

Planning Reliable UMTS Terrestrial Access Networks

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Abstract— The Universal Mobile Telecommunication System (UMTS) will play a very important role in the telecommunication market of the near future. The wide range of services and the increased transmission capacity provide the UMTS become one of the most important type of access networks. The proposed topology of UMTS terrestrial access network is the tree, however the great amount of carried traffic requires a more reliable network structure. In this paper we introduce two types of heuristic algorithms for planning reliable UMTS access network topologies. Our aim is to provide a minimized magnitude of traffic loss in case of failures. One of our algorithms solves this problem by modifying the tree-topology, while others expand the network by inserting extra links. In this paper, we present a detailed tests of the algorithms using realistic network scenarios, and we show a deal between tree topology refinement and network expansion.

Keywords— Network Planning and Optimisation, Reliability and Availability Analysis, Access Networks, GSM and 3G Mobile

I. INTRODUCTION

Today it is already obvious, that the Universal Mobile Telecommunication System(UMTS)[1] will play a fundamental role in the telecommunication market of the near future. The incorporation of multitudinous services with special emphasis of data transfer and the significantly increased transmission capacity provide that penetration of UMTS be very high. Because of the increased volume of data communication, the terrestrial access network of UMTS is a very complex and high capacity system.

The access network of UMTS basically consists of two types of network elements called *Radio Network Controller*(RNC) and *Radio Base Station*(RBS). The task of the RNC is to manage the radio channels of the connected RBS's, and to concentrate/relay their traffic to the upper level core network. The RBS's are connected to the RNC either directly or via some other RBS devices in a cascaded way. That way, the RBS handles their own radio channels, and forwards the traffic of lower level RBS's towards their dedicated RNC.

The optimal construction of this access network topology is one of the most important fields of the re-

cent UMTS related research activities. On the basis of the existing GSM network topologies the approach is that the access topology should be a set of (multi-) constrained trees. In case of these tree topologies, the constraints come from technical limitations of the equipments and the root of a tree is an RNC. However, the great number of RBS's and RNC's, the strongly non-linear cost function of the connections and the equipments, and other technical limitations make the planning of this kind of networks be a computationally difficult optimization task. We have to recognize, that the quality of the obtained solution will determine the long-term performance and service quality of UMTS, which are really critical issues in the competitive mobile market.

Basically two different tasks can be defined, namely:

- Multi-RNC problem: Here the task is two-fold; on the one hand we have to determine the required number of RNC's and their location, while on the other hand we have to construct the tree of RBS's for each RNC.
- Single-RNC problem: Our task is here to find an optimal RBS tree for a pre-defined RNC.

The large size of networks to be optimized and the additional constraints requires to follow algorithmic approach to solve the problem. In the literature there are some papers dealing with the problem of planning tree-structured UMTS access networks and with the construction of multi-constrained spanning trees. Papers [2] and [3] deal with the Multi-RNC problem, [4] deals with the Single-RNC problem, and [5] proposes an approach to solve both problems. In the present paper we deal with the Single-RNC problem.

Work [2] proposes a novel model for UMTS networks, and defines a Simulated Annealing based heuristic algorithm capable of planning the whole access network. Article [3] purposes another model, and solves the design task using Simulated Annealing. Paper [4] constructs a more sophisticated model, improves the bottlenecks of the previous algorithms and gives a solution for the cost-optimal planning of an RNC rooted RBS tree. In [5] the authors propose a

Lagrangian–relaxation based algorithm to solve optimization tasks appearing in UMTS networks.

Beside its simplicity and cost–effectiveness, the tree topology has a very important disadvantage: it is very sensitive to any kind of failure. It is a very critical feature due to the large amount of data, because a single failure may cause significant data loss, and may result in critical degradation of the network performance. These failures occur rarely, however they need to be handled, so a fault–tolerant topology is required. Because of the large number of nodes interconnected, both the mesh–like and the ring–topology can be very uneconomical. This motivated us to examine how to design topology which ensures an overall traffic loss lower than a desired value.

Our first idea is to modify the network while keeping its tree structure. Another possibility is to expand the tree–network with extra links where it is required to decrease the magnitude of data loss on failure. That way, we have introduced two approaches and developed two algorithms, accordingly.

