Optimal Hierarchical Structure of Broadcast Network

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Summary — With the realization of Broadband Integrated Service Digital Network (B–ISDN), broadcast services will occupy a large part of the network traffic. In these services, the same information is distributed to many subscribers through the point-to-multipoint connection paths. This connection form is quite different from that of conventional point-to-point services. Since the conventional network structure is fit for point-to-point services, the current network topology may lower the quality of services or may increase the construction costs. In this paper, the hierarchical broadcast network topology is optimized under the some assumptions: the cost functions, the population distribution, and the percentage of broadcast services are treated as parameters. The result shows that the Ring–Star–Star or Ring–Ring–Star topology can be better than the conventional Mesh–Star topology in some cases, and can be much better in case where the viewing ratio of broadcast services increases.

Key words — Network, B–ISDN, Broadcast, Hierarchical structure, Optimization

1. Introduction

With the realization of Broadband Integrated Services Digital Network (B–ISDN), it is forecasted that not only point-to-point services such as telephone, facsimile, and data transfer, but also broadcast services such as TV broadcasting will be provided. Hence, telecommunication and broadcasting will be integrated[1]. Since most broadcast services have moving pictures and they require wide bandwidth, broadcast services will use a large part of the network resources and will be the major traffic in B–ISDN.

It is an important issue to design the network topology when B–ISDN is constructed. The conventional digital network in Japan has Mesh–Star 2-layer topology. It is optimized and designed to carry telephone traffic that requires point-to-point connections. On the other hand, B–ISDN will be used for many services that require point-to-multipoint connections, such as TV broadcasting, Near Video-On-Demand (NVOD), and broadcast facsimile, as well as point-to-point connections. If the point-to-point connection paths are used to provide these broadcast type services, huge network resources will be required. To avoid that, the point-to-multipoint connection paths will be used. To transmit the same piece of information to two or more destinations, only one packet will be transmitted to the intermediate node, and will be copied there to transfer it to destination nodes. The point-to-multipoint connection will substantially decrease the traffic in the network, and will save network resources and transmission costs. This connection form is quite different from the conventional point-to-point one. If the current network topology is used to provide broadcast services, it may lower the quality of services or may increase the network construction cost.

In this paper, the hierarchical nationwide network topology is optimized under the assumption that the broadcast services account for a large part of the network traffic. Namely, the broadcast network construction costs are calculated, using a geographical model of Japan. The cost functions, the population distribution, and the percentage of broadcast services are treated as parameters. Mesh, Star, and Ring topologies are used as the basic topologies of each layer.

The rest of this paper is organized as follows: Section 2 shows the geographical model of Japan, the population distribution models, the service models, and the basic network topologies. Section 3 describes the methods to calculate the traffic and the costs. Section 4 shows the calculation results. Finally, conclusions are given in section 5.

2. Design models

2.1 Node allocation model

Figure 1 shows the image of hierarchical structure[2]. It reflects the land of Japan, which has a long and narrow shape. The node allocation model is defined as follows:

1. The number of nodes is 1,800 (= 120 × 15). This is almost the same as the number of nodes in the conventional digital network in Japan. The network treated in this paper covers all of these nodes, and has two or three layers.

2. The nodes are allocated at the lattice points. The distance between adjacent nodes is 15km. Let this distance be normalized to 1 on the coordinate system, and let the position of the node be denoted by (x, y), $0 \leq x < 120$, $0 \leq y < 15$, x and y are integer values. This layer is named the 1st layer.

3. The nodes on the 1st layer are connected to the node on the 2nd layer. The number of the nodes on the 1st layer connected to one node on the 2nd layer is a design parameter, which varies from 15 to 75.

4. The nodes on the 2nd layer are connected to the node on the 3rd layer. The number of the nodes on the 2nd layer connected to one node on the 3rd layer is also a design parameter, which varies from 1 to 60. When this parameter is equal to 1, the network has two layers only.

5. If nodes on different layers have the same location, the distance among them is assumed to be 0.

2.2 Population distribution models

Figure 2 shows three patterns of the population distribution. The total population is set to that of Japan, 126,000,000. To make calculations easy, the same populations are assigned if y values are the same in each model.

(1) Flat

In this model, the population distribution is uniform as shown in Figure 2 (a). Each node has 70,000 people ($70,000 \times 1,800 = 126,000,000$).

(2) Center-concentrated

The population distribution is Center-concentrated as shown in Figure 2 (b). The center represents Tokyo area. The ratio of the maximum population to the minimum is 10.0.

(3) Double-peaked

Figure 2 (c) shows the Double-peaked model. Two peaks represent Tokyo and Osaka area. Osaka is the second most densely populated area in Japan. The ratio of the maximum population to the minimum is also 10.0.

Moreover, the number of B–ISDN terminals is assumed to be a half of the population in every model.

2.3 Service models

It is expected that many new services will be provided in B–ISDN in the near future[3]; They are, for example, one way broadcast services such as TV broadcasting, request-answering services such as Video-On-Demand (VOD), interactive services such as TV shopping. These services can be divided into two main categories according to connection forms, namely broadcast services and point-to-point services.

(1) Broadcast services

In the broadcast services, the multicast functions of ATM switching systems can substantially reduce the traffic on the transmission lines and the transmission costs. Therefore, it is expected that more than a half of the video services will be transmitted through point-to-multipoint connection paths. For transmitting videos, the number of calls using point-to-multipoint connection paths will be larger than that of calls using point-to-point connection paths.

