the network cost can be reduced by 6 – 18% depending on the preliminary planning of the input network.

Thesis 3 : Optimization of OSPF Administrative Weights [J5, C2, C3, C11]

The Open Shortest Path First (OSPF) is the most commonly used Interior Gateway Protocol in today's IP networks. OSPF uses the shortest paths for routing packets according to the given administrative weights of the links and applies the so–called Equal–Cost MultiPath (ECMP) principle in cases of multiple shortest paths. Here the optimization problem is how the weight system should be adjusted in order to obtain good network performance; the investigations in this area have started only recently [?],[20],[21]. The problem addressed here is the *capacitated flow allocation problem* (because the capacities of the links are pre–defined) according to the OSPF routing rule. This task is proved to be $\mathcal{NP}$–hard as shown in [C3], therefore it is necessary to use some kind of heuristic algorithms to obtain feasible solution during reasonable running time. I consider *static* weight systems (where the weights do not change dynamically), avoiding flexibility during normal network operation in a short time range. I have proposed two algorithms for this problem.

Thesis 3.1 : A greedy algorithm based Simple Weight Adjustment (SWA)

I have proposed a fast, but efficient method that is able to adjust the OSPF weights during short running time in acceptable way.

In case of the development of this method the most important factor was to obtain a reasonable result *during the shortest possible running time.* It makes possible to use the algorithm in situations, where on-line weight adjustment problems can appear (failures, drastic traffic changes and other kind of extra–ordinary cases) and fast re–configuration is very important. The algorithm is based on the so-called *one–phase* weight adjustment approach, which means that the weights are calculated directly as a function of the link utilization and some other network metrics, during an iterative process. The algorithm is able to handle both real and integer weights.

The proposed method consists of two local search procedures:
– Weight adjustment (WA): This method is used when the network is overloaded (there is at least one link which is overloaded). The weights of the overloaded links will be increased according to a function that depends on the current value of overload and the load of the link during some previous iterations. Considering the previous load values on the link during more than one iteration helps to eliminate the cyclical load increasing/decreasing (oscillation), and helps the convergation. The weights of the underloaded links will be reduced according to their residual capacity, but this decreasing happens in small steps during several iterations to avoid link overload. The goal is here to find a weight system where no overloaded link remains in the network.
– Load optimization (LO): When the network is underloaded only several selected link' weights are slightly changed to achieve the best possible network utilization. The goal is here to maximize the residual capacity in the network.

If during the optimization the algorithm cannot find a feasible solution (i.e., a solution with all demands routed and no link overloads), the user can select between the two best solutions in respect to what is more advantageous for him: to minimize the number of overloaded links, or to minimize the average overload. If the algorithm finds such weight system at which the network is underloaded the final weight system will result the maximal residual capacity in the network.

Using simulation I have shown that SWA is able to find solution comparable to other existing algorithms, while its running time is smaller that of the other methods, and in most of the cases the difference in running time is greater than one order of magnitude.

Thesis 3.2 : The Weight Optimizer (WO) algorithm

I have proposed an efficient robust and scalable ***deterministic*** *method for OSPF weight adjustment, which can obtain better results than the existing algorithms.*

In case of the development of this method the most important factors were the robustness, the scalability (between the running time and the quality of the solution), the deterministic operation, and the so–called *black box* type objective function. The most important feature of this method is the deterministic operation which provides that one run is enough to obtain the best solution the algorithm can find. WO is also based on one–phase approach.

During the optimization process the network can be in two different states:
– Overloaded state (OLS): It means that at least the load of one link exceeds its capacity.

– Normal state (NS): It means that all link loads are less or equal to their capacities (no links are overloaded).

In OLS the algorithm uses two kinds of methods, and these try to reach a state, in which all links are underloaded; in other words, the processes try to move towards NS and reach it as fast as possible, but the state found is good enough for the further optimization. The algorithm uses a modified goal function, which depends on both the number of overloaded links, and statistical parameters of the overload (average and variance of overload, localization of heavy loaded network segments). In OLS the algorithm uses the following procedures:

– Set_link_weight procedure: It tries to re-route the traffic from the most overloaded links and equalize the utilization of network links.

– Load_balancing_#1 procedure: It tries to locate and eliminate the overloaded parts of the network (where some overloaded links are connected to a common node).

If the algorithm finds a weight system that results NS, the user–defined objective function or an original objective, the residual capacity maximization is used. In this state three local search procedures are used as described below:

– MAX-MIN_decreasing procedure: it modifies the weights of the most and least loaded links according to their load.

– Variance_decreasing procedure: it tries to decrease the variance of relative link loads, because tests show that this method provides better network utilization.

– Load_balancing_#2 procedure: it tries to equalize the load between the different network parts.

In many cases the modification of any NS methods can result that the network will get to OLS again, so the algorithm works on an iterative way between the two states. This operation mode helps to leave the local optimum points found during the optimization. The algorithm stops when non of the NS processes can improve the solution during a pre-defined number of steps (it depends on the size of the network and it is set adaptively by the algorithm).

Using simulation I have shown that WO is able to find measurably better solution than the known other methods, furthermore its deterministic operation provides stability.