In the first case we compute the expected traffic loss of a current tree topology and we take into account this value as a virtual additional cost. Hence the total cost of the network consists of the nominal network cost and the traffic loss related cost. The ratio of the two types of cost is adjustable according to the desired traffic loss level. Due to the additional cost, this algorithm is able to plan a tree topology that provides an equilibrium between the network cost and the traffic loss.

In the second case we increase the network reliability by inserting new links into the network. By this, we can provide a more efficient protection strategy, as we assign alternative paths specially to the most failure sensitive traffic demands.

The remainder of the paper is organized as follows. In the next section we will give the mathematical formulation of the planning problem, the used network– and cost models, and we will define our reliability model. Section III and section IV describes the proposed algorithms. In section V we will give a detailed numerical study and performance analysis of the different algorithms. Finally, we conclude the paper with a brief summary and our further plans.

II. PROBLEM STATEMENT

In this section we present our network model for the UMTS networks from the viewpoint of network planning. We will define the applied cost models and the related reliability issues. In the last subsection we formulate the objective function of the optimization.

A. Network Model

Let $\mathbb{S} = \{a_1, a_2, \dots, a_k, \dots, a_N\}$ denote the set of the geographical points, where an RBS is placed, and N stands for the number of RBS’s. Let RBS_k denote the RBS at site a_k , and let $a_0 \notin \mathbb{S}$ denote the site where

the RNC is placed in advance. Let

$$x_{ij} = \begin{cases} 1 & \text{if there exists a link between} \\ & a_i \in (\mathbb{S} \cup \{a_0\}) \text{ and } a_j \in (\mathbb{S} \cup \{a_0\}) \\ & \text{and this is a working link} \\ 0 & \text{if there is no link between} \\ & a_i \in (\mathbb{S} \cup \{a_0\}) \text{ and } a_j \in (\mathbb{S} \cup \{a_0\}) \\ & \text{or this is a backup link} \end{cases} \quad (1)$$

We have the following constraints:

- *Cascading constraint* denoted by L : The maximal number of hops between the RNC and an RBS. The *level* value of a RBS is the length of the shortest path from the given RBS to the RNC in case of the current network topology, and L is an upper bound for *level*.
- *RBS degree constraint* denoted by D : Gives a maximum for the number of lower level RBS’s connected to an RBS. It limits both the number of incoming and outgoing links (i.e., it defines the sum of the input and output degree of the node).

We have to note that the up-to-date technologies let this D be a relatively weak limiting factor, however it could have significant impact on reliability. For example, if we have a strong reliability expectation, it can be fulfilled by a ”very” meshed network only.

B. Reliability model

In our model of reliability, the network consists of 3 types of elements, as shown in Figure 1.

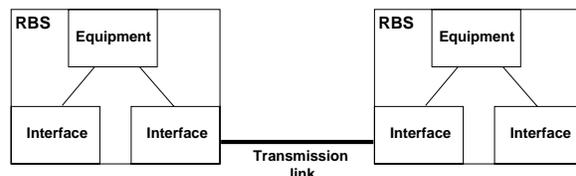


Fig. 1. Network elements: equipment, interface, link

Let $A_{eq}(C)$, $A_{inf}(C)$ and $A_{link}(a_i, a_j)$ denote the availability function of equipments, interfaces and links, where C denotes the required capacity, and a_i, a_j nominate geographical locations. As we can see, A_{eq} and A_{inf} are capacity dependent, while A_{link} depends on the link length and location defined by a_i and a_j . In case of links, the length parameter is used in case of wired lines with the cuts/km/year constant, while the location gives information about some factors (e.g., rainy days) needed to calculate the availability of microwave lines. The number of repeaters, which also affects the value of A_{link} may depend on both the length and the location of the link).

As mentioned previously, the traffic originating from RBS’s is routed towards the RNC, so one or more paths can be assigned for each RBS, for that purpose. If we define path P as a set of network elements (shown above), the availability of P can be calculated as given in (2),

$$A(P) = \prod_{i \in P} A_i \quad (2)$$

where A_i is the availability of the i^{th} element in the path.

