ATM Network Dimensioning for Mixed Symmetrical and Asymmetrical Services with Dynamic Reconfiguration in a Multi-Network Provider Environment

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***Abstract* - This paper presents a procedure for the dimensioning of ATM backbone networks when a combination of symmetric and asymmetric services is to be supported. The dimensioning procedure is done aiming to minimise the operational and maintenance costs of the network. An optimisation model is presented and the proposed solution is based on Lagrangean Relaxation with Sub-Gradient Optimisation. The dimensioning procedure also deals with multi-hour dimensioning and multi-network provider environments. Multi-hour dimensioning is useful when ATM networks have dynamic reconfiguration capabilities. In this case, resources allocated to each service can be reconfigured at the management plane in specific time instants in order to adapt the allocated resources to the expected traffic needs in different time periods.**

1. INTRODUCTION

The need to support traffic patterns with very different profiles and requirements is one of the most important issues in the effective deployment of B-ISDN employing ATM technology. In these networks, different services can be routed from source to destination through different VPCs (Virtual Path Connections) sharing the same physical resources. Using the Virtual Path concept, it is possible on top of an ATM physical network to configure different logical networks [Valadas98]. Assuming deterministic multiplexing between different logical networks, this approach has many advantages: (1) simpler call admission control algorithms, (2) faster call set-up times, (3) easier congestion control, (4) easier procedures for call fairness (5) better hardware performance, among others.

Telecommunication operators started already to update their backbone networks to ATM technology, which is likely the first step towards the future B-ISDN network. These backbone ATM networks are already being deployed, not only because of the "ATM promises" for the future, but also because they have reached enough maturity to become an integrated solution for most of the existing commercial services. In order to accomplish these objectives, ATM networks must support services with a wide spectrum of different characteristics like symmetric vs. asymmetric, conversational vs. retrieval, broadband vs. narrowband, residential vs. business type, etc…

This paper discusses the dimensioning of ATM backbone networks considering three aspects. The first one is to consider a multi-network provider environment. An ATM backbone network operator can either rely on its own links, with the associated operational and maintenance costs, or subcontract other network provider bearer services (PDH or SDH network providers) to connect its ATM nodes. The second aspect is to consider the support of both symmetrical conversational and asymmetrical retrieval services. Typically, existing services are either symmetrical conversational or asymmetrical retrieval. In the first type (e.g., video-telephony), enough resources must be supplied between the nodes where customers are attached (hereafter designated as customer nodes) with the same bandwidth in both directions. The second type of services (e.g., Video-on-Demand, fast Internet access) has a client-server architecture. Each customer establishes a connection to a server to access the service. In this case, resources must be allocated between each customer node and one of the available servers in the network. Typically, these services have significantly more traffic in the downstream direction (from server to client) than in the upstream direction. The third aspect is to consider the mixture of services with different traffic behaviour. It is common sense that existing services do not have the same traffic behaviour during time. For example, business services have higher traffic in periods that are complementary to residential services. This fact can lead to optimisation in network utilisation. This is achieved allocating alternatively the network resources to each of the service types in the periods where they require more bandwidth. In order to achieve optimisation gains, it is necessary to consider that the ATM network has dynamic reconfiguration capabilities. This means that it is possible to reconfigure VPCs in programmable time instants at the management plane of ATM network.

The ATM network dimensioning problem consists in the calculation of sets of VPCs (both their bandwidth and their route through the network) that can support the required traffic. This calculation is a combined capacity design and routing problem where the VPC sets are calculated in order to minimise the network operational costs.

We consider logical networks consisting of end-to-end VPCs. For symmetrical conversational services, a VPC must be calculated (dimensioned and routed) between each customer node pair. For asymmetrical retrieval services, a VPC must be calculated between each customer node and a server node (one of the nodes where servers are located). When a multi-hour approach is considered, these VPCs should be calculated for each time period. We assume statistical multiplexing between VCCs (Virtual Channel Connections) in the same VPC and deterministic multiplexing between different VPCs. As a consequence, we can separate the calculation of the VPC bandwidths from the calculation of the VPC routes.

This paper presents a procedure for the dimensioning of ATM backbone networks. The dimensioning procedure is done aiming to minimise the operational and maintenance costs of the network. An optimisation model is presented and the proposed solution is based on Lagrangean Relaxation with Sub-Gradient Optimisation. A simpler algorithm [Medhi95] was presented recently that also includes dynamic reconfiguration to achieve gains in network operational costs. This paper extends that work by considering also asymmetric retrieval services and multiple interface types on ATM connections.

The remaining of this article is organised as follows. In the next section, we introduce all relevant parameters associated with network topology, transmission facilities and operational and maintenance costs. In section 3, parameters related with the VPCs are explained. Then, section 4 presents the complete optimisation model, i.e., the minimisation function and the constraints of the model. Section 5 describes the dimensioning procedure. Section 6 shows some computational results based on a set of example networks and, finally, section 7 draws some conclusions.

2. NETWORK TOPOLOGY, TRANSMISSION FACILITIES AND COST PARAMETERS

For the dimensioning procedure, the network operator must define a graph *(N,A)* where *N* represent ATM switch locations and *A* represent available transmission facilities between switch locations. Hence, the following notation is introduced:

N Set of nodes of the graph

A Set of arcs *a* of the graph; *a* is defined by an undirected arc *(i,j)* where *i* and $j \in N$; by convention, we rank all nodes with an integer value and the reference to arc *(i,j)* assumes that $i < j$.

In a multi-network provider environment, the network operator may consider the utilisation of third-party bearer services to connect switch locations that do not have transmission facilities between them. In this case, the set of arcs *A* should be augmented between nodes where third-party service providers exist.