Performance analysis of the algorithms

I compared my proposed methods to known heuristics and some obtained test results are presented in Table 3. I have used two known algorithms as references for the comparison: first one is based on Simulated Annealing (SAN), while the other one uses Simulated Allocation method (SAL). For more detailed description of the mentioned methods I refer to [J5].

The notation is used as follows: AVRT - the average running time in seconds (the processor time is measured here), FNCR - the free network capacity ratio. I used network with 28 nodes, in the first case the network is overdimensioned by about 5%,

Table 3: Comparison of my proposed methods and existing ones

Net28_5%	WO	SWA	SAN	SAL
AVRT	68.29s	19.36s	∼15min	47.38s
FNCR	5.04	4.9	4.8	4.9

Net28_10%	WO	SWA	SAN	SAL
AVRT	80.8s	11.43s	∼15min	16.95s
FNCR	9.5	9.2	9.4	9.2

while in the second case by 10%. I have shown that the WO gives 3% – 6% better results than the other known methods, while SWA is the fastest one and can also obtain reasonable results.

I have examined the performance of my algorithms using networks of different sizes (from 7 to 120 nodes) with different traffic patterns and the obtained results show the same tendencies as the above ones.

Thesis 4 : Dynamic Routing and Wavelength Assignment in Multifiber WDM Optical Networks [J7]

The great capacity resource of WDM networks enables to carry substantially more traffic than using other transmission modes. So far the WDM networks were used in a so-called static mode, which means that the wavelength paths were pre–configured and this configuration was fixed. The traffic generated by the current so-called "bandwidth hungry" applications has bursty characteristic, furthermore the continuously increasing traffic volume yields that the traffic demands have rather dynamic characteristic than static. These tendencies result that the data traffic cannot be handled in an optimal way using statically configured networks, therefore the (on–line) dynamic configuration of wavelength paths are needed. The optimization task is two–fold: (a) a suitable wavelength must be selected for the traffic demand (wavelength selection [WS] task), and (b) a path must be established on the selected wavelength for the demand (wavelength routing [WR] task), which provides that the long–term demand blocking probability is as low as possible. Some algorithms were published that are able to solve these tasks, but on the one hand they do not use adaptive routing, on the other hand they consider the two tasks independently, which results in degradation of the final solution. I have proposed a method that handles both tasks in joint way, combined with adaptive (network state dependent routing) resulting in much better solutions than the existing methods.

Thesis 4.1 : An (on–line) algorithm for dynamic resource allocation in multifiber WDM networks

I have proposed an algorithm that handles the Wavelength Selection (WS) and the Wavelength Routing (WR) problem in an integrated way using the current network status information and obtain better results than the existing methods.

I assumed that there is no wavelength conversion in the WDM network (reasoned by the high price of converters) and one link may contain more than one fiber. The most important conditions taken into account are:

- The topology of the network and the available resources (number of fibers/link, number of wavelength channels/fiber) are known and do not change during the working period of the algorithm (except in case of link failures, because the algorithm is able to handle this case).
- The source and sink nodes of the incoming demands are known, while the holding time is not.
- There is no information about future incoming requests. It means that the algorithm can only take the actual network status into account.
- We assume that a demand can reserve one wavelength only.

The proposed method for the WS&WR problem has the following main steps:

Step 1. A new demand allocation request is arrived into the network.

Step 2. The demand is tried to be allocated onto all possible wavelengths using my proposed integrated wavelength selection and routing strategy.

• For the Wavelength Selection (WS) process I have proposed and compared five new modes how we can measure the suitability of a wavelength. The most important factors are the length of the path of demand and the utilization of the wavelength.

• For the Wavelength Routing (WR) process I have proposed several types of weight functions that help to route an incoming demand. The weight functions adaptively depend on different functions of link loads and the tests proves that they play an important role to obtain better solution than the existing methods.

• The WS&WR algorithm considers the fairness criteria, which means that it is an important factor to provide that the difference between the individual user blocking probability (what the user see) and the overall (long–term) blocking probability should be minimal.

Step 3. If it is possible the demand will be allocated, else it will be rejected.

In Figure 2 I compared my proposed WS methods to the so–called First–Fit [26] and the Random Wavelength Selection, in case of a 25 and a 56 node network.