For an RBS having one or more paths (namely one default, and some backup paths), we can calculate its availability, from the joint availability of the paths belonging to it. In case of a path set $\mathbb{P} = \{P_1, P_2, \dots, P_K\}$ belonging to the given RBS,

$$A_{RBS} = A(\mathbb{P}) = \sum_{P_i \in \mathbb{P}} A(P_i) - \sum_{P_i, P_j \in \mathbb{P}} A(P_i \cup P_j) + \sum_{P_i, P_j, P_k \in \mathbb{P}} A(P_i \cup P_j \cup P_k) - \dots \quad (3)$$

where $P_i \cup P_j \cup \dots \cup P_k$ denotes the union of elements in paths P_i, P_j, \dots, P_k , and $i \neq j \neq k$.

Protection algorithms outlined in later sections have the goal to protect the most failure sensitive parts of the network, i.e. the RBS's losing the biggest amount of data in average. Therefore, we define the traffic loss parameter, $\mathbb{L} = (1 - A_{RBS}) \cdot T_{RBS}$, where T_{RBS} is the traffic originating from the RBS. That way, the highest \mathbb{L} value marks the most failure sensitive part of the network.

We note that in case of a tree topology, the average value of \mathbb{L} is always bigger than a lower limit, denoted by \mathbb{L}_{min} , which is the average traffic loss in a star topology network, and calculated as given in (4).

$$\mathbb{L}_{min} = \left(1 - A_{eq}(C_{avg})^2 A_{inf}(C_{avg})^2 A_{link}\right) T_{avg} \quad (4)$$

C. Cost model

The cost model we use is conform to the model presented in [6]. In our model the total cost of the network consists of the cost of the RNC, the RBS devices and the cost of the links.

The link cost $\mathbb{C}_{link}(i, j)$ between sites a_i and a_j has a capacity-independent and a capacity-dependent part, and our cost functions are able to handle both wired (leased-line, fiber, coax) and wireless (microwave) interconnections. The capacity independent part of the transmission link cost consists of two parts. One part is proportional to the distance of the sites, while the other part is the cost of the repeaters required between sites a_i and a_j . In the other hand, the capacity dependent part of the link cost is typically represented by an increasing step-wise or piece-wise function. Our model is able to handle both approaches.

The total cost of a link is calculated as the sum of the previously defined components.

In calculation of the cost of RBS's, let denote \mathbb{C}_{RNC} and \mathbb{C}_{RBS_k} the cost of the RNC and the cost of the

RBS device at site a_k . Both costs consist of three types of sub-costs, namely:

- The cost of the number of ports belonging to the given RBS. This is given by a step-wise function and depends on the number of other RBS's connected to the RBS in question.
- The capacity dependent cost of ports. This cost function is also step-wise and describes the cost of the required capacity of the current port.
- The equipment cost representing the installation and investment cost of required sub-devices, namely processors, boards, etc. This cost is calculated as a linear combination of the sum of traffic passing through the current device and the number of the physical ports in use.

That way, the cost of the whole access network topology (\mathbb{C}_{top}) is calculated from the cost of the elements as given in (5)

$$\mathbb{C}_{top} = \mathbb{C}_{RNC} + \sum_{k \in \mathbb{S}} \mathbb{C}_{RBS_k} + \sum_{(i,j) \in \mathbb{E}} \mathbb{C}_{link}(i, j) \quad (5)$$

where \mathbb{E} denotes the set of transmission links in the network.

Besides the structural cost of the network, we also define a second type of network cost, describing the reliability of the network in question. This kind of penalty cost makes it possible to take care of the reliability of the network during the cost base network planning procedure.

At the calculation of this penalty cost, let we have a limitation on the maximum traffic loss, denoted by \mathbb{L}_{lim} . Assuming a tree topology, $\mathbb{L}_{lim} \geq \mathbb{L}_{min}$, so in case when a stronger limit is given, let \mathbb{L}_{lim} be equal to \mathbb{L}_{min} .

Comparing the \mathbb{L} value of all RBS's with the limit \mathbb{L}_{lim} we can calculate a normalized penalty value denoted by $\alpha \in [0, 1]$, where $\alpha = 0$, if the average traffic loss is below the expected \mathbb{L}_{lim} value for each RBS, and $\alpha = 1$ in case of the worst solution so far.

To bring the penalty cost into a same order of magnitude with the structural cost, we define \mathbb{C}_{net} , derived from \mathbb{C}_{top} in three possible ways:

- It can be equal to the initial \mathbb{C}_{top} .
- It can be updated to \mathbb{C}_{top} frequently during the operation of the algorithm.
- It can be simply equal to the actual \mathbb{C}_{top} .