ATM switches are available with a wide range of different transmission interfaces. E1 2 Mbps, PDH 34 Mbps, SDH 155 Mbps or SDH 622 Mbps are some examples of possible interface types that can be used between ATM switches. Any of them can be implemented through a dedicated point-to-point physical link (a fibre transmission line for example), through a transport network (e.g., a PDH or a SDH network) owned by the network operator or through a third-party service provider. One of the aims of the dimensioning procedure is to calculate the type and number of transmission interfaces that must be implemented between ATM switches. The corresponding notation is as follows:

T Set of possible interface types *t* to install in each arc $a \in A$

α_t Capacity value of interface type *t*

y_{ij}^t Integer variable that defines the number of interfaces of type *t* that are installed on arc $a = (i,j) \in A$

Y_{ij}^t Maximum number of interfaces of type *t* that can be installed on arc $a = (i,j) \in A$

We define operational and maintenance costs on a link by link basis as follows:

C_{ij}^t Operational and maintenance cost associated with the use of one interface of type *t* in the arc $a = (i,j) \in A$

Following this notation we can define the minimisation function of the dimensioning procedure as a function of y_{ij}^t variables in the following way:

$$\sum_{(i,j)\in A}\sum_{t\in T} C_{ij}^t y_{ij}^t \qquad (1)$$

Similarly, the total capacity on each arc to route traffic is also a function of y_{ij}^t variables:

$$\sum_{t\in T} \alpha_t y_{ij}^t \quad \text{, for each } (i,j) \in A \qquad (2)$$

We can separate operational and maintenance costs in switching costs and transmission costs.

Switching costs are due to operation and maintenance of ATM switches. We define an average value for each interface type (*Switching_cost_t*) on the switches.

Transmission costs (the cost to transmit bits between two ATM switch interfaces) is dependent on the type of transmission facilities available. In the case of physical links, we define an average value per Km, (*Transmission_cost_Km*) for the physical infrastructure operation and maintenance costs. In the case of transmission provision through a transport network, we define an average cost per type of interface (*Transmission_cost_t*). In the case of a third party service provision, this cost is the price to be paid to the service provider. In general, this price is different for each pair of nodes and interface type; so, we define these prices as *Transmission_price_t(i,j)*.

Hence, the operational and maintenance costs are given by (note that each link connects two switch interfaces):

C_{ij}^t = 2 x *Switching_cost_t* + *Transmission_cost_Km* x *Length_of_arc*(*i,j*) or

C_{ij}^t = 2 x *Switching_cost_t* + *Transmission_cost_t* or

C_{ij}^t = 2 x *Switching_cost_t* + *Transmission_price_t(i,j)*

depending on the type of transmission facilities in each arc *(i,j)*.

3. VPC PARAMETERS

The proposed dimensioning procedure is based on the configuration of logical networks consisting of end-to-end VPCs and deterministic multiplexing between different VPCs. In this case, the calculation of the capacity of each VPC (the VPC bandwitdh) is independent of the route it takes through the network. For conversational services, a VPC must be configured between all customer node pairs. For retrieval services, there are customer nodes and server nodes and a VPC must be configured between each customer node and one of the server nodes. The dimensioning procedure will choose for each customer node the server node to connect to that minimises the cost of the network solution.

Each VPC is a commodity that should be routed from source to destination by the dimensioning procedure. In a multi-hour scenario, time is partitioned in different periods and the route of each commodity (VPC) can vary between different periods of time. Hence, the following notation is introduced:

H Set of time periods *h* in the multi-hour model

K_h Set of all commodities k_h to be configured in the network in time period h

Each commodity is identified by k_h representing the commodity for the same origin-destination pair for the different time periods. Each k_h has the following attributes:

$o(k_h)$ Origin node of commodity k_h

$D(k_h)$ Set of possible destination nodes $d(k_h)$ of commodity k_h

$b(k_h)$ Bandwidth of k_h in the direction from origin to destination

$\underline{b}(k_h)$ Bandwidth of k_h in the direction from destination to origin

In this notation, $o(k_h)$ is equal for all time periods h. Note that since we are dealing with both symmetric and asymmetric services, we have to consider different bandwidths for each direction of each commodity. However, commodities belonging to symmetrical services have $b(k_h) = \underline{b}(k_h)$. Similarly, since both conversational and retrieval services are considered, we define a set of possible destination nodes $D(k_h)$ for each commodity k_h although for commodities belonging to conversational services, this set has only one element. For retrieval services, $D(k_h)$ is the set of all server nodes. Moreover, this set is equal to all commodities belonging to the same retrieval service.

We model the routing solution for each commodity with the following variables:

x_{ij}^{kh} Route binary variable; when is one, it defines that the commodity k_h passes through arc $(i,j) \in A$ in the direction from node i to node j

$\underline{x}_{ij}^{kh}$ Route binary variable; when is one, it defines that the commodity k_h passes through arc $(i,j) \in A$ in the direction from node j to node i

Following this notation, the solution for the dimensioning procedure must agree with the following restriction:

$$\{ x_{ij}^{kh}, \underline{x}_{ij}^{kh} : x_{ij}^{kh} = 1 \wedge \underline{x}_{ij}^{kh} = 1 \} \text{ is a path from } o(k_h) \text{ to } d(k_h) \in D(k_h) \quad , k_h \in K_h,\ h \in H \quad (3)$$

We can also define the total bandwidth occupied by all commodities in each arc as a function of the route variables:

$$\sum_{k_h \in K_h} (b(k) \cdot x_{ij}^{kh} + \underline{b}(k) \cdot \underline{x}_{ij}^{kh}) \quad \text{, for each } (i,j) \in A \text{ and each } h \in H \quad (4a)$$

in the direction from node i to node j and:

$$\sum_{k_h \in K_h} (b(k) \cdot \underline{x}_{ij}^{kh} + \underline{b}(k) \cdot x_{ij}^{kh}) \quad \text{, for each } (i,j) \in A \text{ and each } h \in H \quad (4b)$$

in the direction from node j to node i.

