

PAPER

Computational Techniques for a Generic and Flexible Telecommunication Network Evaluation Tool

Satoru OHTA[†], *Member*

SUMMARY Telecommunication technologies are making relentless progress. In this circumstance, network cost must be evaluated to assess the effectiveness of emerging technologies. To do such an evaluation efficiently, it is necessary to develop a software tool that can calculate the network cost independent of the employed technologies. This paper describes computational techniques used in developing such a software tool. First, the functional requirements are identified to establish a flexible tool that is applicable to a wide range of technologies. One of the required functions is the function that computes the resource amount and the network cost from the given conditions such as traffic demands, a cable duct network, multiplex hierarchy and the specifications of network elements employed. As this computing function, the paper proposes an appropriate path classification scheme that enables us to evaluate the resource amount correctly when a service protection technique is applied to the target network. Namely, the proposed scheme yields evaluations that isolate the primary path route from the backup path route. This isolation is not always provided without classification. In addition, a classification of network elements is also derived for valid estimation of the necessary interface board number, which is a basis of estimating the required network element amount. This classification allows us to identify the exact points of path cross-connection and termination, which affects the number of interface boards. This paper presents the computing procedures that realize path grouping and an estimation of network elements using these classification schemes. Finally, the paper describes a prototype of the tool to confirm the feasibility and effectiveness of the proposed schemes.

key words: *telecommunication network, multiplex, cross-connect, routing, protection switching.*

1. Introduction

In the recent telecommunications world, technologies have been progressing rapidly in various aspects including network elements[1],[2], service protection methods[3] and multiplexing technologies such as SDH (Synchronous Digital Hierarchy)[4], ATM (Asynchronous Transfer Mode)[5], and the optical path concept[6] based on WDM (Wavelength Division Multiplex). To introduce these technologies into real-world telecommunications, the network planner must confirm the economical benefits offered by the technologies. Therefore, the cost of a telecommunication network with new technologies must be evaluated and compared with the cost of conventional technologies.

The cost of a telecommunication network is computed from the amount of physical resources such as network elements or optical fibers. This resource amount must be large enough to satisfy the estimated traffic demand. The resource amount can be computed manually or with using spreadsheet programs if the network size is not too large. However, manual or spreadsheet calculations become difficult for large and complex networks and often contain data errors caused by human faults. By contrast, a computer program is an alternative way of evaluating network cost. However, such a program often tends to be specialized for a particular technology. This means that a program associated with a technology may not be reusable for a network with another technology, for example, a network element with a different specification or a different protection method. Thus, such programs must be rewritten whenever a new technology emerges. This rewriting requires a considerable amount of labor.

This paper describes a generic telecommunication network evaluation tool that solves the problems of these conventional cost evaluation methods. The tool evaluates the cost of the "transport network[7]" and can flexibly support a wide range of technologies by simply editing the architecture or network element data without rewriting any other part of the program. The paper particularly focuses on the computational techniques employed in the tool.

To develop a generic cost evaluation tool, two problems must be addressed. One is the evaluation of spare capacity needed for the service protection mechanism, and the other is the evaluation of interface boards attached to network elements. For the former, the resource amount must be computed under an appropriate path routing scheme. That is, the primary route of a path should be physically disjoint (isolated) from its secondary route or a valid cost evaluation can not be realized. To assure such routing, this paper categorizes paths into two classes, each of which is associated with a different routing scheme. To solve the second problem, the important point is to identify which network element terminates or cross-connects paths of a particular multiplex layer. For this identification, it is shown that the network elements should be categorized into three classes. On the basis of these classification schemes, this paper presents computing procedures that yield the

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[†]The author is with the NTT Optical Network Systems Laboratories, Yokosuka-shi, 239-0847 Japan.

amounts of the physical carrier (i.e. optical fiber) and the network elements that determine network cost. The feasibility of the required functions and the proposed techniques was confirmed by building a prototype of the tool.

This paper is constructed as follows. Section 2 overviews the generic network structure to be evaluated and the functional requirements for the tool. Section 3 introduces the classification concept of paths and network elements. The detailed computational procedures are presented in Sect. 4. Section 5 presents the experimental prototype of the tool. Finally, the effectiveness of the tool is demonstrated through evaluation examples in Sect. 6.

2. Preliminaries

2.1 Network Structure and Definitions

This section defines the key words in a transport network to prepare for the description of the evaluation tool. The multiplexing technology brings the layer concept [7] into transport networks. Namely, each "layer" corresponds to a multiplex level, and a lower layer means a high-speed multiplex level. In a layer, information is exchanged between two points through the resource termed the "path" which provides the bandwidth specified for the layer between the points. The path ends are referred to as "termination points" in this paper. The connectivity of a path is provided by a set of concatenated paths in the lower layer. That is, a higher layer path is a "client" that is served by "server" paths of the next lower layer. A path is said to be "cross-connected" at the point between the two adjacent lower layer paths. The point is called a cross-connect point in this paper. In the lowest layer, the connectivity is provided by a physical carrier, such as an optical fiber. In this paper, a layer is indexed as $0, \dots, h$ from the lowest layer to the highest layer.

In such a multi-layer network, the structure of layers is similar. This fact suggests that the resource amounts can be computed by repeatedly applying the same computational procedure to each layer. Moreover, the layer structure is also similar regardless of the technologies employed in the network. The number of the multiplex layers depends on the technologies, and the bandwidth provided by a path in a layer also depends on the technologies. However, the structure of each layer does not change with the technology adopted and is constructed by a set of paths, cross-connections, and termination points for any layer in any transport network as seen in SDH paths, ATM virtual paths [8] (VPs) and optical paths [6]. By taking advantage of this layer similarity, it becomes possible to make a technology-independent cost evaluation tool because similar computation procedures can be applied to each layer repeatedly regardless of the technology used.