Using one of these possibilities, the virtual, traffic loss related cost is:

$$\mathbb{C}_{pen} = \alpha * \mathbb{C}_{net} \quad (6)$$

D. The Optimization Problem

To find a proper relation between the topological cost and the penalty cost we can use a variable cost-ratio, denoted by $\beta \in [0, 1]$.

The total cost of the network is as follows:

$$\mathbb{C}_{total} = \beta * \mathbb{C}_{pen} + (1 - \beta) * \mathbb{C}_{top} \quad (7)$$

Let l_j and d_j denote the current level and degree value of RBS at site a_j . Using these notations our objective is to minimize \mathbb{C}_{total} subject to the following constraints:

$$\begin{aligned} l_j &\leq L && \text{for all RBS's } j \\ d_j &\leq D && \text{for all RBS's } j \\ \sum_{j \in S} x_{ij} &= 1 && \text{for all RBS's } i \\ \bar{\mathbb{L}} &\leq \mathbb{L}_{lim} \end{aligned} \quad (8)$$

III. PENALTY-TREE ALGORITHM (PTA)

In this section we propose an algorithm to find a tree-topology ensuring the average traffic loss of the network be less than a predefined value \mathbb{L}_{lim} .

This algorithm has the following inputs:

- The place of RBS's and the RNC: \mathbb{S} and a_0 .
- Constraints: L , D and the maximum loss value \mathbb{L}_{lim} .
- Availability functions: $A_{eq}(C)$, $A_{inf}(C)$ and $A_{link}(a_i, a_j)$.

The key of this approach is to modify the tree-topology in such a way that we keep this basic structure without any redundant link. In [4] we have proposed an algorithm, that builds up a cost-efficient (near optimal) degree- and level-constrained tree topology under similar conditions.

Shortly, the algorithm is the following:

- Determines which RBS's have to be placed one hop from the RNC.
- Connects the remaining set RBS's to these "first level" RBS's in such a way that provides the obtained network topology be the best (cheapest).
- Uses *Simulated Annealing* (see [7]), a meta-heuristic method. In each step of the method, reassigns the RBS's in the first level, and rebuilds the topology. The acceptance of the actual configuration is decided according to the cost of the configuration.

In current case we use the same algorithm, but in each step we compute the total cost of configuration as a linear combination of the physical, and a virtual, traffic loss related cost (penalty cost).

A. Penalty cost calculation

In order to calculate the penalty cost \mathbb{C}_{pen} , first we have to determine the expected traffic loss for each RBS as described in Section II-B. To take into consideration the reliability, let us introduce a penalty value denoted by ω . The calculation of ω is as follows.

- At the beginning, calculate the cost of the initial network and the traffic loss for every RBS (\mathbb{L}_k).
- Determine the penalty value ω_k for the RBS at site a_k , where

$$\omega_k = \begin{cases} (\mathbb{L}_k - \mathbb{L}_{lim})^2 & \text{if } \mathbb{L}_k > \mathbb{L}_{lim} \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

- Calculate the penalty value ω , where

$$\omega = \sum_{k \in S} \omega_k$$

and where \mathbb{S} denotes the set of RBS's.

The advantage of the applied quadratic function is that it effects lower traffic loss values as it penalizes the most critical RBS's much more than the less critical ones.

To calculate the virtual penalty cost of the network as given in (6) we have to determine the previously defined α value by normalizing the penalty value ω to the range $[0, 1]$. For that purpose, we use ω_{max} , the value of ω in the first iteration. For better performance ω_{max} can be updated several times during the algorithm, however this can change (increase) the weight of the penalty cost in the total cost.

As we mentioned in II-C, the value of α is not in the same order of magnitude with \mathbb{C}_{top} . That way, it still remains a question, how to do this "normalization", namely what value should be substituted into \mathbb{C}_{net} . We have two basic choices:

1. First, we can use the initial cost of the network (\mathbb{C}_{top} at time 0), but in this case the optimization procedure emphasizes more and more the penalty-cost during the operation, as the base of the normalization is fix.
2. The second possibility is to use the actual \mathbb{C}_{top} . In this case formulas (6) and (7) give the following total network cost:

$$\begin{aligned} \mathbb{C}_{total} &= (1 + \beta * (\alpha - 1)) * \mathbb{C}_{top} \\ &\leq \mathbb{C}_{top} \end{aligned} \quad (10)$$

This way, we can keep the ratio between the penalty- and the topology cost constant, however the random movements of the Simulated Annealing technique bring some fluctuation into the base of the normalization.