The bandwidth of each VPC depends on the required call level and cell level quality of service. At the call level, the usual requirement is to keep the blocking probability of VCCs bellow a pre-defined level. In our case, since VPCs are end-to-end and are used to multiplex VCCs belonging to a single service, the Erlang B formula can be used, provided that the offered traffic is Poisson. At the cell level, the bandwidth per VCC can be calculated assuming peak cell rate allocation or exploiting the statistical multiplexing gains taking place at the entry buffer of each VPC. In the last case, there are many possibilities, depending on the statistical model of the source and on the cell level quality of service parameter under consideration (e.g., cell loss ratio, cell average delay,

...). One of the most popular approaches is the effective bandwidth approximation [Kelly91].

4. OPTIMISATION MODEL

We can now define a complete mathematical model for the proposed optimisation problem. For clarity, the complete notation of all parameters is here repeated:

N Set of nodes of the graph

A Set of arcs a of the graph; a is defined by an undirected arc (i,j) where i and $j \in N$; by convention, we rank all nodes with an integer value and the reference to arc (i,j) assumes that $i < j$.

T Set of possible interface types t to install in each arc $a \in$ A

α_t Capacity value of interface type t

Y_{ij}^{t} Maximum number of interfaces of type t that can be installed on arc $a = (i,j) \in A$

C_{ij}^{t} Operational and maintenance cost associated with the use of one interface of type t in the arc $a = (i,j) \in A$

H Set of time periods h in the multi-hour model

K_h Set of all commodities k_h to be configured in the network in time period h

- $o(k_h)$ Origin node of commodity k_h
- $D(k_h)$ Set of possible destination nodes $d(k_h)$ of commodity k_h
- $b(k_h)$ Bandwidth of k_h in the direction from origin to destination
- $\underline{b}(k_h)$ Bandwidth of k_h in the direction from destination to origin

y_{ij}^{t} Integer variable that defines the number of interfaces of type t that are installed on arc $a = (i,j) \in A$

x_{ij}^{kh} Route binary variable; when is one, it defines that the commodity k_h passes through arc $(i,j) \in A$ in the direction from node i to node j

$\underline{x}_{ij}^{kh}$ Route binary variable; when is one, it defines that the commodity k_h passes through arc $(i,j) \in A$ in the direction from node j to node i

Following this notation we model the network dimensioning problem, which we refer to as the OP (Original Problem) as follows:

OP: $$\text{Minimise} \sum_{(i,j)\in A} \sum_{t\in T} C_{ij}^{t} y_{ij}^{t} \qquad (5a)$$

Subject to:

$$\{ x_{ij}^{kh}, \underline{x}_{ij}^{kh} : x_{ij}^{kh} = 1 \wedge \underline{x}_{ij}^{kh} = 1 \} \text{ is a path from } o(k_h) \text{ to } d(k_h) \in D(k_h) \quad , k_h \in \mathrm{K}_h, h \in \mathrm{H} \qquad (5b)$$

$$\sum_{k_h \in K_h} (b(k) \cdot x_{ij}^{kh} + \underline{b}(k) \cdot \underline{x}_{ij}^{kh}) < \sum_{t\in T} \alpha_t y_{ij}^{t} \quad , (i,j) \in \mathrm{A}, h \in \mathrm{H} \qquad (5c)$$

$$\sum_{k_h \in K_h} (b(k) \cdot \underline{x}_{ij}^{kh} + \underline{b}(k) \cdot x_{ij}^{kh}) < \sum_{t \in T} \alpha_t y_{ij}^t \qquad , (i,j) \in A , h \in H \qquad (5d)$$

$$y_{ij}^t < Y_{ij}^t \qquad , (i,j) \in A , t \in T \qquad (5e)$$

$$x_{ij}^{kh} = 1 / 0; \quad \underline{x}_{ij}^{kh} = 1 / 0; \quad y_{ij}^t > 0 \text{ and integer} \qquad (5f)$$

The objective function (equation 5a) was explained in previous section and represents the cost of the network solution as a function the number of interfaces of each type installed in each network arc (equation 1). Constraint (5b) was also previously explained (equation 3) and forces the solution to choose a path from origin to destination for all commodities (VPCs) to be supported by the network. Constraints (5c) and (5d) impose that the total bandwidth installed in each arc (equation 2) is enough to support the total bandwidth occupied by the commodities that cross the arc defined in (4a) and (4b) in all time periods. Finally, constraint (5e) imposes that the number of interfaces of each type in each arc is not greater then a defined maximum value.