Moreover, we can classify broadcast services into the following three groups:

(a) Nationwide TV broadcasting (Class 1)

In the future, many subscribers are anticipated to watch the TV broadcasting with nationwide scale. Since this kind of services will not be so many, the number of these sources is assumed to be 10. Considering the conventional TV, the viewing probability of each source will be almost the same. Therefore, it is assumed to be equal.

(b) Other TV broadcasting (Class 2)

All other TV broadcasting services belong to Class 2. The number of service sources should not be limited. It is assumed that 200 service sources have at least a viewer at one time, and that the viewing probabilities are given by the geometrical distribution. The constant value of geometrical distribution, denoted by a, is set to 0.9.

(c) Near Video-On-Demand (NVOD) (Class 3)

In NVOD, information is transmitted through the point-to-multipoint connection paths to reduce the transmission costs, while the point-to-point connection is used to achieve an interactive operation between the server and each client in VOD. Namely, the same information is repeatedly distributed using several channels with shifted starting times in NVOD. Viewers can watch programs from their beginnings without waiting so long time. Since point-to-multipoint connection paths are more effective when there are many destinations, NVOD is fit for popular video programs. The viewing probabilities of such programs will be approximately equal, and viewing probability of each channel of the same program will be also approximately equal. Therefore, the viewing probability of each channel of each program is assumed to be equal. The number of NVOD programs is 50, referred to the number of new movies showing in metropolitan areas. Each program has 8 channels.

(2) Point-to-point services (Class 4)

Let us consider the point-to-point video services such as VOD. The number of calls of these services may be smaller than that of broadcast services. The point-to-point services, however, occupy the transmission lines in proportion to the number of calls, since these calls are independent of each other. Therefore, we cannot ignore the point-to-point services. Incidentally, the narrowband communication services, such as conventional telephone services and facsimile, are included in this category.

Since all services in the Class 4 are transmitted through the point-to-point connection paths, the conventional teletraffic theory can be used. However, the necessary bandwidth of narrowband services is quite different from that of broadband services such as VOD. Therefore, we need to normalize the bandwidth of all services. In this paper, 1 Erlang means 1 video bandwidth.

Furthermore, the traffic per terminal is assumed to be 0.5.

2.4 Basic network topologies

Mesh, Star, and Ring topologies are used as the basic network topologies to design the hierarchical network in this paper. The features of these topologies are as follows:

(1) Mesh topology

Mesh topology, shown in Figure 3 (a), has high reliability since every node pair has a direct link. However, the traffic will not be enough to get the high multiplexing efficiency in most cases, and the construction cost will be high. In this paper, this topology can be used as the 3rd layer only.

(2) Star topology

Figure 3 (b) shows Star topology. This is the simplest among three topologies. Since all nodes on the lower layer are connected to only one node on the upper layer, the construction cost might be low. However, most calls are transmitted by way of the upper layer and there is no alternative route between every node pair, since Star topology has few direct links. From the viewpoint of the reliability, it is better not to use this topology as the 3rd layer. Therefore, this topology can be used as the 1st layer and the 2nd layer in this paper.

(3) Ring topology

Figure 3 (c) indicates Ring topology. All nodes are connected in an annular form, and the total link length is the shortest among three topologies. The traffic will be enough to get high multiplexing efficiency in most cases. At the same time, however, a fault will influence the whole network. From the viewpoint of point-to-multipoint connection, this topology might be the most suitable. This topology can be used as every layer in this paper.

3. Calculation

The goal is to get the optimal hierarchical structure under the criteria of the network construction cost using the models given in section 2. In this section, we explain how to calculate the cost.

3.1 Broadcast traffic in nodes and that on the trunk lines

For point-to-point services, the number of active terminals is equal to that of busy trunk lines, as shown in Figure 4 (a). We can get the outgoing traffic of each node by summing all traffic of the terminals in the node. On the other hand, for the broadcast services, such calculation can not be used, since branch connections may occur at the various nodes. Figure 4 (b) shows that the number of busy trunk lines is not equal to that of active terminals, but equal to that of the services in use. Therefore, it is necessary to figure out the traffic per each broadcast service in each node.

Table 1 Probabilities to choose services.

Class	Contents	Probability Type 1	Probability Type 2
1	Nationwide TV broadcasting services	0.65	0.75
2	Other TV broadcasting services	0.10	0.10
3	NVOD	0.05	0.05
4	Point-to-point services	0.20	0.10