During tests, we examined the behavior of PTA in both cases, and found no significant differences, except the fact that in the second case we have to use higher value of β to obtain the same results.

IV. RELIABILITY ENHANCEMENT ALGORITHMS

In this section we propose algorithms for increasing the network reliability by inserting additional links. As an input, we get a tree topology network, and a \mathbb{L}_{lim} parameter (\mathbb{L}_{lim} denotes the maximum of average traffic loss in the network). The output is a network topology with a guaranteed average traffic loss less than \mathbb{L}_{lim} .

The following assumptions were used.

- Single failure scenario (i.e., at a time, only one error can occur within the network).
- Backup paths are allowed to be at most one hop longer, than default path of the RBS.
- The degree of each RBS in the input network is less than D . (Otherwise, no new link can be created).
- The newly added backup links do not carry any traffic, except the case of failures.

The assumption of the single error scenario enables the use of shared protection strategies. (See Fig. 2 for an example)

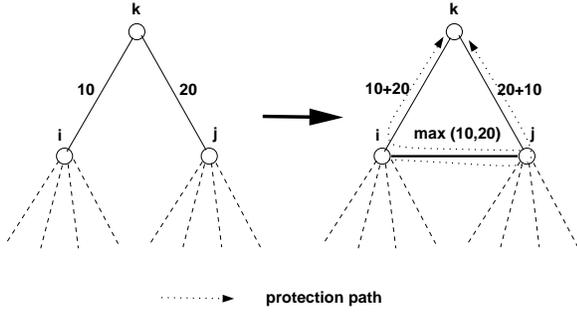


Fig. 2. An example of shared protection

As we can see, protecting RBS at a_i and a_j , we created a new (a_i, a_j) , and assigned backup paths $a_i \rightarrow a_j \rightarrow a_k$ and $a_j \rightarrow a_i \rightarrow a_k$, accordingly. On creation of the backup paths, we need to increase the capacity of links (a_i, a_k) and (a_j, a_k) , to make them capable of handling the protection traffic. If we suppose only one error, only one of links (a_i, a_k) and (a_j, a_k) can fail at a time, so only one of the traffics $T_{sum}(i), T_{sum}(j)$ had to be rerouted through link (a_i, a_j) . ($T_{sum}(i)$ denotes the aggregated traffic coming from RBS_i). That way, the link (a_i, a_j) only need a capacity of $\max(T_{sum}(i), T_{sum}(j))$.

In the following two algorithms, we use this strategy when creating protection paths.

A. Greedy Reliability Enhancement(GRE)

To analyze the performance and the efficiency of our RRE algorithm (see Section IV-B) we created a simple algorithm, that inserts backup links between first level RBS pairs. It works as follows:

1. Let F denote the set of first level RBS's and let $U \subseteq F$ be the set of RBS's without backup links (initially $U = F$). Let \mathbb{L}_{act} be the actual average traffic loss in the network.
2. Find the closest $RBS_i - RBS_j$ node pair in U , remove RBS_i and RBS_j from U , and add both (a_i, a_j) and (a_j, a_i) to the network. Set up backup path $a_i \rightarrow a_j \rightarrow a_0$ for RBS_i , and $a_j \rightarrow a_i \rightarrow a_0$ for RBS_j . Increase capacity in nodes and links along the backup paths as needed. After the insertion of the new links, recalculate the value of \mathbb{L}_{act} .
3. Repeat Step 2 until $|U| \leq 1$ or $\mathbb{L}_{act} \leq \mathbb{L}_{lim}$.
4. If $|U| = 0$, STOP.

Otherwise, find the closest $RBS_k \in F$ to RBS_i (the remaining RBS in U) and add link (a_i, a_k) to the network. Set up backup path $a_i \rightarrow a_k \rightarrow a_0$ for RBS_i , and increase capacities along the backup path as needed.

We note, that this algorithm can insert maximally $\lceil |F|/2 \rceil$ new links into the network. Therefore, it works well only in the case, when the traffic loss expectation given in \mathbb{L}_{lim} can be fulfilled with that number of new links.