2.2 Cost Evaluation-Overview

The cost of a transport network is evaluated by the amounts and unit prices of physical resources such as optical fibers, multiplexers, and cross-connect systems. The amounts of these physical resources must be determined so as to satisfy a given demand. A demand is defined as a set of paths that must be placed between specified source-destination pairs. Here, the specifications of the multiplex hierarchy, fiber system, and network elements are assumed to be given. It is also assumed that the locations of offices (nodes) and cable ducts are given. This paper calls the network constructed with offices and cable ducts the "duct network."

To evaluate the physical network resource amount from the given conditions, several problems must be solved. First, it is necessary to determine the source-destination pairs of the lower layer server paths into which higher layer client paths are multiplexed. It is also required to decide the relation between lower layer and higher layer paths. Then, the path bandwidths of each layer must be computed. This procedure is often called "path grouping" [9] and is repeated from the highest layer to the lowest layer. Meanwhile, the routes of paths of each layer must be also assigned in the given duct network. After grouping and routing of paths are determined for every layer, the amounts of fibers and network elements are computed. The network cost can be calculated from these resource amounts and the unit prices. Figure 1 explores the relation between these computations and the given conditions.

2.3 Functional Requirements

The generic cost evaluation tool must have the following functions to support a variety of technologies and networks.

- (1) Editing function
- (2) Computation function

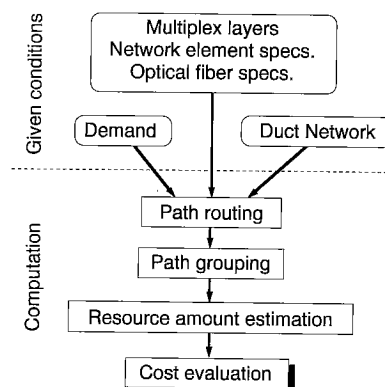


Fig. 1 How the given conditions are used in the network cost evaluation.

(3) Report and display function

The editing function is necessary to input and modify the given conditions. The computation function determines the resource amount and the network cost. This function is detailed in later sections. The report and display function shows the total network cost or the specified resource cost as well as the routing or grouping state of paths.

Among these functions, the editing function must handle the following categories of data to provide flexibility against different technologies.

(a) Multiplex hierarchy structure

The function must allow users to input and change the structure of the multiplex hierarchy. The editable attributes of the structure include the bit rate of each layer and the number of multiplex layers.

(b) Network elements and fiber systems

It is necessary to define the network elements and the fiber systems employed in the network. Also, their attributes must be edited. The attributes of a network element include the interface rates, capacity, and unit price. The attributes of fiber systems are the bit rate, unit price, and regenerator interval.

(c) Duct network

Users need to be able to define the locations of offices and cable ducts between offices to match their network. The editable attribute of a duct is its length.

(d) Intra-office configuration

It is necessary for users to define the set of network elements for each office. This is because the required types of network elements often differ with the office.

(e) Demand

The function allows users to input and change the demand. The demand information includes the multiplex layer of demanded paths, source-destination pairs, and number of paths.

Among these categories, the hierarchical structure and the network elements are particularly important in achieving the flexibility needed to support technology changes. In addition, the computation function must be able to handle any number of multiplex layers and any network element specifications. The following sections describe how this is achieved.

3. Resource Classes

Appropriate resource classification schemes are indispensable in implementing a computation function that can flexibly deal with a wide range of technologies. This section describes the necessity of such classifications and proposes resource classification schemes. These schemes include path classification, necessary to evaluate service protection methods, and network element classification, which is necessary to estimate the number of network elements.

3.1 Service Protection and Path Classes

Comparison of alternative service protection methods is one of the most important applications of the cost evaluation tools [10], [11]. This is because the types of the protection methods vary in the sharing scheme of back-up resources as well as the protected layers, and thus it is critical to decide which method is best.

For the comparison of protection methods, the resource amount for the back-up bandwidth must be correctly computed. Since this bandwidth depends on the path routes, the tool needs to compute the primary and back-up routes of a path appropriately.

Consider the case of a two layer network whose higher layer paths are protected in a one-to-one manner. In this network, the back-up route of each higher-layer path must be set disjoint from its primary route in a duct network to ensure sufficient reliability against failure like a cable duct penetration. Assume that the primary and back-up routes of each higher layer path are determined to satisfy this requirement. Then, suppose that the lower layer paths are determined with an appropriate method that groups higher layer paths. In this case, setting the route of a lower layer path may impact the routes of higher layer paths served by it. For example, routing the lower layer may break the disjointness of primary and back-up routes in the higher layer. An example of such a case is shown in Fig. 2. Therefore, any evaluation based on this routing scheme may be meaningless from the service protection viewpoint, and the evaluation result becomes invalid.

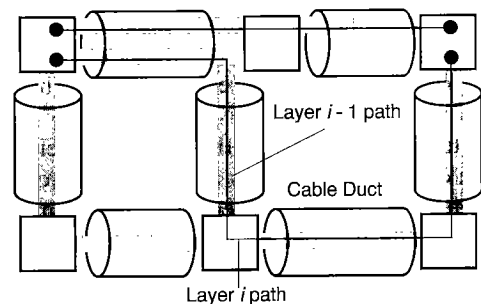


Fig. 2 Primary and back-up routes that are disjoint in the higher layer but not disjoint in the physical layer.