Here, we define two probability types to choose the services per each terminal as Table 1. Let the probability that one or more terminals are active to receive the service j in the Class i (service (i,j) in the rest of this paper) in the node (x,y), be denoted by $P(i,j;x,y)$. It can be calculated by

$$P(i,j;x,y) = 1 - \{1 - p(i,j)\}^{N(x,y)}, \tag{1}$$

$$p(i,j) = \begin{cases} c_0 \dfrac{p_g(i)}{n(i)} & (i = 1,\ 3) \\ c_0(1-a)a^{j-1}p_g(i) & (i = 2) \end{cases} \tag{2}$$

where c_0 is the traffic of each terminal, $p_g(i)$ is the probability that each terminal is active to receive the service in the Class i, $p(i,j)$ is the probability that each terminal is active to receive the service (i,j), $n(i)$ is the number of the service sources in the Class i, a is a constant value of geometrical distribution, and $N(x,y)$ is the number of terminals in the node (x,y). $P(i,j;x,y)$ represents the traffic per broadcast service (i,j) in each node (x,y). The sum of $P(x,y;i,j)$ over i and j represents the total broadcast traffic in the node (x,y). Namely, the total broadcast traffic, $P_b(x,y)$, is calculated by

$$P_b(x,y) = \sum_{i=1}^{3} \sum_{j=1}^{n(i)} P(x,y;i,j). \tag{3}$$

For the point-to-point service class, the total point-to-point traffic in each node, $P_p(x,y)$, is calculated by

$$P_p(x,y) = c_0 p_g(4) N(x,y). \tag{4}$$

The trunk lines are used only when the video source does not exist in the same node. Therefore, a part of broadcast traffic $P_b(x,y)$, and a part of point-to-point traffic $P_p(x,y)$ does not pass the trunk lines. In Figure 4, this kind of traffic is omitted.

3.2 Traffic pattern of origination–destination pairs

In a theoretical model, the destinations of the calls are usually assigned based on both the distance and the population distribution. In this paper, broadcast service sources are not so many that these can be assumed to be in specific nodes. To keep the generality, however, it is preferable to distribute the broadcast sources in proportion to the population. Therefore, the service sources are distributed as follows:

- The viewers of every broadcast service will exist in the whole country. The broadcast service sources, namely the destinations of the broadcast calls, are assumed to be distributed in the whole country in proportion to the number of subscribers.
- Most point-to-point calls will direct to the neighboring nodes, because of their contents or the telecommunication tariff. These destinations are therefore assumed to be distributed in proportion to the number of subscribers and inversely exponential to the distance.

This can be formulated as follows: The broadcast service traffic from (x, y) to (x', y'), $P'_b(x, y; x', y')$, and the point-to-point service traffic from (x, y) to (x', y'), $P'_p(x, y; x', y')$, are calculated by

$$\begin{aligned} P'_b(x, y; x', y') &= \frac{N(x', y')}{N_a} P_b(x, y), & (5) \\ P'_p(x, y; x', y') &= A(x, y) e^{-k\sqrt{(x-x')^2+(y-y')^2}} N(x', y') P_p(x, y) & (6) \end{aligned}$$

where N_a represents the number of subscribers in the whole country, and $A(x, y)$ is the normalized function that meets

$$A(x, y) = \frac{1}{\sum_{s,t} N(s, t) e^{-k\sqrt{(x-s)^2+(y-t)^2}}}. \tag{7}$$

The sum of $P'_p(x, y; x', y')$ over x' and y' is equal to $P_p(x, y)$. k is a constant value, and is less than 1.

The calculation methods mentioned above are applied to each layer. First, we can compute the calls in each calculating area on the 1st layer. This area consists of some nodes on the 1st layer, connected to the same node on the 2nd layer. This node on the 2nd layer is what is called a tandem node.

Since the transversal links are not considered in this paper, both outgoing traffic from the calculating area and incoming traffic to that area are transmitted by way of the tandem node. Therefore, for the calculating area on the 1st layer, we can compute by supposing that all terminals and service sources in non-calculating area exist in the tandem node as shown in Figure 5 (a). This method makes computations easy, because the calculation in each area is independent of the other areas or different layers. The total outgoing calls from this area can be computed and memorized.

Secondly, we can compute the calls in each calculating area on the 2nd layer using the memorized calls above. This area consists of some nodes on the 2nd layer, connected to the same node on the 3rd layer. The same as the calculations on the 1st layer, it can be supposed that all terminals and service sources in non-calculating area exist in the tandem node as shown in Figure 5 (b). This also enables independent calculation of the other areas or the other layers. We memorize total outgoing calls from each calculating area.

Finally, the calls on the 3rd layer are computed using the memorized values in the calculations on the 2nd layer.

3.3 Cost

The total network construction cost, C, is expressed in the form of the function of the number of link units $m(l)$, and the distance $d(l)$ of the link l.

$$C = c_1 + c_2 \sum m(l) + c_3 \sum d(l) + c_4 \sum m(l)d(l) \tag{8}$$

where c_1, c_2, c_3, and c_4 are constant values. The first clause c_1 is the cost of buildings. It is entirely fair to omit it, because it is equally involved in every case. The second clause $c_2 \sum m(l)$ is in proportion to the number of link units of the link l. It represents switch cost, that is, the cost of switching systems. It may be approximately in proportion to the number of the terminal ports. The third clause $c_3 \sum d(l)$ is in proportion to the distance of the link l. It represents the tunnel construction cost, and so on. The last clause $c_4 \sum m(l)d(l)$ is in proportion to both the number of link units and the distance of the link l. It expresses the optical fiber cable cost. $\sum m(l)$, $\sum d(l)$, $\sum m(l)d(l)$ can be uniquely computed if the population distribution, the viewing probability of each service, and the network topology are given to our calculation program. However, the switch cost per port c_2, the tunnel construction cost per meter c_3, and the optical fiber unit cost per meter c_4, will be varying in the future. Then, we modify C to

$$C = \frac{c_2}{c_4} \sum m(l) + \frac{c_3}{c_4} \sum d(l) + \sum m(l)d(l) \tag{9}$$

by using the ratio of the switching system unit cost to the optical fiber unit cost c_2/c_4, and the ratio of the tunnel construction cost to the optical fiber unit cost c_3/c_4. In the following section, some graphs will be shown to illustrate the optimal network structure with these two parameters, c_2/c_4 and c_3/c_4, as variables.