B. Randomized Reliability Enhancement(RRE)

In this algorithm, we use randomization for choosing the RBS's to be protected. The algorithm is as follows:

Step 0: Initialization

- Let $T_{prot}(i)$ be the sum of traffic we need to protect for RBS_i . Initially, we have a tree topology, so $T_{prot}(i)$ is the sum of traffic in all child nodes of RBS_i plus the traffic of the RBS_i .
- Let $\mathbb{L}_{prot}(i) = T_{prot}(i) \cdot (1 - A_{RBS_i})$ denote the traffic loss at RBS_i .
- As $\mathbb{L}_{prot}(i)$ corresponds to an aggregated traffic, we need to give a limit for the aggregated traffic loss also. Therefore, let \mathbb{L}_{plim} be that limit value calculated from the input parameter \mathbb{L}_{lim} .
- Let $P_{def}(i)$ denote the default path and $P_{back}(i)$ the set of backup paths for RBS_i .

Step 1: Let \mathbb{B} be a set of RBS's, where $\mathbb{L}_{prot}(i) > \mathbb{L}_{plim}$. If $|\mathbb{B}| = 0$, STOP.

Let RBS_i be chosen by a weighted random function from set \mathbb{B} . $\mathbb{L}_{prot}(i)$ is a parameter of the random function, so the highest the $\mathbb{L}_{prot}(i)$ value, the highest the probability the RBS_i is chosen.

Step 2: Find new backup path P_{new} for RBS_i .

First, we need to find an RBS_j , where $l_j = l_i$ or $l_j = l_{i-1}$. The path $(a_i, a_j) \cup P_{def}(j)$ gives P_{new} .

Let \mathbb{C}_{new} denote the cost of P_{new} . (\mathbb{C}_{new} includes the cost of the new link (a_i, a_j) , and the capacity increment cost along $P_{def}(j)$). Let A_{prot} denote the joint availability of $P_{def}(i)$, $P_{back}(i)$ and P_{new} , and let \mathcal{L} be the length of P_{new} . To find the proper RBS_j to create a backup link to, we use rate value R , where

$$R = \gamma \cdot (\mathbb{C}_{new}) + \delta \cdot (1 - A_{prot}) + \lambda \cdot \mathcal{L}$$

and where $\gamma, \delta, \lambda \in [0, 1]$ are constants used to find a compromise between these three objectives.

To take the degree constraint D into consideration let $R = \infty$ if d_j already equals to D . Using the R value, let $RBS_j \in \mathbb{H}$ be the RBS where R is minimal. In this case, let \mathbb{H} denote the set of RBS's being closer than a given distance limit to RBS_i .

Step 3: Create backup path for RBS_i through RBS_j .

- Create a new link (a_i, a_j) with capacity $T_{prot}(i)$, and increase the capacity of each link l by $T_{prot}(i)$, where $l \in P_{new}, l \notin P_{default}(i)$ and $l \notin P_{backups}(i)$.
- Insert P_{new} into set $P_{back}(i)$.
- For each RBS_k , where $RBS_i \in P_{def}(k)$, let $P_{back}(k) = P_{back}(i) + P_{k \rightarrow i}$, if the $T_{prot}(k) \neq 0$. ($P_{k \rightarrow i}$ denotes the part of $P_{def}(k)$ between RBS_k and RBS_i .)
- For each RBS $_r$, where $RBS_r \in P_{def}(i)$, $RBS_r \notin P_{new}(i)$, decrease the $T_{prot}(r)$ by the $T_{prot}(i)$, if $T_{prot}(r) \neq 0$ already. After, let $\mathbb{L}_{prot}(i) = 0$.

Step 4: Recalculate $\mathbb{L}_{prot}(i)$ values for each RBS_i . GOTO Step 1.

V. NUMERICAL RESULTS

In this section we examine the behavior of our proposed algorithms.