The above observation implies that the lower layer path should be routed to assure disjoint primary and back-up routes in the higher layer. To achieve this goal with fast computation, the tool categorizes paths into the following classes and applies a different routing procedure to each class.

(1) Service path

The service path class is a category of paths that offer the connectivity needed to serve traffic demands. Thus, paths of this class are given as a demand and does not play a server path role.

(2) Multiplex path

The multiplex path class is a category of paths that are required to serve higher layer client paths. Paths of this class are not given as demands, but are generated only by the grouping procedure.

With this scheme, the protection mechanism is applied only to the service paths. Path routing then proceeds from a higher layer to a lower layer, starting with the service paths. That is, the primary and back-up routes are first determined for service paths in the duct network using, for example, the disjoint path algorithm of [12], [13]. Let i ($1 \leq i \leq h$) denote the index attached to a layer. Each multiplex path of the lower layer $i-1$ is assigned the same route as the layer i client paths. By repeating this procedure to determine the path routes of every layer, the resulting primary and back-up routes of a service path are obviously unchanged and thus physically disjoint in the duct network. This certifies that the evaluation is correctly executed by defining the above path classes and by applying different procedures to each class.

3.2 Network Element Classes

A transport network is composed of several network elements such as cross-connect systems and multiplexers. A network element consists of interface boards and common parts. For such a network element, network operators insert as few interface boards into a frame as possible so as to operate their network with the least cost. Thus, the cost of network elements is determined by two factors: one is the common part cost, which is proportional to the number of network element frames, while the other is the interface board cost. The number of frames needed in a office is determined by the number of interface boards and the frame capacity. Since the frame capacity is given as a specification of the network element, the network element cost is computed by enumerating the number of the interface boards. This number is in turn obtained from the number of paths accommodated by the interfaces.

The number of the paths accommodated at interface boards depends on the cross-connection point for

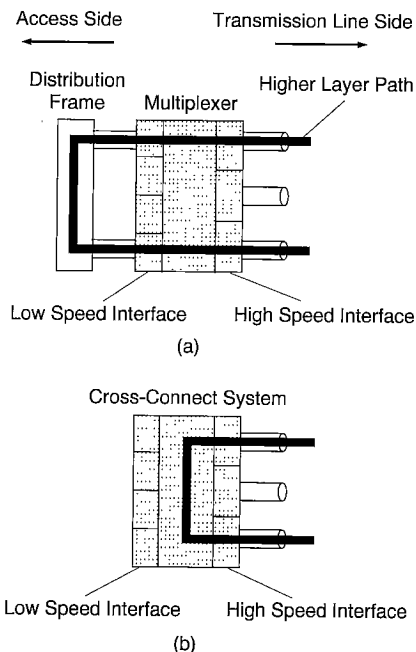


Fig. 3 Relationship of the interface board number and the cross-connection point; (a) case where the cross-connect is executed outside the network element, (b) case where the cross-connect is executed within the network element.

the paths in the office, and the cross-connection point depends on the function of the employed network element. Figure 3 shows two cases of cross-connection. Each case employs a network element that has a low speed access side interface and a high speed transmission line side interface. The employed network element is a multiplexer in Fig. 3(a) and a cross-connect system in Fig. 3(b). In Fig. 3(a), the paths go through the low speed interface and are physically cross-connected at the distribution frame. By contrast, the paths do not go through the low speed interface in Fig. 3(b) because the network element has a cross-connect function and because there is no need for physical cross-connection at a distribution frame. This means that the number of paths accommodated by the low speed interface differs between the cases in Figs. 3(a) and (b), and thus the number of interface boards is also different.

From the above example, the following observations are obtained for enumerating the interface board number.

Observation 1: In an office, the interface board number of a network element depends on the location of the cross-connection point for the paths accommodated by the interface. It is necessary to identify whether the path is cross-connected within or outside the network element.

Observation 2: The function of the network element determines the location of the cross-connection point for paths of a layer in an office.

For a valid enumeration of interface board number,

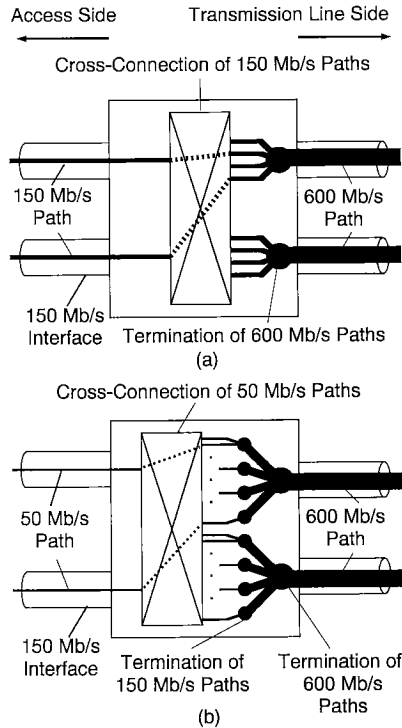


Fig. 4 The interface number is determined by the layer; (a) the case where 150 Mb/s layer determines the number, (b) the case where 50 Mb/s layer determines the number.

the location of termination points are also important. To see this, Fig. 4 shows two cross-connect systems designed for a fictional multiplex hierarchy that consists of 50 Mb/s, 150 Mb/s and 600 Mb/s layers. One cross-connect system (Fig. 4(a)) has a cross-connect function at the 150 Mb/s layer, while the other (Fig. 4(b)) has a cross-connect function at the 50 Mb/s layer. For the former, the access side interfaces accommodate the 150 Mb/s paths terminated. On the other hand, the 150 Mb/s paths are not included in the access side interfaces for the latter, because the 150 Mb/s paths are terminated in the network element. Thus, the number of the access side interfaces must be assessed by the 50 Mb/s paths. This example leads to the next observation.