4. Calculation results

Based on the models in section 2 and the calculation method in section 3, the network construction cost is computed. Many topologies (384 in total) are compared, and the most economical topologies are shown in the graphs. Although the network topologies are explained in the section 2.4, the tunnel topology will not be the same as the network topology for most cases. The reason for this is that the total tunnel construction cost will be very high if the tunnel is built along the network topology. Therefore, it is assumed that the links are constructed along the lattice.

To make calculations simple, it is also assumed that the call origination follows the Poisson distribution, and the holding time follows the exponential distribution. Moreover, the Erlang B formula is used to dimension the network so that the blocking rate is less than 0.1%. The number of links calculated by Erlang B formula represents that of optical fiber units. The bandwidth of link unit is 156Mbps, and a link unit can carry five service calls that need 30Mbps to transmit the high–definition TV (HDTV) using MPEG 2.

Figure 6, 7, and 8 show the calculation results in case of probability type 1, and Figure 9, 10, and

11 show in case of probability type 2. The vertical axis represents the ratio of the switch cost per 156Mbps port to the optical fiber unit cost per meter, and the horizontal axis represents the ratio of the tunnel construction cost per meter to the optical fiber unit cost per meter. Figure 6 and 9 are the results of Flat population distribution. Figure 7 and 10 are the results of Center-concentrated, and Figure 8 and 11 are those of Double-peaked. Symbols "M", "S", and "R" represent Mesh, Star, and Ring topologies, respectively. For example, "R–S–S" means that the optimal structure has Ring topology as the 3rd layer, and Star topologies as the 2nd and the 1st layer. The numbers attached under this description, such as "6, 30", represent the number of the nodes on the 2nd layer connected to one node on the 3rd layer, and the number of nodes on the 1st layer connected to one node on the 2nd layer, respectively. The description "M–S" means that the optimal structure has only two layers, Mesh topology as the 2nd layer and Star topology as the 1st layer. The number attached under that, such as "75", represents the number of nodes on the 1st layer connected to one node on the 2nd layer.

First, those graphs show that there are two main optimal topologies: One is the Mesh–Star 2-layer topology, which is the same as the conventional digital network topology in Japan, another is the Ring–Star–Star 3-layer topology. The former is the best if the switch cost is high, or if the tunnel construction cost is low. Moreover, as the optical fiber unit cost becomes lower, the number of nodes on the 1st layer connected to one node on the 2nd layer increases, that is, the number of nodes on the 2nd layer decreases. On the other hand, the latter, the 3-layer topology with Ring topology as the top layer, is the optimal if the switch cost is low, or if the tunnel cost is high. In this case, as the optical fiber unit cost becomes lower, the number of nodes on the 1st layer connected to one node on the 2nd layer increases, that is, the number of nodes on the 2nd layer decreases. Simultaneously, the number of nodes on the 3rd layer decreases.

Secondly, let us consider from probability types. In case of probability type 2, the optimal area of 3-layer topologies that have Ring topology as the top layer becomes bigger. Thus we see that Ring topology is more effective in broadcast traffic for the 3rd layer.

Furthermore, from the viewpoint of the population distribution, the optimal area of Ring–Ring–Star 3-layer topology exists between the area of Mesh–Star topology and that of Ring–Star–Star topology only when Flat distribution is applied. This can be explained as follows. In cases of concentrated models, almost all of broadcast traffic directs to densely populated points, since the destinations of the broadcast calls are, as mentioned in section 3.3, assumed to be distributed in proportion to the number of subscribers. Namely, much traffic from whole model must be transmitted through the 2nd and 3rd layers. Star topology, which has direct links between each node on the lower layer and a node on the upper layer, is effective in transmitting that kind of traffic. In case where the population distribution is Flat, the amount of broadcast traffic that is transmitted through the 3rd layer is smaller than in cases of concentrated models, and much traffic directs to neighboring nodes. Thus Ring topology is more effective in this population distribution model.

This rule can be applied to the 1st layer. Star topology is optimal for the 1st layer in every case since much broadcast traffic that directs to another calculating area exists.

In case where the population distribution is Double-peaked, the area of “M–S 60” is bigger. “M–S 60” means Mesh–Star 2-layer topology. In this topology, there are 30 (10×3) nodes on the upper layer, and each node on the upper layer has 60 nodes on the lower layer. When the nodes on the upper layer are arranged on our geographical model, coordinates of some nodes are the same as those of the most densely populated points. In the densely populated area, there are many calls that direct there, as well as many calls that originate there. Therefore, the ratio of the local traffic, which does not have to be transmitted through the upper layer, increases. On the other hand, no nodes on the upper layer have the same coordinates as those of population concentrating points when “M–S 50” or “M–S 75” is selected. The traffic between nodes that sandwich the most densely populated points must be transmitted through the upper layer. This increases the number of link units on the upper layer and network construction costs.