First, we show planning results obtained by the PTA (see III). Using a network of 100 RBS's, we created several network topologies, by changing the parameter β . Figure 3 shows the cost and the traffic loss values, normalized to the value given for $\beta = 0$. We performed the above test using different \mathbb{L}_{lim} values. In Figure 3, case A and B mark results for a weaker ($\mathbb{L}_{lim} = \bar{\mathbb{L}}_0$) and a stronger ($\mathbb{L}_{lim} = \mathbb{L}_{min}$) reliability expectations. ($\bar{\mathbb{L}}_0$ denotes the initial average of traffic loss in the network)

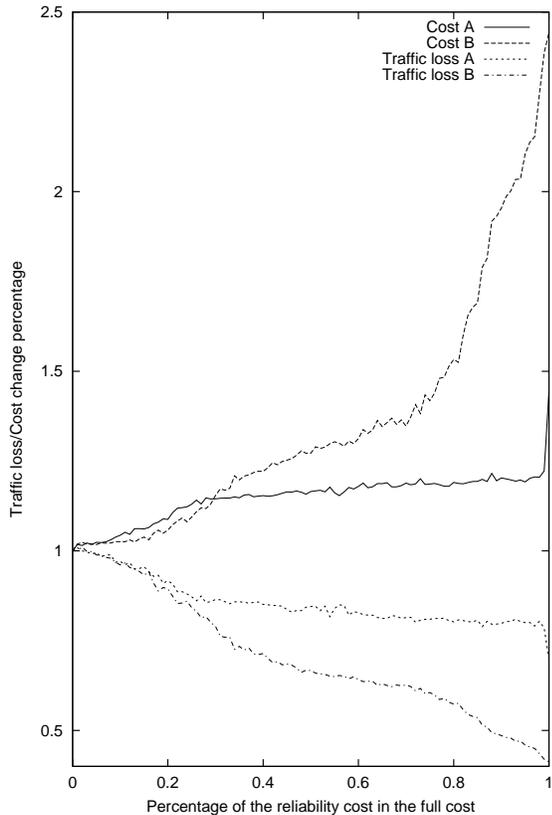


Fig. 3. Network cost and traffic loss using different β and \mathbb{L}_{lim} parameters

As parameter β increases, the structure of the network diverges from the cost-optimal tree-topology. As we can see, in both cases A and B, the cost and the traffic loss functions have two major inflexion points, and three major parts accordingly (the inflexion point are located at β values of approx. 0.3 and 0.8). The explanation of the different parts of the curves is the following:

- Until the first inflexion point, the traffic loss in the network decreases as the average degree of RBS's decreases.
- Between the inflexion points, besides the low degree values the average level of RBS's decreases as well. That way, the number of first level nodes increases.
- Beyond the second inflexion point, parameter β makes the penalty cost so dominant, that the tree topology begins to transform into a star topology.

We have the following comments:

- As the difference between case A and B shows, the position of these inflexion points depends on the choice of \mathbb{L}_{lim} . Of course, these characteristics also depend on the chosen penalty cost function, and on the optimization method as well.
- On the other hand, until the first inflexion point, our design method is more cost-efficient in case B. Since a higher \mathbb{L}_{lim} value provides a higher penalty cost, the algorithm may have larger degree of freedom to change the topology in a cost-optimal way. That is the reason of the lower cost values in case B.

Since \mathbb{L}_{lim} in case B belongs to the lower bound of traffic loss in a tree-topology (namely the traffic loss of a star-topology), we use this \mathbb{L} value in the following tests.

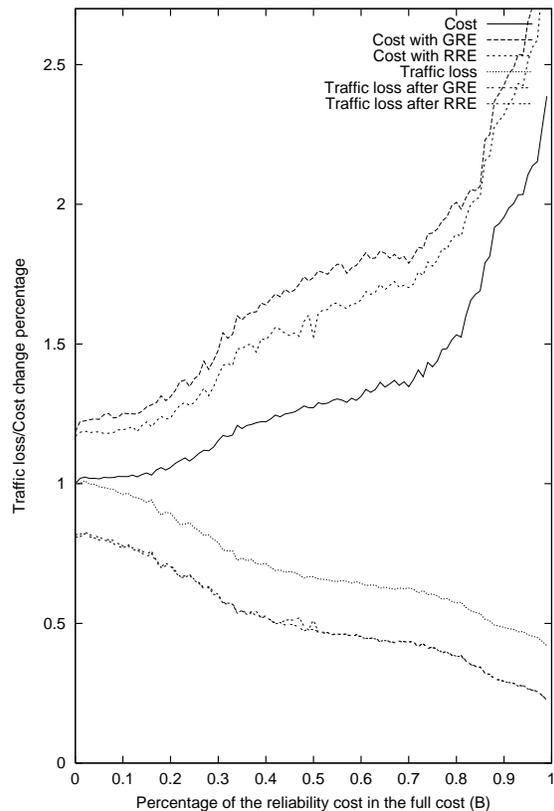


Fig. 4. Network cost and traffic loss using different β parameters, comparing RRE and GRE

Based upon network topologies resulted by the PTA in case B, we have made further tests comparing the behavior of our GRE and RRE algorithms (defined in Section IV-A and IV-B). During the tests, in case of GRE we set $\mathbb{L}_{lim} = 0$ in order to obtain the most reliable network as possible. On the other hand, in case of RRE, we set \mathbb{L}_{lim} to the average traffic loss value of the GRE resulted networks. That way, the two algorithms were providing the same traffic loss level, so we could compare them by the cost of the resulted networks.