Observation 3: The multiplex layer of paths, which decides the number of interfaces, is not determined by the interface bit rate. The layer should be decided from the termination points of layers.

The above observations imply that termination and cross-connection points must be correctly identified for valid cost evaluation. Thus, this study categorizes network elements into the following classes.

(1) Cross-connect system (DXC)

The cross-connect system class represents the category of network elements that cross-connect paths as well as terminating paths or fibers.

(2) Multiplexer (MUX)

A multiplex class network element bundles signals from several higher layer paths into a lower layer path and splits a signal from a lower layer path into several higher layer paths. This means that these elements terminate higher layer paths. Namely, if a network element of this class multiplexes layer i paths into a layer j path ($0 \leq j < i \leq h$) and demultiplexes a layer j path into layer i paths, it terminates layer $j, j+1, \dots, i-1$ paths. Note that this class does not have any cross-connection function.

(3) Distribution frame (DF)

This class represents the functionality of physical cross-connection, i.e., no path termination.

These classes differ in terms of the functions offered. Thus, the procedure of identifying the cross-connection and termination points depends on this classification of network elements.

4. Computational Procedures

The resource classification schemes makes it possible to evaluate the amount of physical network resources as well as the network cost. This section introduces computing procedures that estimate the amounts of the two classes of physical resources, fibers and network elements, that determine the cost.

4.1 Path and Fiber Evaluation

It is necessary to determine the routing and grouping of all paths for evaluating the amount of network elements and fibers. The routing procedure determines the sequence of nodes that a path goes through. Meanwhile, the grouping procedure determines where to set multiplex paths and which lower layer multiplex path is used to establish a higher layer client path. Namely, the grouping procedure automatically constructs the logical network topology of the lower layer.

Routing uses the scheme described in Sect. 3.1. Unfortunately, the strictly optimal path grouping is a very complex problem [9], [14]. From the performance requirement, it is not appropriate to employ a complex grouping algorithm for the cost evaluation tool. Instead, this study exploits a simple grouping method that is also well suited to routing. Namely, path grouping is executed from the highest layer h to layer 1 by repeating the following procedure, called *path_grouping(i)*.

Procedure path_grouping(i)

comment: This procedure determines the multiplex paths of layer $(i-1)$ as well as assigning layer i client paths to layer $(i-1)$ server paths.

1. Determine the routes for layer i service paths;

2. **for** each path p in layer i **do**
begin
 3. $a :=$ (the source of p);
 4. $z :=$ (the second office that p goes through);
 5. **while** $a \neq$ (the destination of p) **do**
 6. **if** p can be cross-connected in layer i at z **then**
begin
 7. **if** there exists a multiplex path q of layer $(i - 1)$ that goes through the same route as i from a to z
 8. **then** Let p be a client path of q ;
 - else**
begin
 9. construct a multiplex path q of layer $(i - 1)$ from a to z along the route of p ;
 10. Let p be a client path of q ;
 - end**
 11. $a := z$;
 12. $z :=$ (the next office from z on p);
 13. **else** $z :=$ (the next office from z on p);
 - end**
- end**

The above procedure is based on the policy that a path is cross-connected as frequently as possible. For each layer i path, the procedure identifies layer $i - 1$ server paths sequentially from the source to the destination in steps 5–13. In step 6, the cross-connection capability in layer i at office z is judged from the intra-office configuration and the network element specification. Namely, if there is a network element of the DXC or the DF class in the office, and if the network element can cross-connect layer i paths, then the office is judged to be capable of cross-connection. If office z can cross-connect the path, offices a and z are selected as the source-destination pair of the layer $i - 1$ server path. Here, a is the source or the previous office that has the cross-connection capability. Steps 7–10 create the server path if necessary, and assign the layer i path to the server path according to the routing policy identified in Sect. 3.1. That is, if there is no available multiplex path between offices a and z , step 9 creates a new multiplex path. This means that step 9 adds a new edge to the layer $i - 1$ logical network. Thus, when steps 3–13 are completed for every layer i path, every necessary edge is added to the layer $i - 1$ logical network topology. If a path is protected by a back-up route, steps 3–13 are also executed for the back-up route.

By executing *path_grouping*(i), the required number of layer $(i - 1)$ paths is determined because it is known how many client layer i paths must be served for each layer $i - 1$ path. Therefore, the number of fibers is computed by repeating the procedure from $i = h$ to $i = 1$ since the layer 0 path represents the physical carrier. The fiber cost can be obtained from the numbers and the distances of the physical carriers and their unit prices.

Obviously, the procedure *path_grouping*(i) does not yield a strictly optimal solution. However, it provides good solutions for many cases (see Appendix).

4.2 Network Element Evaluation

As observed in Sect. 3.2, the number of network elements is evaluated through the number of their interfaces, which is in turn computed from the paths accommodated in the interfaces. If the routing and grouping of paths are completed, the computed path information provides the set of cross-connected paths and that of terminated paths for each office. Accordingly, the number of interfaces can be derived from this information as well as the termination and cross-connection points of each layer in the office.