5. Conclusion

In the near future, the broadcast services will account for a large part of the network traffic. Assuming such a situation, the hierarchical network structure was optimized. The node allocation, the population distribution, the traffic, and the viewing probabilities were modeled to fit for Japan. Since it is difficult to forecast the optical fiber cable unit cost, the switching system unit cost, and the tunnel construction cost in the future, these costs were treated as variables to draw the cost minimum maps.

The results show that not only Mesh–Star 2-layer topology, which is the same shape as the conventional digital network topology in Japan, but also Ring–Star–Star and Ring–Ring–Star 3-layer topologies are the optimal depending on the variables. In case where the ratio of broadcast service traffic increases, optimal area of Ring–Star–Star becomes bigger. This result leads to the conclusion that the topologies that have Ring as the 3rd layer are more effective in broadcast traffic. In case where the population distribution is Center-concentrated or Double-peaked, we can see that Star topology is better than Ring as the 2nd layer. It is also found that Star topology is the best as the 1st layer since there is much outgoing traffic that must be transmitted through the 2nd or 3rd layer, and that good arrangement of the nodes on the upper layer makes network construction costs small.

In this paper, some restrictions were provided in the geographical model, the traffic model, and the service models, to make cost calculations simple, since it is difficult to analyze the broadcast traffic theoretically[3]. If the theoretical analysis becomes easy, more appropriate models will be used, and the optimization will be done better. It is also necessary to investigate the service models and to forecast them more exactly. Furthermore, the addition of transversal links might lead to the other results, while the network treated in this paper is a purely hierarchical network. It is left for further study.

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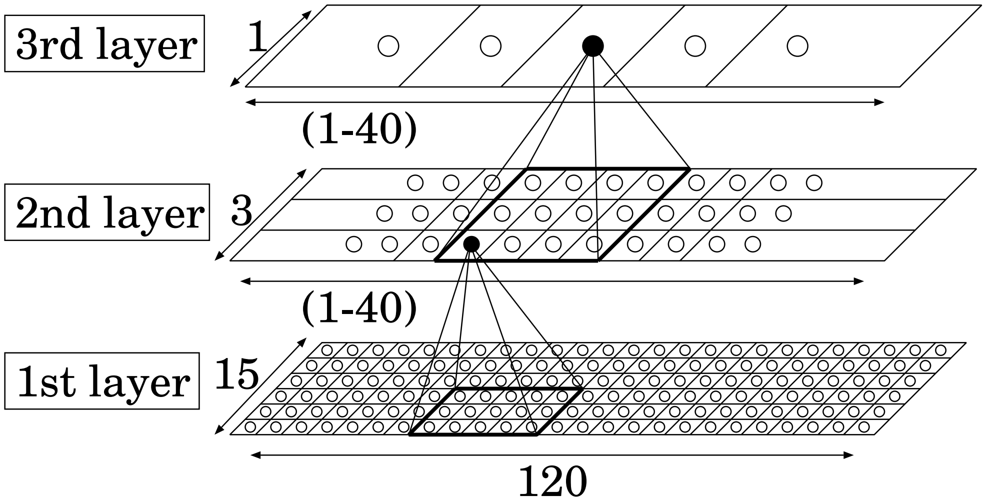


Figure 1 Image figure of hierarchical structure.

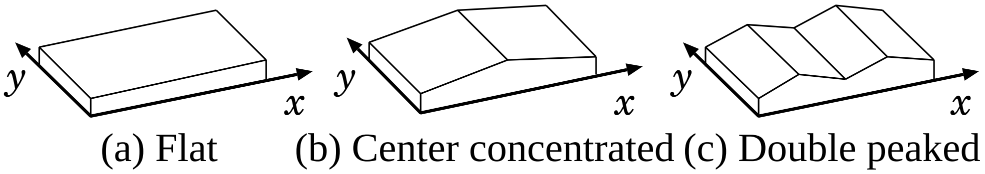


Figure 2 Regional distribution of the population.

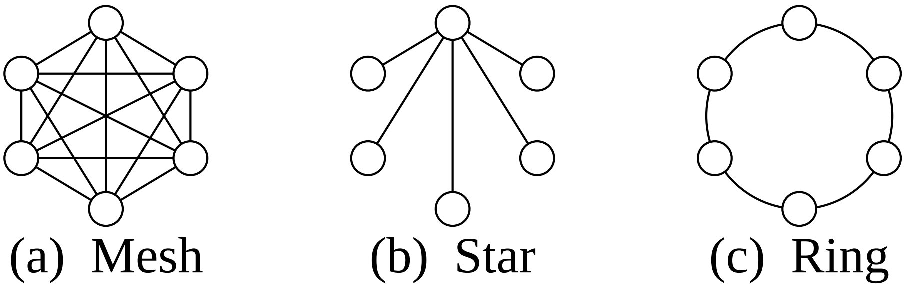


Figure 3 Basic network topologies.

