OPTIMIZATION OF MESH-STRUCTURED CIRCUIT SWITCHED NETWORKS

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Mesh-structured networks are introduced primarily in military applications. The networks will often utilize decentralized adaptive routing strategies. In the paper a method for optimization of such networks is described. The method can be used to find approximations to end to end blockings in the networks as well. A simplified performance function is used and the optimization and analysis process will thereby become computationally efficient.

1. INTRODUCTION

The main topic of the paper is modelling of a particular type of telecommunication networks which primarily are introduced in military applications. The networks can be classified as circuit switched, non-hierarchical and mesh structured. Compared with the circuit switched public non-hierarchical networks which have been introduced recently, the objective networks have the following characteristics:

- The direct high-usage links between two end nodes will not be present. A typical shortest path for a connection can because of the mesh structure contain more than 5 transit nodes. The high number of possible paths in the network will thereby make the problem of finding the optimized routing pattern difficult.

- The routing pattern are found in real time with adaptive decentralized routing strategies.

The networks will often consist of a large number of nodes (50 to 100). The number of links as well as the number of channels in each link are, however, low. One example of such a network is given in figure 1, where the outline of the strategic Norwegian Defence Digital Network (NDDN) is shown.

In the present paper a method for optimization and analysis of these mesh structured networks will be presented. The paper is based on the work in (1).

In chapter 2 a discussion around the applicability of existing methods for analysis and optimization of telecommunication networks will be given. In chapter 3 the proposed method is described. Results from the use of the method are presented in chapter 4.

* The paper is based upon a Dr.ing. dissertation at the University of Trondheim. The author is now at Siemens AG, Munich.
The method is verified by simulations of a network with an adaptive routing strategy which was published in (2). The optimization method is not restricted to this routing strategy. The strategy is however a typical example of a routing method for these networks. The adaptive routing strategy (2) uses the residual capacity in each link as parameter when choosing the paths in the network. These paths will be fixed for a given time interval (typically a few seconds). A spanning tree is established for each node in the network. The spanning tree is updated regularly and stored decentralized in each node in the network. For a given time interval, one (and only one) path are thereby defined between two end nodes. When updating the trees saturation searches are used. These are delayed in each transit node relative to the residual capacity in each link. The new spanning tree will thereby reflect the network occupancy.

![Diagram of the NDDN network](image)

Figure 1. The NDDN network

2. EXISTING OPTIMIZATION METHODS

The following two problems are examined:

A. Optimization problem.
   Find the optimal number of channels in each transmission link given network topology, traffic matrix and the cost function for each link. End to end grade of service are often constraints to the optimization process.

B. Analysis.
   Find the end to end grade of service (blocking) given a network (network topology as well as the size of each link).
Problem B has traditionally been solved with the use of discrete event simulations for adaptive routing strategies. For large networks this solution will, however, require too much of processor resources to be feasible.

For problem A a number of optimization methods for communication networks have been published. The optimization problem is extremely complicated because of the existence of nonlinear performance functions and non-separable constraint functions (the link blockings are found through the solution of the complex "network system of equations" (see (14)). The general optimization problem cannot be solved in an exact manner for non-trivial networks.

Several optimization methods for the non-hierarchical inter-city network in USA (3) are published (see (3), (4), (5) and (6)). A method for optimization of Bell Northern Research's new adaptive routing strategy (7) is described in (8) and (9). All these methods are primarily developed for a non-hierarchical network where the number of tandem nodes in a path is restricted to at most one. The graph theoretical flow allocation problem is thereby not as complex as for the mesh-structured networks and the methods are unsuitable for these.

Many of these methods use the marginal link cost function as metric when allocating flow to the different paths. The cost functions for a link in the objective networks will typically be discrete step-like functions. These functions will not be suitable as link metric when allocating flow. The convergence property of the method will for example be difficult to examine.

All of the above mentioned methods require that the "network system of equations" are solved repeatedly. This will represent the single most time-consuming part for the optimization method and is therefore a major limitation for the method when optimizing large networks.

Yaged (10) proposed a method for allocating flow in a large network with the marginal cost of carrying one extra channel in each link as link metric. The method is efficient, but models a non-blocking network.

A method which is primarily developed for military networks is presented in (11). Garbin & Knepley proposed to use the marginal cost of carrying one extra unit of traffic as link metric when allocating flow. Optimal link blockings must be manually calculated.

3. THE METHOD

3.1. Problem formulation

The modelling of adaptive routing strategies is difficult. Ash proposed to use an optimization method for a network utilizing a non-adaptive routing strategy when optimizing the network with an adaptive strategy (12). Pioro & Wallström indicated that this approach gave good results in (6). For packet switched networks this approach has been successfully followed, as shown by Gerla in (13). In the present method the same procedure is chosen and the following fundamental hypothesis is defined for the method:

5.2B.3.3
"A network which is optimized for a specific static routing strategy will be a near optimal network for an adaptive routing strategy. The chosen static strategy defines one path between each demand pair in the network. These paths shall be globally optimized so that the performance function in the optimization problem is minimized."

In the following, these assumptions are made: Poisson arrival process, ned call holding times, non-blocking nodes, negligible call set-up times, blocked calls cleared and do not return, network in statistical equilibrium, link blockings statistically independent and call arrival on any link is a Poisson process. For the static routing strategy described above (with no use of alternate routing), the assumptions are reasonable. Lin indicated that the assumptions gave acceptable results for large networks (like the European AUTOVON), (14).