Assign indices $0, 1, \dots, n$ to network elements in an office such that the network element on transmission line side has a smaller index. Then, let $T_{i,k}$ denote the index of the network element that terminates the paths of layer k at office i . Similarly, let $X_{i,k}$ denote the index of the network element that cross-connects the paths of layer k at office i . Also, let $l_{i,j}$ be the number of the transmission line side interfaces of network element j of office i , while let $d_{i,j}$ be the number of access side interfaces of network element j of office i . By using $T_{i,k}$ and $X_{i,k}$, the number of interfaces, $l_{i,j}$ and $d_{i,j}$, are computed by the following procedure:

Procedure interface_number(i)

1. **for** $j = 0$ **to** n **do**
begin
 2. **if** $j = 0$ **then**
begin
 3. $l_{i,j} :=$ the number of fibers terminated at i ;
 4. **if** $X_{i,j} = 0$ **then**
 5. $l_{i,j} := l_{i,j} + 2 \times$ (the number of fibers that transit i);
 - end**
 6. **else** $l_{i,j} := d_{i,j-1} -$ (the number of service paths of the interface layer);
 7. $k :=$ the minimum x such that $T_{i,x} > j$;
 8. $d_{i,j} :=$ the sufficient number to accommodate the layer k paths terminated at i ;
 9. **if** $X_{i,k} > j$ **then** $d_{i,j} := d_{i,j} +$ (the sufficient number to accommodate twice the layer k paths transiting i);
 - end**

For network element j , the interface board number of the line side is basically evaluated from that of the access side of network element $j - 1$ by step 6, or from the number of optical fibers by steps 3–5 when j is directly connected to fibers. The interface board number of the access side is calculated by steps 7–9. Step 7 identifies the multiplex layer that determines the

interface board number on the basis of Observation 3. Steps 8 and 9 compute the board number according to Observations 1, 2.

If $d_{i,j}$'s and $l_{i,j}$'s have been determined by the above procedure, the number of frames can be computed from them and the frame capacity. The network element cost is obtained from the numbers of interface boards and frames together with their unit prices.

The values of $T_{i,k}$ and $X_{i,k}$ are calculated by the following procedure.

Procedure compute_T_and_X(i)

1. **for** $k = 0$ **to** h **do**
2. $T_{i,k} := n_i + 1$;
3. $X_{i,k} := -1$;
- end**
4. **for** $j = 0$ **to** n **do**
5. $l :=$ layer index of the line side interface of network element j ;
6. **if** the class of j is DF and $X_{i,l} := -1$
7. **then** $X_{i,l} := j$;
8. **else if** the class of j is DXC **then**
9. $p :=$ index of cross-connection layer of network j ;
10. **if** $X_{i,p} = -1$ **then** $X_{i,p} := j$;
11. **for** $m = p + 1$ **to** l **do**
12. **if** $T_{i,m} > j$ **then** $T_{i,m} := j$;
13. **end**
14. **else if** the class of j is MUX **then**
15. $p :=$ the layer index of the access side interface of j ;
16. **for** $m = p + 1$ **to** l **do**
17. **if** $T_{i,m} > j$ **then** $T_{i,m} := j$;
18. **end**
19. **end**
20. **end**

Thus, the classification of network elements is indispensable to determine the values of $T_{i,k}$ and $X_{i,k}$.

5. Prototype

A prototype of the tool was made to confirm the feasibility of the described functional requirements and computational procedures. The prototype satisfies all functional requirements identified in Sect. 2.3. Figures 5 and 6 show the graphical user interfaces of the prototype. Figure 5 is the main window that provides the duct network editing function. The duct network can be edited in a manner similar to that offered by common drawing software. Meanwhile, the intra-office configuration editor is shown in Fig. 6. The editor allows a user to add, delete and change the combination of network elements placed in an office. These user interfaces are well con-

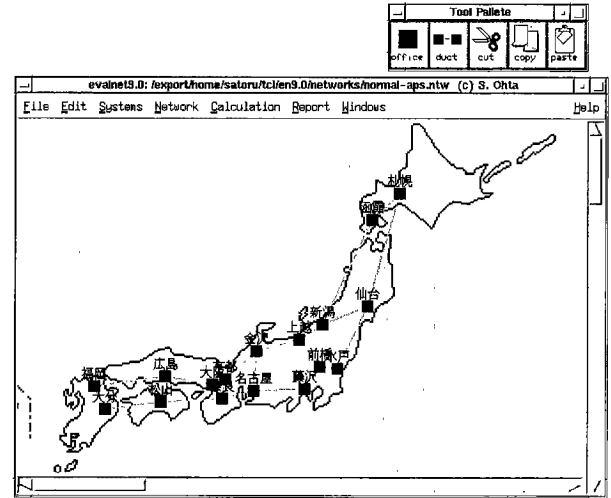


Fig. 5 The main window of the prototype tool.

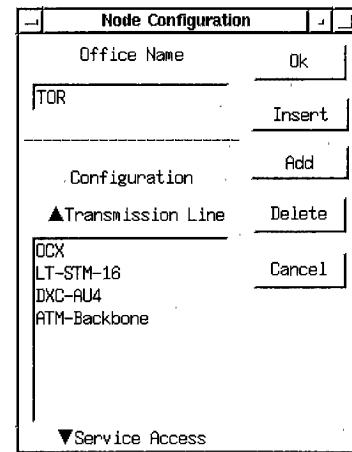


Fig. 6 The intra-office configuration editor.

structed by utilizing the Tcl/Tk language [15], which is frequently used in the telecommunication field [16].

