FLEXIBLE ROUTING IN THE GLOBAL COMMUNICATION NETWORK

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ABSTRACT

Flexible Routing, which means a flexible selection of connecting paths including detours, will be made in the future communication network in order to efficiently operate it. Generally speaking, although the effective utilization of idle links is an advantage, the increase of the number of used links per call is a disadvantage of flexible routing. Thus it becomes important to investigate the effects of flexible routing from the both viewpoints.

In this paper, some symmetrical network models are considered and effects of flexible routing are examined by a new analytic method. In particular, some peculiar properties like hysteresis are found in the behavior of network through the quantitative analysis. That is, once congestion occurs, it does not disappear immediately even if the load is lessened thereafter. The results obtained here are important for efficient and stable operation of the network where flexible routing is made.

1. INTRODUCTION

Flexible routing will be introduced in future, in order to efficiently operate the communication networks which will be provided with highly developed network structure and advanced switching functions realized by the stored-program-control exchanges. The flexible routing means a flexible selection of connecting path in accordance with the traffic distribution in the network, so as to improve the network efficiency utilizing idle links. From the viewpoint of improving the efficiency, therefore, flexible routing is effective only when the traffic distribution is not uniform in the entire network.

Such non-uniformity of the traffic distribution may be found in the following cases:
(1) The traffic distribution is not uniform on the average;
(2) The traffic distribution is not uniform instantaneously, even if it is uniform on the average.

In the actual network, the non-uniformities of the traffic distribution in the sense of the case (1) and that in the sense of the case (2) are combined and the effect of flexible routing depends on both of them. To make analysis simple, however, it is advisable that the effect due to the non-uniformity in the sense of the case (1) and that in the sense of the case (2) should be discussed separately.

In the case (1), the effect of flexible routing can easily be expected. For this case, the problem is that of optimum traffic assignment to each link and can be discussed statically. This problem will be left for further studies.

In the case (2), it is extremely important to provide some adequate restrictions on the path selection so as to obtain the tradeoffs for an advantage and a disadvantage caused by the flexible routing. The advantage is the effective utilization of idle links and the disadvantage is the increase of used links per call caused by the use of large detours. For this case, some stochastic analysis will be needed. The problem, in general, is so complicated that the properties of flexible routing have been little known other than a few(1), (2) clarified partially by simulation.

The discussions in this paper are limited to the case (2). For the object of discussions, some symmetrical network models are considered. In particular, the regular polyhedron-type networks(3) which are considered as the models of the global network covering the earth are mainly analyzed. Since the uniform traffic distribution can be assumed in these symmetrical networks for the uniformly offered traffic, we can easily extract the effects due to the non-uniformity in the sense of the case (2). Thus it is the purpose of this paper to induce the fundamental properties of the flexible routing through the quantitative analysis of these simplified models.

2. NETWORK MODELS

The object of analysis is a network with N switching stations and n links. For the purpose of examining the effects of flexible routing due to the non-uniformity of the traffic distribution in the sense of the case (2) mentioned in preceding paragraph, the net-
work structure and the traffic condition are assumed as follows:
(1) The network is topologically symmetric;
(2) The traffic capacity of each link is the same;
(3) The routing procedure in each switching station is the same;
(4) The traffic volume flowing between any pair of the stations is the same.

If the foregoing conditions are satisfied, the traffic distribution would be uniform in the entire network and the blocking probability would be all the same in respective links of the network.

For examples of this model, regular polyhedron-type networks, mesh-type networks and ring-type networks may be considered as shown in Fig. 1. In particular, regular polyhedron-type network can be considered as a model of the global network covering the earth.

For routing technique, several selection systems of connecting path are considered as follows:
A) Progressive selection system, in which idle link is hunt in link-by-link at each tandem station to conduct a tandem connection;
B) Foreseeing selection system, in which each tandem station foresees the state of links incident to nearby stations and then selects the next link; and
C) Matching selection system, in which the originating station knows the state of all links in the network and select the connecting path by matching the possible paths with the link states.

The system A) is the most simple and, therefore, is the most practical in the present time, taking account of the limitation on switching functions of the current communication network. The systems B) and C) are advantageous in the efficient use of links, though more complicated controls are needed. It is, therefore, expected that they will be employed as the switching functions of the current communication network. The flexible routing may be the most effective in the system C) and the analysis of this system may reveal the most typical properties of flexible routing.

As mentioned above, the network model discussed in this paper is a symmetrical one to which the matching selection system is applied.

3. ANALYSIS

3.1 DEFINITIONS AND ASSUMPTIONS

For convenience' sake, the following terms are used:
A link is a connection between two switching stations, which may be composed of any number of trunks;
A connecting path is the path which is allowed to carry traffic between the two stations concerned;
The link blocking probability is the probability that all of the trunks in the link are busy; and
The end-to-end blocking probability is the probability that all of the connecting paths between two stations concerned are not available.

To simplify the analysis, we assume that:
(1) arrival of calls is random and distribution of holding time is exponential;
(2) traffic is uniform over the entire network (as mentioned in 2);
(3) links are blocked independently; and
(4) control time for the connection is much less than the average holding time of calls and is negligible.