5. DIMENSIONING PROCEDURE

Departing from OP, we can reach another optimisation problem applying Lagrangean relaxation to constraints (5c) and (5d). The new problem, which we will refer to as LLBP (Lagrangean Lower Bound Problem) has the following formulation:

LLBP: $G1(\Lambda) + G2(\Lambda)$ (6)

Where

G1(Λ): Minimise $$\sum_{(i,j) \in A} \sum_{t \in T} \left[C_{ij}^t - \sum_{h \in H} \left(\lambda_{ij}^h + \underline{\lambda}_{ij}^h \right) \right] y_{ij}^t \qquad (7a)$$

Subject to:

$$y_{ij}^t < Y_{ij}^t \qquad , (i,j) \in A , t \in T \qquad (7b)$$

$$y_{ij}^t > 0 \text{ and integer} \qquad (7c)$$

G2(Λ): Minimise
$$\sum_{h \in H} \sum_{k_h \in K_h} \sum_{(i,j) \in A} \left(\left(\lambda_{ij}^h \cdot b(k_h) + \underline{\lambda}_{ij}^h \cdot \underline{b}(k_h) \right) \cdot x_{ij}^{kh} + \left(\lambda_{ij}^h \cdot \underline{b}(k_h) + \underline{\lambda}_{ij}^h \cdot b(k_h) \right) \cdot \underline{x}_{ij}^{kh} \right) \qquad (8a)$$

Subject to:

$\{ x_{ij}^{kh}, \underline{x}_{ij}^{kh} : x_{ij}^{kh} = 1 \wedge \underline{x}_{ij}^{kh} = 1 \}$ is a path from $o(k_h)$ to $d(k_h) \in D(k_h)$, $k_h \in K_h$, $h \in H$ (8b)

$$x_{ij}^{kh} = 1 / 0; \quad \underline{x}_{ij}^{kh} = 1 / 0; \qquad (8c)$$

To derive the LLBP, a set of Lagrangean multipliers $\Lambda = \{ \lambda_{ij}^h$ and $\underline{\lambda}_{ij}^h, (i,j) \in A, h \in H \}$ was introduced, one for each of the relaxed constraints. For any arbitrary set Λ of non-negative Lagrangean multipliers, the solution of LLBP is a lower bound of OP [Beasley93]. The solution of LLBP is the sum of the solutions of sub-problems G1(Λ) and G2(Λ). The solution for G1(Λ) is straightforward:

$$y(\Lambda)=\left\{ y_{ij}^{t} : y_{ij}^{t}=\begin{cases} 0 & ,C_{ij}^{t} > \sum_{h\in H}\left(\lambda_{ij}^{h}+\underline{\lambda}_{ij}^{h}\right) \\ Y_{ij}^{t} & ,C_{ij}^{t} < \sum_{h\in H}\left(\lambda_{ij}^{h}+\underline{\lambda}_{ij}^{h}\right) \end{cases} ,(i,j)\in A,\ t\in T \right\} \tag{9}$$

Sub-problem G2(Λ) can be solved through the implementation of a shortest past algorithm using the coefficients of x_{ij}^{kh} and $\underline{x}_{ij}^{kh}$ variables in equation 8a as distance values for the arcs of the network. So, for each commodity k_h, we consider the original graph defined by *(N,A)* with arc distances given by:

$$d_{ij}^{kh}=\left(\lambda_{ij}^{h}\cdot b(k_h)+\underline{\lambda}_{ij}^{h}\cdot \underline{b}(k_h)\right) \tag{10a}$$

in the direction from node *i* to node *j* and:

$$\underline{d}_{ij}^{kh}=\left(\lambda_{ij}^{h}\cdot \underline{b}(k_h)+\underline{\lambda}_{ij}^{h}\cdot b(k_h)\right) \tag{10b}$$

in the opposite direction. The result of the shortest path algorithm in this graph defines whose values of x_{ij}^{kh} and $\underline{x}_{ij}^{kh}$ are equal to 1. Let us represent the shortest path algorithm by SPA(Set_of_nodes, Set_of_arcs, Distance_vector_forward_direction, Distance_vector_backward_direction, Origin_node, Destination_node). Then, the solution for sub-problem G2 can be represented by:

$$x(\Lambda)=\left\{ x_{ij}^{kh},\underline{x}_{ij}^{kh} : SPA\left(N,A,d_{ij}^{kh},\underline{d}_{ij}^{kh},o(k_h),d(k_h)\right) ,(i,j)\in A,\ k_h\in K_h,\ h\in H \right\} \tag{11}$$

In our implementation, the calculation of *x(Λ)* in equation 11 was implemented using the Dijkstra shortest path algorithm. For commodities belonging to retrieval services, we have to run equation 11 for all $d(k_h) \in D(k_h)$ and choose the one that has the shortest path.

Equations 9 and 11 are the solution for the LLBP for a particular set Λ of Lagrangean multipliers and equation 6 gives the value of the solution of LLBP. The next step is to derive a feasible solution for the OP. This is done by setting x_{ij}^{kh} and $\underline{x}_{ij}^{kh}$ variables in equations 5c and 5d equal to *x(Λ)* and then calculating the y_{ij}^{t} variables values. For this solution, the total cost of the network is given by equation 5a.

So, given a set Λ of non-negative Lagrangean multipliers, we calculate a theoretical lower bound (through the solution of LLBP) and a feasible solution for the OP. The difference on these values gives a measure of the quality of the calculated solution.

To compute different sets of Lagrangean multipliers, we use sub-gradient optimisation technique [Held74]. This technique is an iterative process that, for a given set of Lagrangean multipliers Λ_n, calculate another set of multipliers Λ_{n+1} that try to maximise the objective function value of LLBP. This operation is done in the following way. First, a sub-gradient value is calculated for each relaxed constraint in the following way:

$$G_{ij}^{h}=\sum_{k_h=K_h}\left(b(k_h)\cdot x_{ij}^{kh}+\underline{b}(k_h)\cdot \underline{x}_{ij}^{kh}\right)-\sum_{t\in T}\alpha_t y_{ij}^{t} \tag{12a}$$

$$\underline{G}_{ij}^{h}=\sum_{k_h=K_h}\left(\underline{b}(k_h)\cdot x_{ij}^{kh}+b(k_h)\cdot \underline{x}_{ij}^{kh}\right)-\sum_{t\in T}\alpha_t y_{ij}^{t} \tag{12b}$$