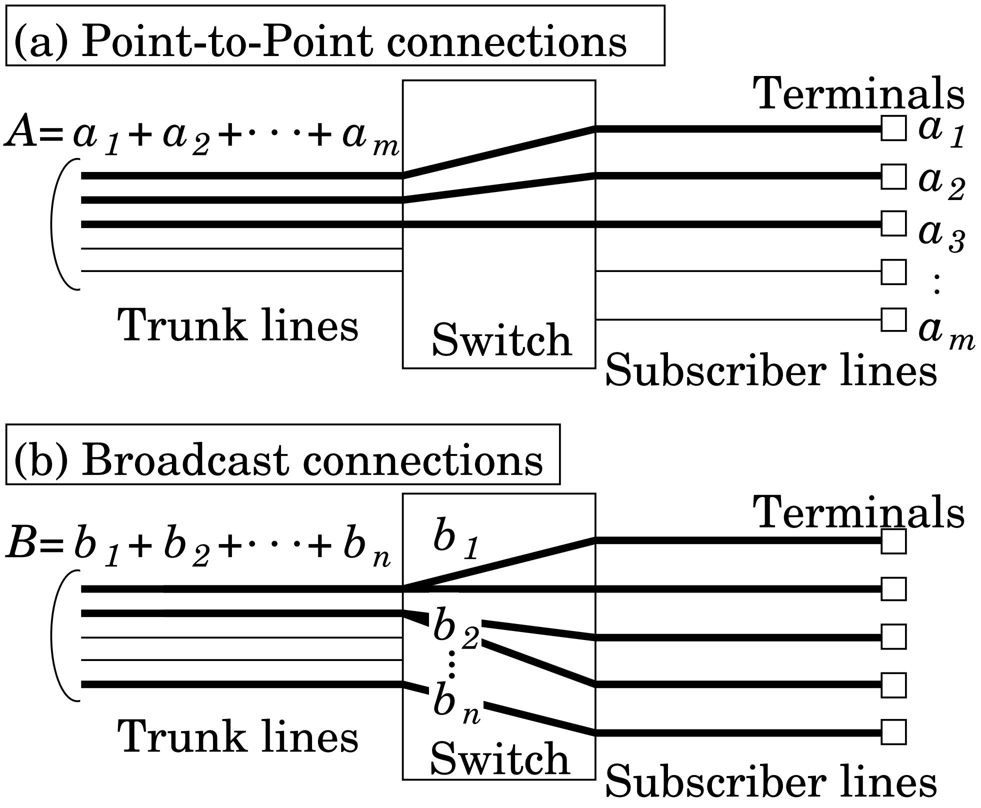
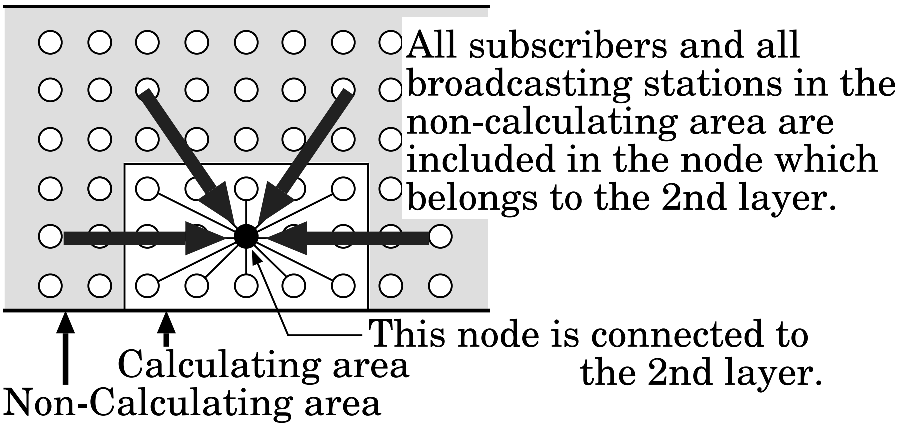
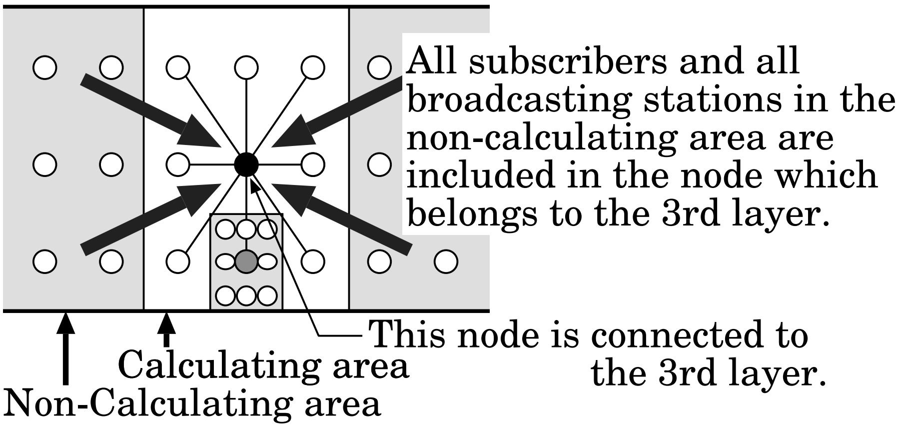


Figure 4 Calls on trunk lines of point-to-point connections and multicast connections.



(a) Calculation in the 1st layer.



(b) Calculation in the 2nd layer.

Figure 5 Calculation examples based on hierarchical structure.