It was confirmed that the tool, and its user interfaces, can be used to edit network data for a wide range technologies such as ATM networks constructed with ATM cross-connect systems, ATM over SDH networks, and WDM networks. The network cost and various path data were also successfully computed and reported. A cost evaluation of a 32 node ATM-over-SDH network [17] took 94.1 seconds on a SUN SparcStation 5 computer. This network consists of three multiplex layers (2.488 Gb/s fiber, 150.3 Mb/s SDH VC4, and 8.0 Mb/s ATM VP), and there are 70 cable ducts set up among nodes. The given service paths (demand) include SDH VC-4s required for 355 source-destination pairs and ATM VPs required for 86 source-destination pairs. The considered network elements are SDH multiplexers, SDH cross-connect systems, and ATM cross-connect systems.

6. Evaluation Examples

The purpose of the described tool is to evaluate the economic benefit of introducing new technologies. This section shows the effectiveness of the tool through two evaluations. One example is an assesment of employing the WDM technology, while the other is a comparison of path protection schemes.

In the first example, the network cost with and without WDM is compared for the same duct network and demand model. For the case with WDM, the multiplex hierarchy consists of four-wavelength WDM fibers (9.776 Gb/s), SDH VC4-16c (2.444 Gb/s), SDH VC4 (155 Mb/s), and ATM VP (9.39 Mb/s). Meanwhile, the hierarchy consists of SDH VC4-16c, SDH VC4, and ATM VP for the case without WDM. The cable duct network and the demand model were taken from Ref. [17]. The duct network is shown in Fig. 7. The demand is given as VC4 paths among all nodes and ATM VPs among six nodes. The considered network elements are ATM cross-connect systems, SDH cross-connect systems, SDH Multiplexers, and WDM cross-connect systems. Among these, ATM cross-connect systems are equiped only at the nodes that terminate the VPs. Additionally, WDM cross-connect systems are used only for the case with WDM.

The hierarchy editing function and the proposed computing function of the tool are indispensable to complete this WDM technology assesment because it is required to compute network cost for the models with different multiplex levels. Additionally, since the network element configuration differs depending on the node, the node editing function of the proposed tool are also required.

The result is shown in Fig. 8. The figure shows that the WDM technology is effective in reducing the link cost. However, it also shows that the cost of the WDM cross-connect system must be made much smaller to reduce the total network cost. As this example shows, the tool is useful in assesing a new technology and finding out what is the dominant part of network cost.

The second example shows how the tool can be used to compare two path protection schemes. For this example, the duct network is the one used in Ref. [10] (Fig. 9), and the multiplex hierarchy consists of SDH VC4-4c (600 Mb/s) and ATM VP (10 Mb/s). It was assumed that every node is equiped with ATM cross-connect systems. For this network, a constant number of virtual paths were set up between every pair of nodes. The total bandwidth of demand was set at about 10 Gb/s. The network cost was evaluated for the 1:1 dedicated backup path scheme and the shared backup path scheme.

Figure 10 is the result of the evaluation. The figure suggests that the effect of the shared backup path scheme is not very large for the considered network model in comparison with the dedicated backup path scheme. To

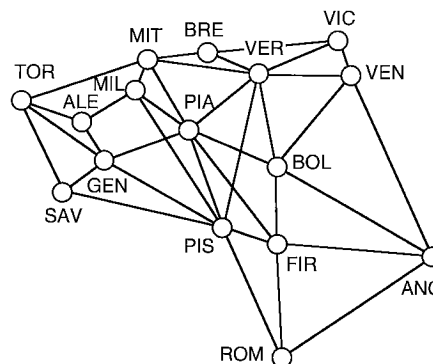


Fig. 7 Duct network model for assesing the effectiveness of the WDM technology [17].

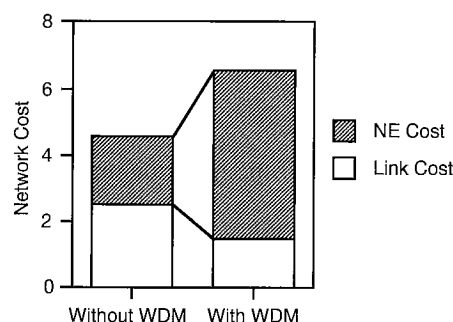


Fig. 8 Network cost comparison for the cases with WDM and without WDM.

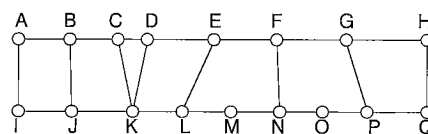


Fig. 9 Duct network model for the evaluation example of comparing two path protection schemes [10].

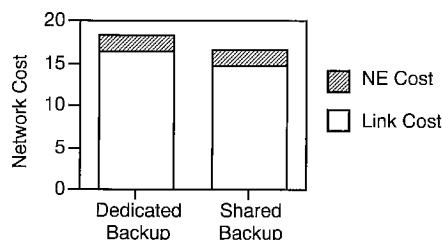


Fig. 10 Economical comparison between the dedicated backup path scheme and the shared backup path scheme.

evaluate these schemes more precisely, the path routing scheme of the tool is significant because it assures the disjointness of the working and backup routes of a path.

7. Conclusion

This paper described the computational techniques employed in a new software tool that evaluates network cost. The main feature of the tool is its flexibility in

supporting a wide range of technologies. This paper first identified the functional requirements of such a tool. In particular, it was shown that parameters such as the multiplex layers and network element specifications must be editable to achieve independence from the technologies. Next, appropriate classifications of network elements and paths were introduced. These classifications are indispensable to evaluate resource amounts correctly. A simple grouping procedure was presented as well as the procedures used to compute the network element amount. Finally, the techniques presented in the paper were realized in a prototype and confirmed to be feasible through tests.