Then, a scalar step size T is defined as:

$$T = \pi \cdot \frac{Z_{UB} - Z_{LB}}{\sum_{h \in H} \sum_{(i,j) \in A} \left(\left(G_{ij}^{h} \right)^2 + \left(\underline{G}_{ij}^{h} \right)^2 \right)} \tag{13}$$

where Z_{LB} is the current lower bound (the solution value of LLBP) and Z_{UB} is an upper bound (the best solution found for OP). π is a relaxation parameter such that $0 < \pi < 2$. Finally, a new set of Lagrangean multipliers are calculated from previous ones in the following way:

$$\lambda_{ij}^{h} = \max\left(0, \lambda_{ij}^{h} + T \cdot G_{ij}^{h}\right) \tag{14a}$$

$$\underline{\lambda}_{ij}^{h} = \max\left(0, \lambda_{ij}^{h} + T \cdot \underline{G}_{ij}^{h}\right) \tag{14b}$$

In our implementation, we set the total number of iterations to 1000. Initially, we set π to 2 and we halved it whenever the solution for LLBP does not improve in 40 iterations. In conclusion, the complete network dimensioning procedure is as follows:

(i) Compute the graph *(N,A)*, the transmission facilities parameters and all cost parameters.

(ii) Compute $b(k_h)$ and $b(k_h)$ values for all commodities to be supported by the network.

(iii) Consider the initial set Λ_0 with all Lagrangean multipliers set to 0. Set $n = 0$ and $\pi = 2$.

(iv) Calculate $x(\Lambda_n)$ and $y(\Lambda_n)$ with equations 11 and 9. Calculate Z_{LB} with equation 6. If Z_{LB} is the best solution for LLBP found so far, save it as the TLB (Theoretical Lower Bound). If Z_{LB} did not improve in the last 40 iterations, set $\pi = \pi / 2$ in equation 13.

(v) Calculate a feasible solution setting the x_{ij}^{kh} and $\underline{x}_{ij}^{kh}$ variables equal to $x(\Lambda_n)$ and using equations 5c and 5d to calculate suitable y_{ij}^{t} variables. With this solution, calculate the cost value for the resulting network with equation 5a. If this value is the best found so far, set Z_{UB} with it and save the current solution as the final solution.

(vi) Set $n = n+1$. If $n=1000$, stop. Otherwise, from Λ_{n-1}, calculate Λ_n using equations 14a and 14b and go to (iv).

At the end on this procedure, a final solution is calculated in step (v) and a Theoretical Lower Bound for the OP is calculated in step (iv).

6. COMPUTATIONAL RESULTS

We have implemented the dimensioning procedure in C++ for a PC platform using Microsoft Operating System. We have run the dimensioning procedure for some example networks. These networks were produced by node elimination of the 50 node network presented in Figure 1. Nodes were eliminated randomly while ensuring that the resulting networks remain connected.

The dimensioning of each network was done assuming that fibre physical links were available between the switching nodes with an operation and maintenance cost

(*Transmission_cost_Km*) of 10. Similarly, we have assumed that interface types of PDH 34Mbps, SDH 155Mbps and SDH 622Mbps were available between the switching nodes with switching cost per interface (*Switching_cost_t*) of 1000, 3000 and 10000 respectively.

For the dimensioning of each network, we have considered three services (one symmetrical conversational service and two asymmetrical retrieval services) and two time periods (e.g., between 9:00 and 18:00 and between 18:00 and 9:00). For each network, we have randomly assigned customer and server nodes. In all cases, we assumed that 80% of the nodes were customer nodes for the conversational service. For retrieval services, we have assumed 80% of the nodes as either customer or server nodes. For networks above 25 nodes, we have assumed 3 server nodes for each retrieval service while below 25 nodes, only 2 server nodes.

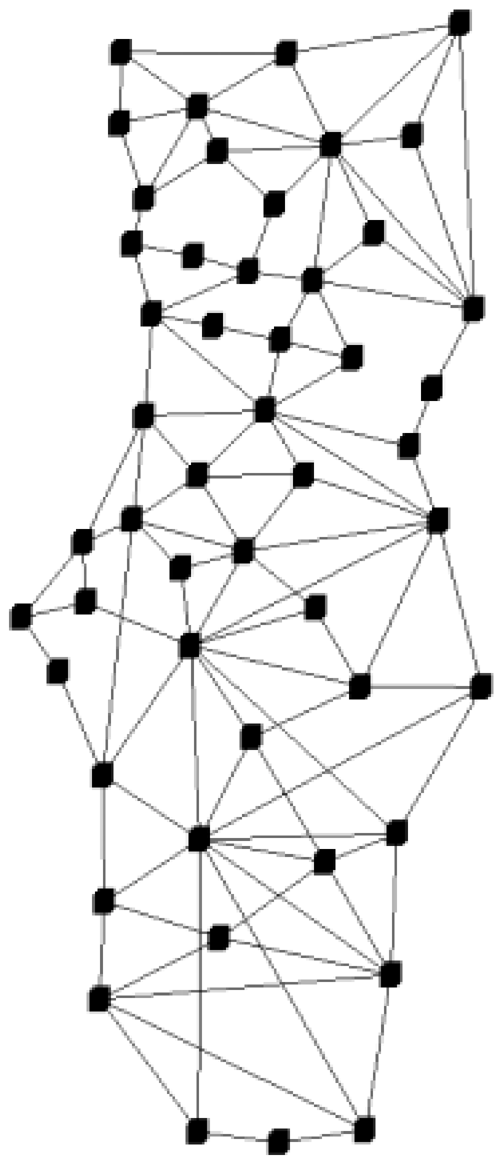

Figure 1: An example network with 50 nodes

For the calculation of each VPC bandwidth, we have assumed different bandwidth values for the VCCs of each service (Table 1).