The average network blocking

\[ G = \frac{\sum_j \sum_k r_{jk} B_{jk}}{\sum_j \sum_k r_{jk}} \]

where \( r_{jk} \) and \( B_{jk} \) denote the offered traffic and end to end blocking for node pair \( j,k \) respectively, is for the objective networks the preferred performance function when allocating flow. The often used marginal link cost function is less suitable because of the complex mathematical model.

For the static routing strategy the end to end blocking can be expressed with the individual link blockings \( y_i \) as

\[ B_{jk} = 1 - \text{P}(q_{jk} \text{ available}) = 1 - \prod_{i \in L_j \in q_{jk}} (1 - y_i) \]

where the multiplication is done for all links being part of the path \( q_{jk} \) between two end nodes. For lightly loaded networks the average network blocking can be approximated with

\[ G = \frac{\sum_j \sum_k r_{jk} ( \sum_{i \in L_j \in q_{jk}} y_i )}{\sum_j \sum_k r_{jk}} \]

Through exchanging the order of summation \( G \) will become

\[ G = \frac{\sum_{j} \sum_{k} y_i r_{jk}}{\sum_{j} \sum_{k} r_{jk}} \sum_{i \in L_j \in q_{jk}} \]

where the summation is done for all \( r_{jk} \) with a path containing \( L_i \) (link \( i \)). \( y_i \) is a function of the network flow in a complex way through the "network system of equations". The function

\[ P = \frac{\sum_{i} \sum_{j} y_i \sum_{k} r_{jk}}{\sum_{j} \sum_{k} r_{jk}} \sum_{j} \sum_{k} L_j \in q_{jk} \]

5.2B.3.4
(where $Y_i^*$ denotes the link blocking assuming that the offered traffic equals the sum of $r_{jk}$ elements over each link (offered traffic equals carried traffic)) is a much simpler function when optimizing multicommodity flow in a network. It is separable, convex (as function of the network flow), do not require that the "network system of equations" are solved and is continuous and differentiable. In the proposed method the assumption is made that the optimization of $P$ will give a near optimal result also for the average network blocking $G$.

The complex optimization problem $A$ has thereby been exchanged with the much simpler problem

Minimize the function $P$ as defined above
Given: Network topology
Traffic requirement matrix
A static routing strategy as defined above
Design variables: Link capacities and routing pattern
Constraint: The total transmission cost is fixed

3.2. Optimization of the function $P$

The method is divided into a routing optimization phase (link capacities fixed) and a second phase where the routing pattern is fixed (the link capacities are design parameter).

In the routing optimization phase the Flow Deviation method developed by Gerla (13) is used. This method was primarily developed for optimization of packet switched networks. For the proposed performance function $P$ the method is very suitable. The method will always converge and for the objective networks give results which are close to the global minimum, see (1).

For the second phase in the optimization process the method with generalized Lagrange multipliers is used (15). This method is very suitable for a general constraint function as must be assumed for the link cost function in the objective networks.

After having optimized the routing pattern in phase 1 the end to end blocking figures can be found. Under the assumption that the static routing strategy models the adaptive strategy well, these figures are approximations to the analysis problem $B$ above.

4. RESULTS

Several networks have been optimized using the method, and the results are published in (1). In the following some results from optimization of a 32 nodes network will be given. The results for the average network blocking for the static routing strategy ($G$) are found with the iterative fixed point method (14).

The adaptive routing strategy is simulated with a discrete event simulation technique. Repeated independent simulations are used and the results are given with the 95% confidence interval.
In table 1 the relation between P, G and the average network blocking when using the adaptive routing strategy are given. The results are shown for different steps in the optimization process where one iteration consists of the routing optimization phase and a capacity assignment phase. The results indicate that the average network blocking with the static routing strategy (G) is closely associated with the average network blocking when using the adaptive strategy. The modelling of the adaptive strategy with a static one has given good results for all the networks which have been optimized. For lower blocking levels (around 1%) the results will however be too inaccurate as indicated in the results for iteration 11. When the static strategy is less than 1%, the adaptive routing strategy will utilize the network much better and have significant better blocking figures.

The assumption that a network optimized for the performance function P will be near optimal for the average network blocking has been verified in the experiments. For all the experiments an improvement in P has lead to an improvement in G. This indicates that the network is near optimal for G as well. The approximate equality for P and G with lower blocking levels indicates the same. For highly overloaded networks (average blocking above 50%) P and G will be less strongly associated and the method will not be suitable.

The optimization of a 32 node network used approximately 500 seconds with a IBM AT compatible PC with separate mathematical co-processor. The processing time required to solve the "network system of equations" when finding the individual end to end blocking figures and G for the static routing strategy depends on the blocking level, but is normally below 100 seconds. The computational efficiency is of grat importance when analysing military networks because of the need to repeatedly analyse different degraded modes of the networks.

5. CONCLUSIONS

The proposed method is from a computational viewpoint very efficient. The results from the experiments indicate that the method will give good results when the average network blocking in the network is reasonable (better than 50%).
figures for end to end blockings for the adaptive routing strategy are acceptable approximations when the blocking level is higher than 1%.

The reason for being able to use a performance function which is significantly less complex than for the public networks is:

- The typical paths consist of a relatively large number of links. In order to ensure a reasonable end to end grade of service, the individual link blockings must be better than for high-usage links in the public networks. The absence of alternate routing will contribute to lower link blockings as well. (The performance function $P$ is approximately equal with $G$ when the blocking is low.)

REFERENCES

(1) Bottheim, R., A method for optimization of large mesh-structured circuit switched networks, Dr.ing.dissertation The University of Trondheim, The Norwegian Institute of Technology.