Given the relentless progress in telecommunication technologies, the concept of the proposed tool and the procedures will become more important.

References

- [1] K.Y. Eng, M.A. Pashan, G.D. Martin, and C.R. Crue, "An ATM cross-connect system for broadband trials and applications," Proc. GLOBECOM '93, Houston, TX, pp.1454–1460, Nov. 1993.
- [2] Y. Kobayashi, Y. Sato, K. Aida, K. Hagimoto, and K. Nakagawa, "SDH-based 10Gbit/s optical transmission system," Proc. GLOBECOM '94, San Francisco, CA, pp.1166–1170, Nov. 1994.
- [3] P. Veitch and D. Johnson, "ATM network resilience," IEEE Network, vol.11, no.5, pp.26–33, Sept. 1997.
- [4] K. Asatani, K.R. Harrison, and R. Ballart, "CCITT standardization of network node interface of Synchronous Digital Hierarchy," IEEE Commun. Mag., vol.28, no.8, pp.15–20, Aug. 1990.
- [5] M. De Prycker, "Asynchronous Transfer Mode," Ellis Norwood, New York, 1993.
- [6] K. Sato, S. Okamoto, and H. Hadama, "Optical path layer technologies to enhance B-ISDN performance," Proc. ICC '93, Genova, Switzerland, pp.1300–1307, 1993.
- [7] ITU-T Recommendation G.803, "Architectures of transport networks based on the synchronous digital hierarchy (SDH)," March 1993.
- [8] S. Ohta, K. Sato, and I. Tokizawa, "A dynamically controllable ATM transport network based on the virtual path concept," Proc. GLOBECOM '88, Hollywood, FL, pp.39.2.1–39.2.5, Nov. 1988.
- [9] J. von Puttkamer, "The path grouping algorithm WEGA," Proc. NETWORKS '96, Sydney, Australia, pp.633–638, Nov. 1996.
- [10] S. Ohta and K. Nunokawa, "Comparison of alternative service protection mechanisms for wide area ATM networks," Proc. NETWORKS '96, Sydney, Australia, pp.281–286, Nov. 1996.
- [11] M. Gryseels, S. Ohta, R. Clemente, and P. Demeester, "A cost evaluation of service protection strategies in ATM on SDH networks," Proc. DRCN '98, Brugge, Belgium, paper O38, May 1998.
- [12] J.W. Suurvalle, "Disjoint paths in a network," Networks, vol.4, pp.125–145, 1974.
- [13] J.W. Suurballe and R.E. Tarjan, "A quick method for finding shortest pairs of disjoint paths," Networks, vol.14, pp.325–336, 1984.
- [14] T. Kawata and Y. Okano, "A heuristic algorithm for circuit grouping," IEICE National Convention Record, no.1828, March 1986.
- [15] J.K. Ousterhout, "Tcl and the Tk Toolkit," Addison-Wesley, 1994.
- [16] R. Doverspike, M. Maeda, S. Narain, J. Pastor, C.-c. Shen, N. Stoffel, Y. Tsai, and B. Wilson, "Network management research in ATDNet," IEEE Network, vol.10, no.4, pp.30–41, July 1996.
- [17] M. Gryseels, S. Ohta, R. Clemente, and P. Demeester, "Optimal design for service resilience in ATM on SDH backbone networks," Proc. IEEE ATM Workshop '98, Fairfax, VA, May 1998.
- [18] S. Ohta, "Improved path grouping and routing algorithms for the generic network evaluation tool," Proc. 1998 Communications Society Conference of IEICE, B-7-64, Kofu, Japan, Sept. 1998.

Appendix: Accuracy of the Path Grouping Procedure

This appendix formulates the path grouping problem described in Sect. 4.1 and assesses the accuracy of the solution obtained by the procedure `path_grouping(i)` in comparison with the exact solution.

Let us assume that the network uses a fictional hierarchy that consists of the multiplex levels called S_1 (50 Mb/s), S_2 (150 Mb/s), and S_3 (600 Mb/s). Let $M_i (i = 1, 2)$ denote the maximum number of the S_i level paths served by a S_{i+1} path.

The employed network elements include two types of multiplexers as well as distribution frames that accommodate the S_1 , S_2 , and S_3 levels. One type of the multiplexers, called $M_{1,2}$, converts the signals between the S_1 and S_2 levels while the other type of multiplexers, called $M_{2,3}$, converts the signals between the S_2 and S_3 levels. Consequently, each node is configured as shown in Fig. A·1. For multiplexer $M_{i,i+1}$, the price of a high speed interface is L_{i+1} for one direction, while the price of low speed interface is denoted by D_i . The distribution frame cost and the fixed part cost of multiplexers are assumed to be zero.

The cable duct network is assumed as shown in Fig. A·2. In this duct network, the set of nodes is $V = \{1, 2, \dots, M\}$, while the set of path source-destination pair is $P = \{1, 2, \dots, N\}$. The source and destination of $p \in P$ are denoted by $A(p)$ and $B(p)$, respectively. The fiber cost between the source-destination pair p is $C(p)$. For this network, $T(p)$ paths of level S_1 are demanded for source-destination pair $p \in P$.

For the formulation, let us introduce the following

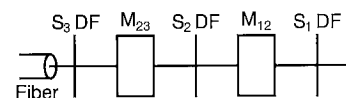


Fig. A·1 Node configuration for the problem formulation.