Service	Origin-destination bandwitdh per VCC	Destination-origem bandwitdh per VCC	Maximum number of VCCs
Conversational	64 Kbps	64 Kbps	800
Retrieval 1	64 Kbps	2 Mbps	50
Retrieval 2	64 Kbps	4 Mbps	20

Table 1: Parameters related with the bandwidth dimensioning of VPCs

For each network, we have run 10 different network dimensioning calculations. In each run we have randomly varied: (i) the set of customer and server nodes and (ii) the number of VCCs supported by each VPC with an uniform distribution between one and the maximum value given by Table 1.

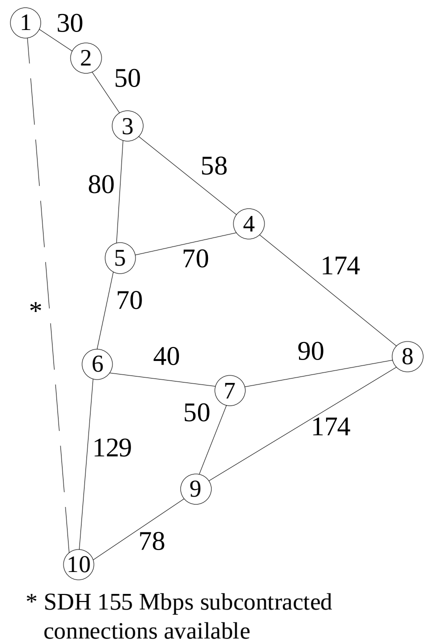

Figure 2: An example network with 10 nodes

Service	Server nodes	Customer nodes
Conversational	-	1,3,5,6,7,8,9,10
Retrieval 1	3,4	1,2,5,7,8,9
Retrieval 2	1,7	3,4,5,6,8,9

Table 2: Customer and server node assignment for the example shown in Figure 2

For illustration purposes, we present in Figure 2 the 10 node network considered for dimensioning, together with the arc distances. We have considered the existence of an SDH 155 Mbps bearer service provider between nodes 1 and 10 with a cost per connection, *Transmission_price_t(1,10)* = 6000. Figure 3 presents the dimensioning results for one of the runs (Table 2 presents the customer and server node assignment for this run). It shows the dimensioning results for four different cases: (i) a network with no dynamic reconfigurations (no subcontract connections) where the VPCs are configured at the initial set-up stage and are dimensioned taking into account the highest bandwidth value of all time periods (Figure 3a); (ii) a network with no dynamic reconfiguration capabilities and considering the possibility of subcontracting 155 Mbps SDH connections (Figure 3b); (iii) a network with dynamic reconfiguration capabilities (no subcontract connections) where VPCs are configured at the transition of time periods (Figure 3c) and are dimensioned for the bandwidth value of each time period and (iv) a network with dynamic reconfiguration capabilities and considering the possibility of subcontracting 155 Mbps SDH connections (Figure 3d).

The operational and maintenance costs for these network are a) 153850, b)146950, c) 135540 and d) 135540. These values represents a cost saving of 4.7% when the possibility of sub-contracting bearer services is used in the uni-hour case. They represents also a cost saving of 12% when we consider a multi-hour solution compared with the uni-hour solution. Note that the possibility of sub-contract third party bearer services does not necessarily result in a less expensive network. In the presented example, the availability of a 155 Mbps bearer service provider between nodes 1 and 10 did not result in a lower cost network in the multi-hour approach.