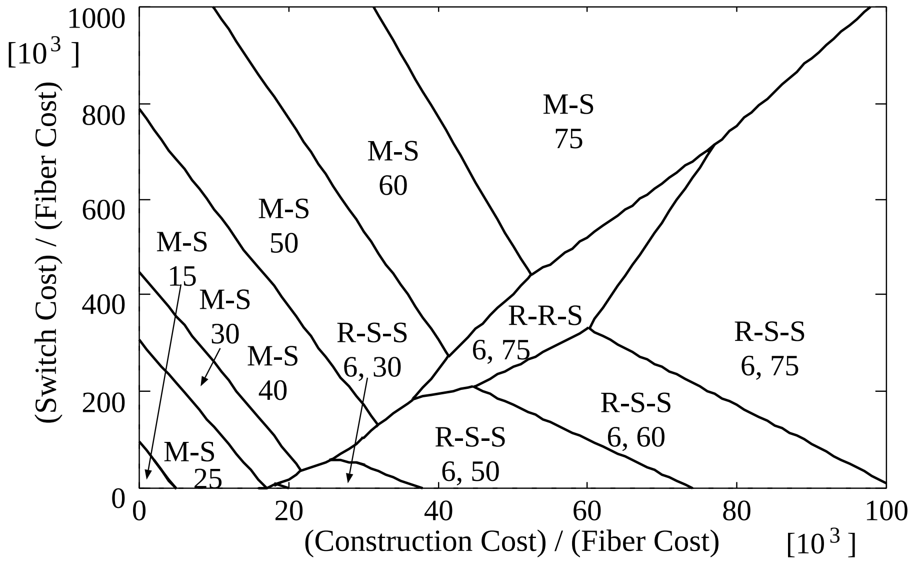


Figure 6 Cost minimum map (Probability type 1, Population distribution: Flat).

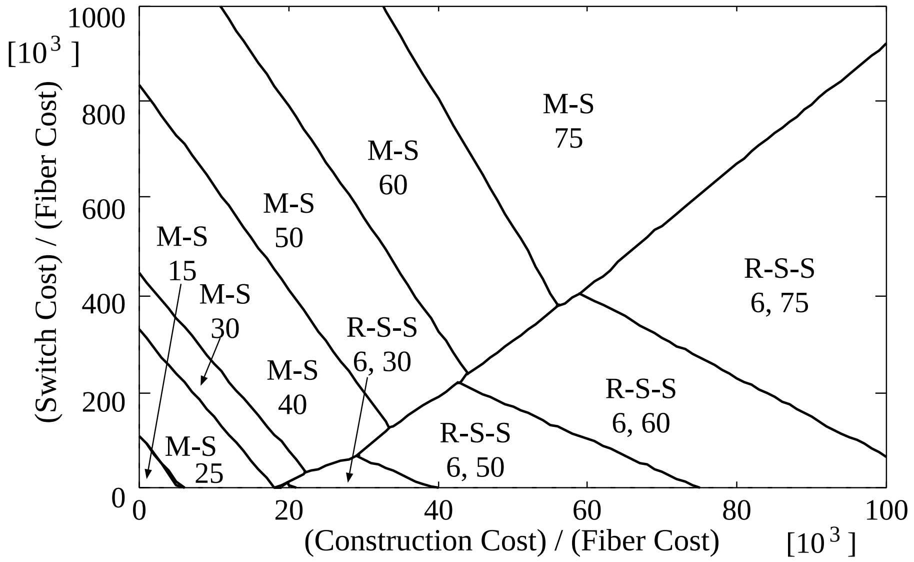


Figure 7 Cost minimum map (Probability type 1, Population distribution: Center-concentrated).

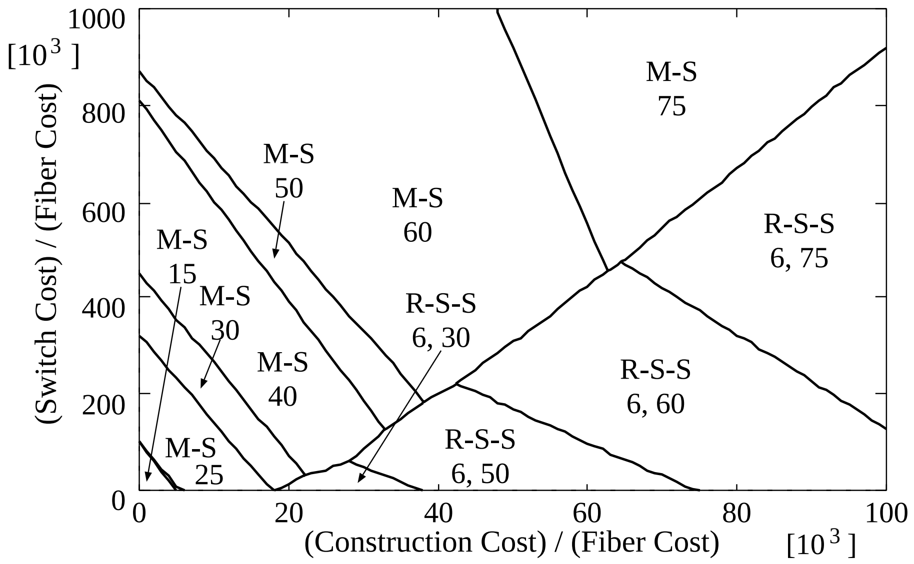


Figure 8 Cost minimum map (Probability type 1, Population distribution: Double-peaked).