As Figure 4 shows, the RRE algorithm was giving better performance in all cases. The difference between GRE and RRE was 7%-15%, depending on β . The

relatively greater difference on the segment between the two inflexion points has the following reason: as RRE is not limited to protect only first level nodes, the resulting cost does not depend so strongly on the number of first level nodes, so RRE is able to provide a more cost effective solution.

In the third tests, we used the networks obtained by PTA in case of $\mathbb{L}_{lim} = \mathbb{L}_{min}$ again, but in this case, we used this value for RRE, too. So in the first step, we created a preoptimized network using PTA with a given β and \mathbb{L}_{lim} value, and after we extended the network with extra links to have the required traffic loss limit. In this test, we wanted to find the optimal value of β , where the final cost of the network is minimal. As Figure 5 shows, we can find an optimum, around the first inflexion point (approx. at $\beta = 0.3$ on Figure 5).

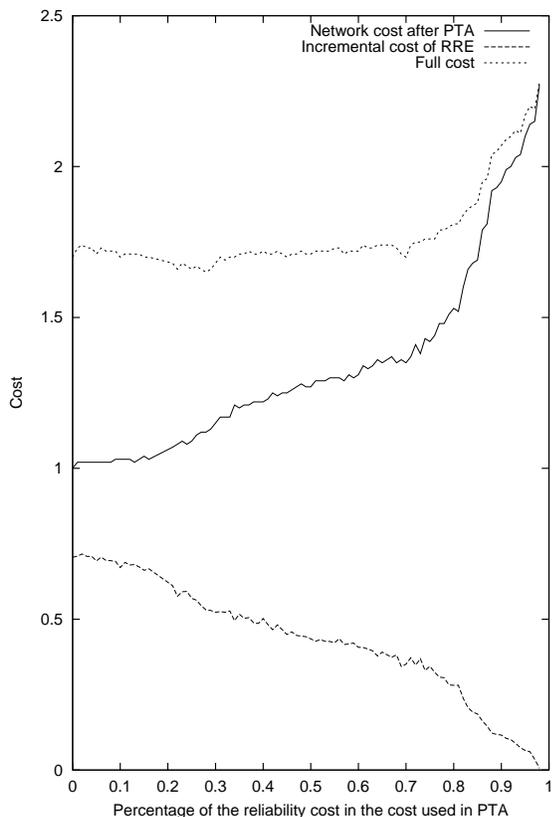


Fig. 5. Network and expansion cost with fixed \mathbb{L}_{lim} and variable β parameters

VI. CONCLUSIONS AND FUTURE WORK

In this paper, we made proposals for the creation of reliable UMTS access networks. Based on networks obtained by a tree topology network planner algorithm and using Simulated Annealing, we developed two new methods to reach the required reliability level. In our first method (PTA), we modified the original network planner algorithm to take the reliability of the network into consideration during the network planning phase. Therefore, in PTA we just modified the network topology while keeping the tree structure. In the

second method (RRE), we made an expansion on the network, protecting the most failure sensitive parts of the topology.

We found that in case of relatively weak traffic loss requirements, it is more efficient to use the PTA algorithm only, while in case of a higher reliability demand, we also need expansion algorithms. In our tests, the PTA was efficient until we had a traffic loss requirement approx. 80 percent of the traffic loss value of the initial network.

Moreover, we found, that the level of PTA preoptimization (β) highly influenced the efficiency of RRE, and we presented a β value, where the joint use of PTA and RRE gives an optimal solution.

In the future we want to work out a more sophisticated and adaptive algorithm for the problem of reliability enhancement. We also want to examine some other objective functions, namely defining the connection between penalty cost and network cost to get a better joint result of tree planning and extension planning.

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