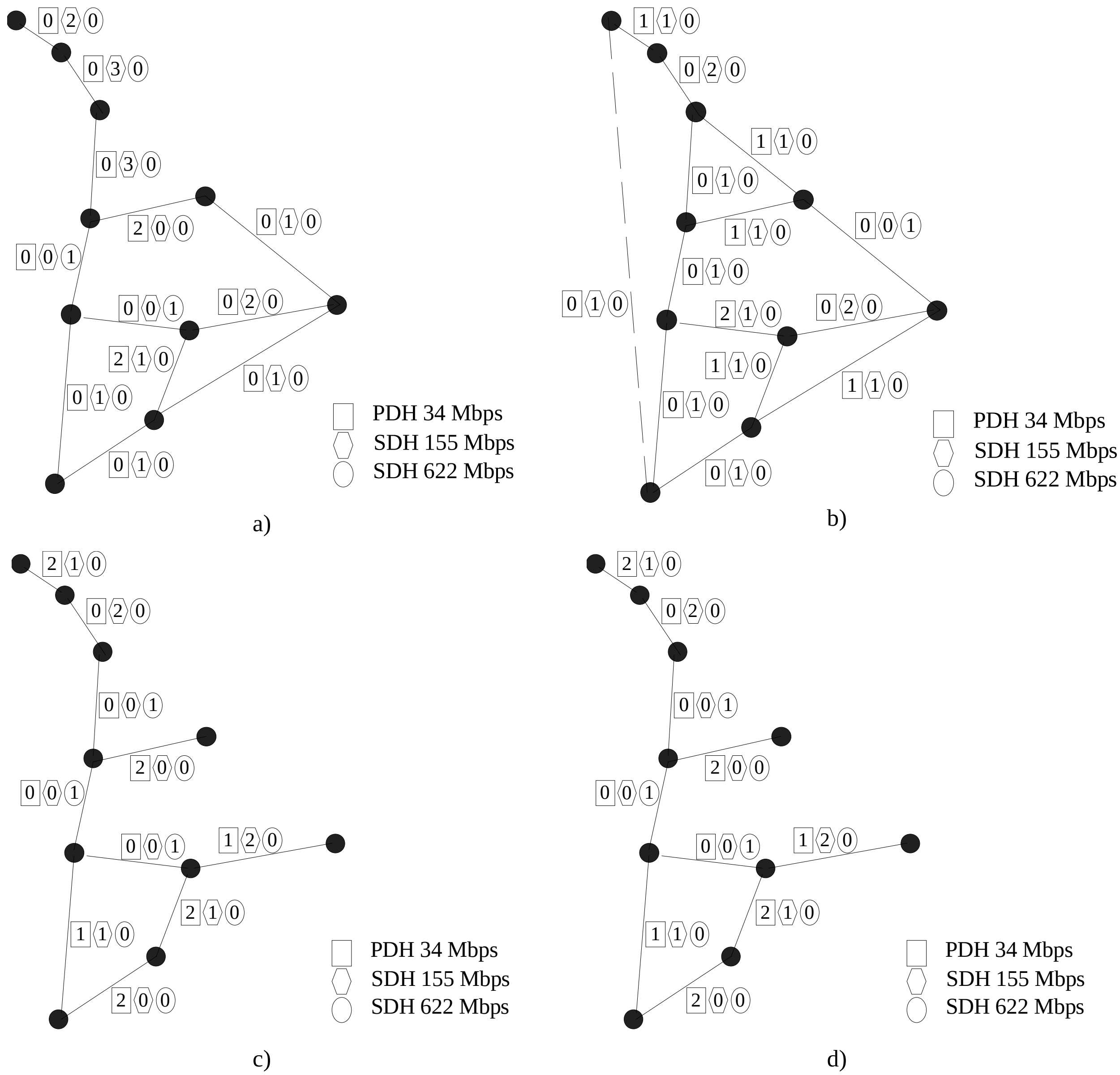

Figure 3: Results of network dimensioning for the 10 node network

We have run all calculations for all networks in a standard PC platform (a 200MHz Pentium II with 128MB of RAM) with Windows 98 operating system. Figure 4 shows for each network, the average of the computing times of the computed 10 different runs.

The computational results show that, in the uni-hour case, the proposed dimensioning procedure can treat small networks (up to 30 nodes) in less then one minute and medium sized networks (up to 50 nodes) in less then four minutes. In the multi-hour model, the computing time is almost twice of the uni-hour model. We have also run the dimensioning procedure for multi-hour models with more then two time periods. These runs have shown that the complexity of the dimensioning procedure is linear with the number of time periods.

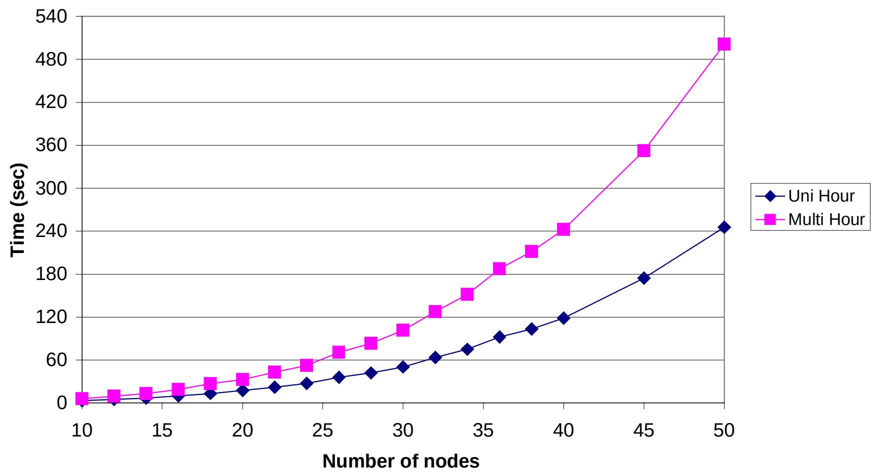

Figure 4: Computing times for the different networks

The proposed dimensioning procedure is an heuristic that, through an iterative process, calculates several feasible solutions for the dimensioning problem and selects the best one among all. Besides computing a feasible solution, it calculates also a Theoretical Lower Bound (TLB) for the optimum solution cost. In mathematical terms, this means that the optimal solution for the problem has a value that is between the best solution found and the TLB. Figures 5 and 6 present the best solution cost values and the TLB cost values for all calculated networks (each plot is the average of the 10 run solutions and TLBs). The distance between the two curves of these figures shows how far the optimal solution can be from the best solutions calculated by the dimensioning procedure.

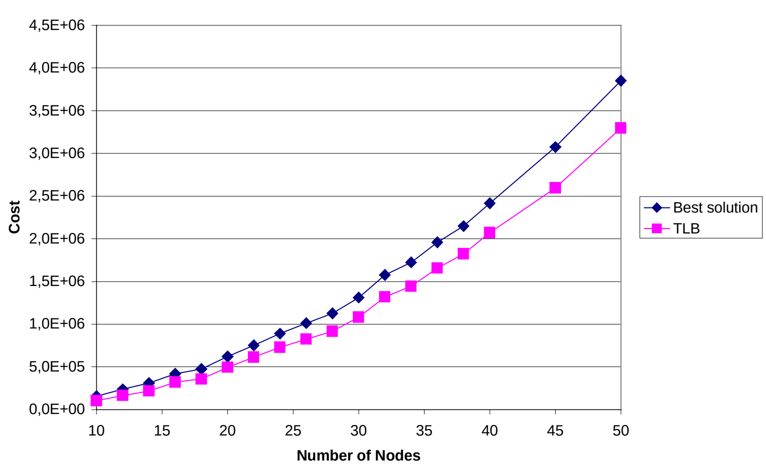

Figure 5: Average values of best solution costs and TLB costs in the uni-hour case