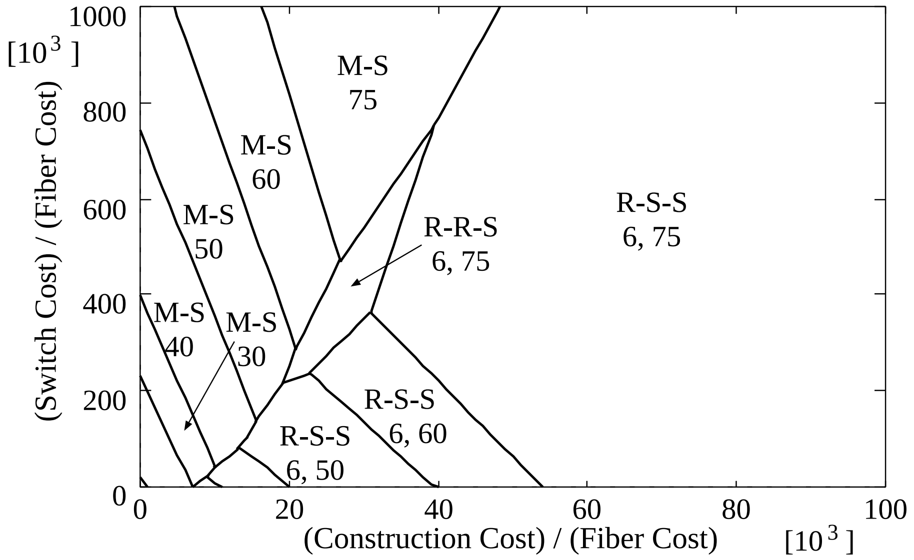


Figure 9 Cost minimum map (Probability type 2, Population distribution: Flat).

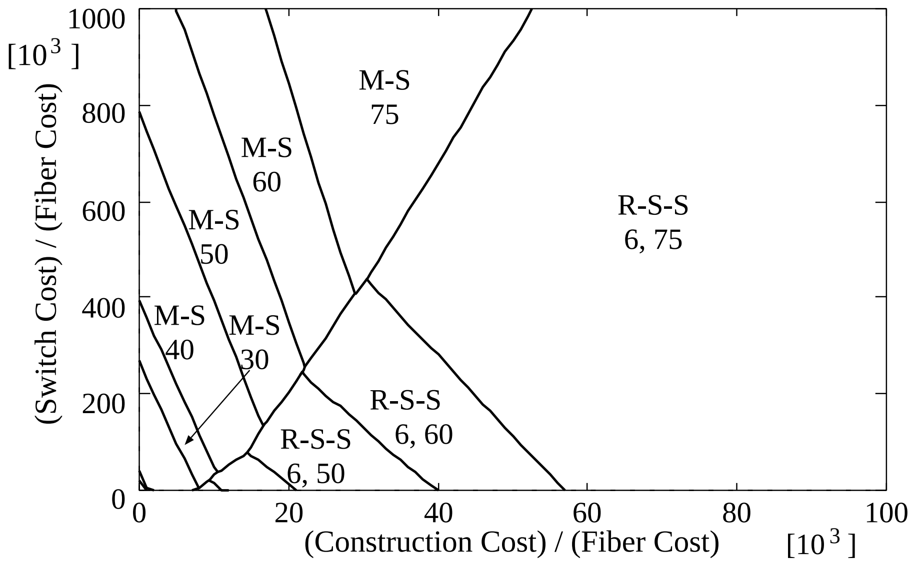


Figure 10 Cost minimum map (Probability type 2, Population distribution: Center-concentrated).

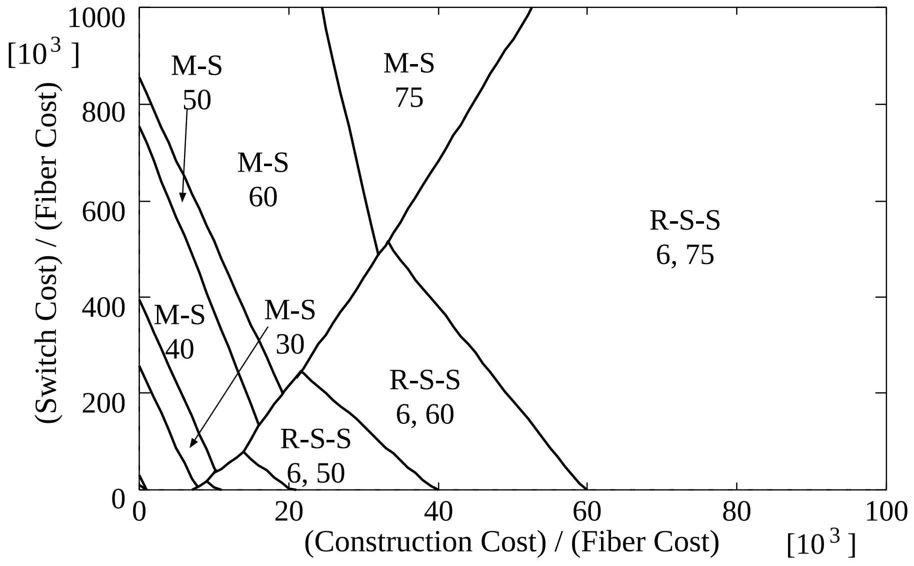


Figure 11 Cost minimum map (Probability type 2, Population distribution: Double-peaked).