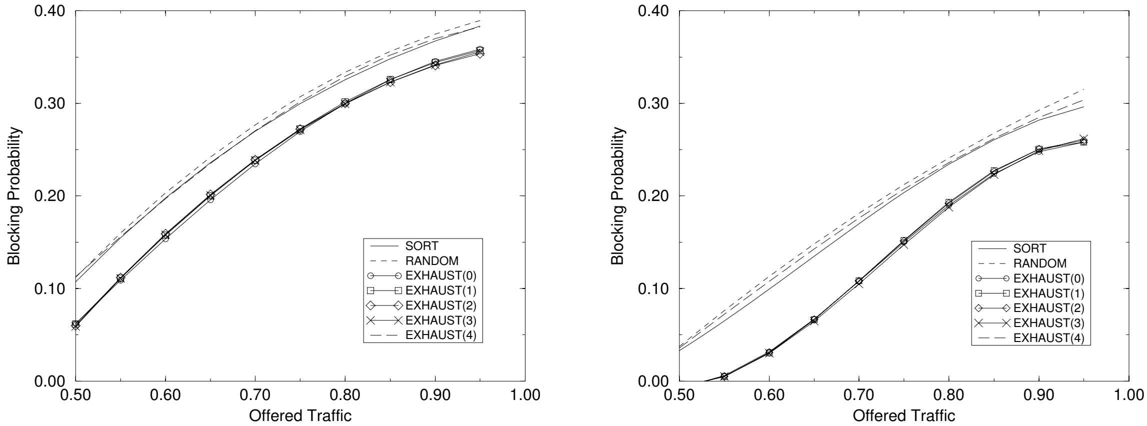

Figure 2: Blocking probability using different WS strategies in Net_{25} and Net_{56}

The results show that four of my five proposed WS methods (that consider the load and length of the path and the load of the current wavelength), with any of my proposed weight functions for the WR problem, provide at least 5–10% lower blocking probabilities than the existing algorithms independently from the network size, traffic pattern and arrival process, due to the integrated handling of WS&WR problems. The last of my method (that considers only the load of the path) obtains results comparable to the known strategies.

Thesis 4.2 : Dimensioning and configuration of WDM networks

I have proposed a possible way to apply my WS&WR method to solve the planning and configuration tasks that appear in WDM Networks, which results better–fitted network to the dynamic wavelength allocation.

Here the task is to find the needed (a) number of fibers contained by a link ($F_{num}(l), \quad l \in \mathcal{L}$, where $\mathcal{L}$ denotes the set of links) or/and number of wavelengths in the network (W_{num}) to provide the pre–defined long–term blocking probability (P_{goal}) in case of a known (or estimated) demand arrival process.

The basic steps of the proposed method are the following:

Initial Step. Both the $F_{num}(l)$ and W_{num} values will be set to 1.

Step 1. Using the given network resources (number of fibers and wavelengths) the above proposed WS&WR algorithm is used to establish the incoming demands, simulating a working network. During this establishment process the current blocking probability (P_{curr}) is measured. After some demand establishment requests we got the long–term value of P_{curr}, then P_{goal} and P_{curr} are compared. If $P_{goal} < P_{curr}$, it means that the current network resources are not sufficient to obtain the pre-defined blocking probability level, therefore resource extensions are required. If $P_{goal} \geq P_{curr}$ the optimization is finished at *Final Step.*

Step 2. – Network Extension. The network can be extended if $F_{num}(l)$ or W_{num}, as well as both of them are increased in the following way:
- $F_{num}(l) = F_{num}(l) + n(l)$ for all link $l \in \mathcal{L}$
- $W_{num} = W_{num} + m$
- $F_{num}(l) = F_{num}(l) + n(l)$ for all link $l \in \mathcal{L}$ and $W_{num} = W_{num} + m$

where $n(l)$ and m are integer numbers which can be set by the user, or can be set adaptively during the optimization according to the difference between P_{goal} and P_{curr} (the value of $n(l)$ and m are decreasing with this difference). After the network extension the optimization is continue at Step 1.

Final Step. It is possible that the final network is overdimensioned (if $n(l)$ or m was greater than 1 during the optimization). Therefore in this final step the algorithm starts to decrease the network resources one by one, while the steady state value of P_{curr} is checked continuously. In this way the network can be dimensioned very precisely for the pre–defined blocking probability in case of the incoming traffic pattern. The optimization is finished with the last network configuration, where P_{curr} is valid.

The above method can also be used to solve the static dimensioning task in the following way. We are working with final set of demands (they must be routed in the network); and P_{goal} is set to 0, which means that we find such a state where all demands are installed into the network, what is a possible static configuration of the network. The algorithm repeats the above process to find some other valid network configurations. Then the algorithm selects among the most resource–saving configurations that one, which results the best network utilization (which contains the most free resource in case of the same $F_{num}(l)$ and W_{num}) values.

Using about 50 randomly generated test networks with different number and distribution of demands I compared my algorithm with the dimensioning method presented in [35] and I got the following results:

- My proposed algorithm is able to allocate all demands using on average 8.4% less resources.
- For the same values of $F_{num}(l)$ and W_{num} values my algorithm can offer such a routing configuration than results about 5% more residual resources (e.g. wavelengths) in the network.

5 Application of the Results

The algorithms presented in Thesis 1 are used in the UMTS Network Planning and Analysis Tool of Ericsson Telecommunication Ltd. The results of the UMTS core network planning research (Thesis 2) was sponsored by a Product Unit of Ericsson Hungary, and they will be used in a Network Configurator Tool. The OSPF related research was carried out in the frame of cooperation between Ericsson Research Hungary and Warsaw Technical University. The dynamic path establishment algorithm in WDM network related work was a result of cooperation between Ericsson and the High Speed Networks Laboratory, Budapest University of Technology and Economics and it will be used as a configurator method in WDM Network Planning Tool.

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