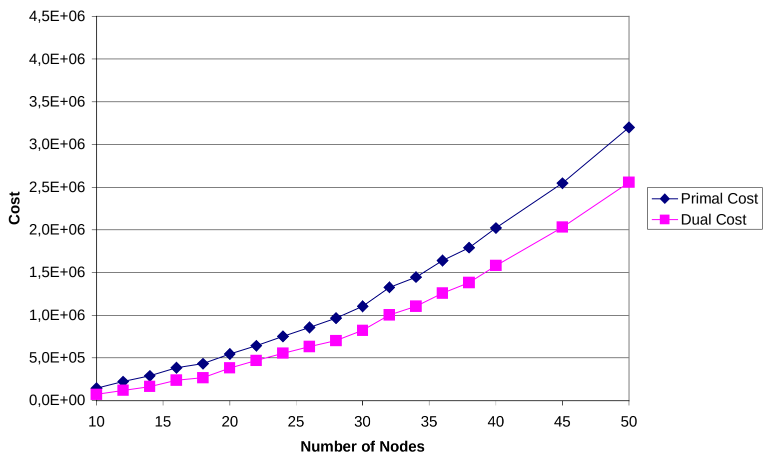

Figure 6: Average values of best solution costs and TLB costs in the multi-hour case

Let us represent the cost of the best solution as *S* and the Theoretical Lower Bound as *B*. Then, a measure of the quality of the result usually adopted is the duality gap which is given by (*S* - *B*) / *B*. Figures 7 and 8 show the best and the worst duality gap of the 10 runs computed for each example network.

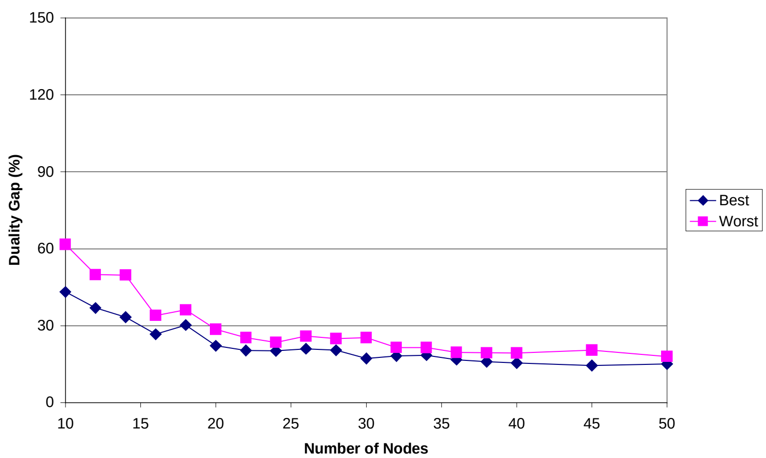

Figure 7: Best and worst duality gap values for each example network in the uni-hour case

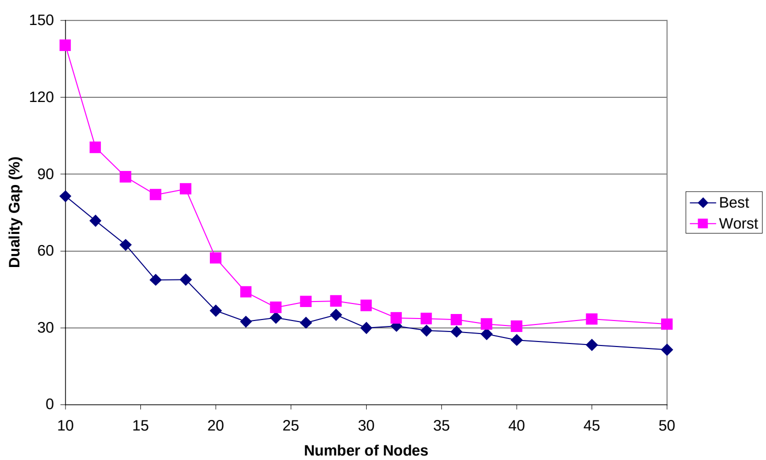

Figure 8: Best and worst duality gap values for each example network in the multi-hour case

The main conclusions drawn from results presented in Figures 5 to 8 are the following. The comparison between Figures 5 and 6 confirm that using a multi-hour model lead to network solutions with lower operational and maintenance costs. Duality gaps for the multi-hour case are worst than for uni-hour case (Figures 7 and 8) which means that the degree of confidence in the uni-hour solutions is higher. In both cases, the duality gaps improve for networks with higher number of nodes. This behaviour is very important since for small networks, there are standard linear programming algorithms that calculate the optimal solution for the dimensioning problem. However, these standard algorithms are computationally heavy and can not calculate solutions for large networks in reasonable computing times.

Remember that an high duality gap value does not mean that the best solution found by the procedure is good or bad. We do not know where the optimal solution cost value is in the interval between the TLB value and the solution cost value. For the small example networks, we have also used a standard linear programming algorithm to compute the optimal solutions. In most of the runs done with the proposed procedure, the best solutions were near the optimal solution. This can possibly mean that the procedure solutions are good and the TLB values are not. However, a final conclusion on this topic requires further investigation on the computation of “good” theoretical lower bounds.

7. CONCLUSIONS

This paper presented a procedure for the dimensioning of ATM backbone networks when a combination of symmetric and asymmetric services is to be supported.. The dimensioning procedure was done aiming to minimise the operational and maintenance costs of the network. An optimisation model was presented that can cope also with multi-hour dimensioning and multi-network provider environments.

Computational results showed that reasonable large network (up to 50 nodes) can be treated in computational times around a few minutes. The quality of the solutions was assessed through duality gap criteria and we have shown that the quality confidence of the results is higher for higher network sizes.

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