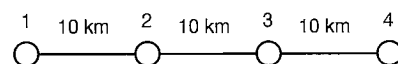


Fig. A·2 Duct network for the grouping problem formulation.

decision variables.

$$f_{i,p,q} = \begin{cases} 1 & \text{if } S_i \text{ level paths between } p \in P \text{ are served by } S_{i+1} \text{ level paths between } q \in P, \\ 0 & \text{otherwise.} \end{cases}$$

$$y_{i,p} = \begin{cases} 1 & \text{if an } S_i \text{ level path exists between } p \in P, \\ 0 & \text{otherwise.} \end{cases}$$

$n_{i,p}$: the number of S_i level paths set up between $p \in P$.

$z_{i,p,q}$: the number of the S_i level paths between $p \in P$, served by the S_{i+1} level paths between $q \in P$.

The problem is formulated as follows:

$$\begin{aligned} \text{minimize} \quad & \sum_{p \in P} C_p n_{3,p} + 2 \sum_{i=2}^3 L_i \sum_{p \in P} n_{i,p} \\ & + 2 \sum_{i=1}^2 D_i \sum_{p \in P} \sum_{q \in P} z_{i,p,q} \end{aligned} \quad (\text{A} \cdot 1)$$

subject to

$$n_{1,p} = T, \text{ for all } p \in P, \quad (\text{A} \cdot 2)$$

$$z_{i,p,q} \geq n_{i,p} - K(1 - f_{i,p,q}), \quad \text{for } i = 1, 2 \text{ and all } p, q \in P, \quad (\text{A} \cdot 3)$$

$$U y_{i,p} \geq n_{i,p}, \text{ for } i = 2, 3, \text{ all } p \in P, \quad (\text{A} \cdot 4)$$

$$\begin{aligned} & \sum_{q \in \{q | a(q)=v\}} f_{i,p,q} - \sum_{q \in \{q | b(q)=v\}} f_{i,p,q} \\ & = \begin{cases} y_{i,p}, & \text{if } v = A(p) \\ -y_{i,p}, & \text{if } v = B(p) \\ 0, & \text{otherwise} \end{cases}, \\ & \text{for } i = 1, 2, v \in V \text{ and } p \in P, \end{aligned} \quad (\text{A} \cdot 5)$$

$$\begin{aligned} M_i n_{i+1,q} & \geq \sum_{p \in P} z_{i,p,q}, \\ & \text{for } i = 1, 2 \text{ and all } q \in P, \end{aligned} \quad (\text{A} \cdot 6)$$

$$\begin{aligned} f_{i,p,q} & = f_{i,p',q'}, \text{ for } i = 1, 2 \text{ and} \\ & (p, p'), (q, q') \in \{(p, p') | A(p) = B(p') \\ & \text{and } B(p) = A(p')\}, \end{aligned} \quad (\text{A} \cdot 7)$$

where K and U are large positive constants.

In the above formulation, the objective function (Eq.(A·1)) consists of three terms; the link cost, the multiplexer high speed interface cost, and the multiplexer low speed interface cost. Equation (A·2) is the definition of service path demand. The condition that sets the value of $z_{i,p,q}$ is Eq.(A·3). Equation (A·4) presents the relationship between path existence and path number. The connectivity of a path is reserved by Eq.(A·5). Equation (A·6) specifies the relation between the number of server paths and that of the served client paths. Finally, Eq.(A·7) is necessary because paths are managed in a bi-directional manner in real world networks.

Since the formulated problem is an integer programming problem, it can be solved with using optimization software. Figure A·3 compares the cost of

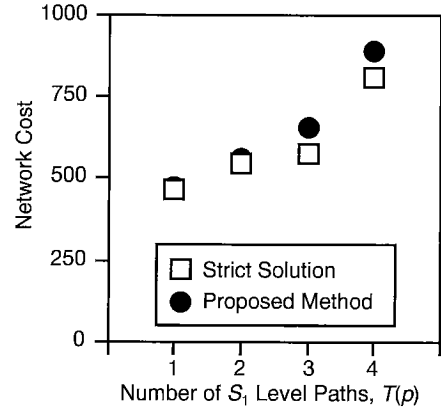


Fig. A·3 Comparison between the strict optimum and the solution derived by the proposed method.

the strict solution derived by the integer programming approach with the cost derived by the proposed tool. Here, the fiber cost was set 5 (/km) for one direction. Parameters D_1 , D_2 , L_2 and L_3 were 1, 2, 2, and 6, respectively. The figure shows that the proposed method yields good solutions. However, the solution derived by the proposed method becomes worse as demand increases, for example, the case of $T(p) = 3$ or $T(p) = 4$.

In this example, no backup routes were considered. For the case that backup routes exist, it was also shown that the proposed method does not always yield a good solution [18]. Thus, if it is necessary to know the network cost that is very close to the strict optimum, some improved algorithms [18] should be employed instead of the proposed method.



Satoru Ohta received the B.E., M.E., and Dr. of Engineering degrees from the Tokyo Institute of Technology, Tokyo, Japan, in 1981, 1983, and 1996, respectively. Since 1983 he has been with NTT, where he worked on research and development of cross-connect systems, transmission network synthesis, network management, and broadband ISDN. He is currently involved in research of optimization techniques for transport networks at

NTT Optical Network Systems Laboratories.

Dr. Ohta is a member of the IEEE. He received the Excellent Paper Award in 1991 from IEICE.