3.2 METHOD OF ANALYSIS

A network to be analyzed is a symmetrical network with N switching stations and n links. In this network, consider a connecting path Y consisting of 1 links, X1, X2, ..., Xn, where j = 1, 2, ..., n-1 or n. Let X1, X2, ..., Xn and Y represent the symbols as follows:

Xj = 1, if link Xj has at least one available trunk;
Xj = 0, if link Xj has no available trunk;
Yj = 1, if path Yj is available; and
Yj = 0, if path Yj is not available.

Then the following relations hold.

\[ Y_j = X_1, X_2, \ldots, X_n. \]

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Now, consider the connections between two arbitrary stations, Vp and Vq, where \( \mu, \nu = 1, 2, \ldots, N \). To denote such connections, we add \( (\mu, \nu) \) to any symbol, for example, \( Y_{(\mu, \nu)} \), \( X_{(\mu, \nu)} \), etc. We assume that there are \( m(\mu, \nu) \) connecting paths \( Y_{(\mu, \nu)} \), \( Y_{(\mu, \nu)} \), \ldots, \( Y_{(\mu, \nu)} \) (listed in the order of priority of path selection) between \( V_p \) and \( V_q \). New symbols corresponding to connecting paths are defined as follows:

\[ Z_1(a, s) = Y_1(a, s), \]
\[ Z_2(a, s) = Y_1(a, s) Y_2(a, s), \]
\[ \cdots \]
\[ Z_n(a, s) = Y_1(a, s) Y_2(a, s) \cdots Y_n(a, s). \]

Clearly,

\[ Z_j(a, s) \neq Z_j(a, s) (j \neq j'). \]

Hence, more than two of \( Z_{(\mu, \nu)} \) cannot be equal to 1 at the same time. Thus, for call originating from \( V_p \) and terminating into \( V_q \), \( Y_{(\mu, \nu)} \) will be selected if and only if \( Z_{(\mu, \nu)} = 1 \), and a call will be blocked if all of \( Z_{(\mu, \nu)} \) are zero. Consequently, the end-to-end blocking probability for calls from \( V_p \) to \( V_q \) can be denoted as the probability that all of \( Z_{(\mu, \nu)} \) are zero.

Generally, \( Y_{(\mu, \nu)} \) are not independent because they include the same \( x_i (1=1, 2, \ldots, n) \), so the probability of \( Z_{(\mu, \nu)} = 1 \) cannot be obtained directly. As \( Y_{(\mu, \nu)} \) are the functions of \( Xs \) as

\[ Y_{(\mu, \nu)}(X_1, X_2, \ldots, X_n) \]

\[ Y_{(\mu, \nu)}(X_1, X_2, \ldots, X_n) \]

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shown by equation (1), \( Z_j(a,v) \) can be written in the form

\[
Z_j(a,v) = Z_1(a,v) \cdot X_1, X_2, \ldots, X_n,
\]

where \( X_1, X_2, \ldots, X_n \) are independent by assumption (3). Then \( Z_j(a,v) \) can be expanded into the minterm-type expression.

\[
Z_j(a,v) = \sum \frac{N}{N-1} \frac{N}{N-2} \cdots 1 \frac{m(a,v)}{d_j(a,v) q_j(a,v) (b) a(a,v)} (0, 0, 0, \ldots, 0) + \sum \frac{N}{N-1} \frac{N}{N-2} \cdots 1 \frac{m(a,v)}{d_j(a,v) q_j(a,v) (b) a(a,v)} (1, 0, 0, \ldots, 0) + \cdots + \frac{m(a,v)}{d_j(a,v) q_j(a,v) (b) a(a,v)} (1, 1, 1, \ldots, 1).
\]

Any term in equation (5) is exclusive one another. Thus, if \( Z_j(p,b) = 1 \) one and only one of them equals 1 and others 0. Accordingly, the probability that \( Z_j(p,b) = 1 \) is the sum of the probability that each term of equation (5) equals 1. The link blocking probabilities can be estimated to be uniform in virtue of the symmetry of the network and the uniform loads (by assumption (2)). Hence for all 1.

\[
\text{Prob}(X_1 = 1) = 1 - b \\
\text{Prob}(X_1 = 1) = b.
\]

Then we get

\[
q_1(a,v) \equiv \text{Prob}[Z_1(a,v) = 1] = b + b^{n-1}(1 - b) Z_1(a,v) (0, 0, 0, \ldots, 0) + b^{n-2}(1 - b) Z_1(a,v) (1, 0, 0, \ldots, 0) + \cdots + (1 - b)^n Z_1(a,v) (1, 1, 1, \ldots, 1).
\]

The probability that the connection between \( V_\mu \) and \( V_\nu \) succeeds is

\[
p(a,v) = \frac{m(a,v)}{d_j(a,v) q_j(a,v) (b)}.
\]

Finally we get end-to-end blocking probability for a call from \( V_\mu \) to \( V_\nu \) as follows;

\[
B(a,v) = 1 - \frac{m(a,v)}{d_j(a,v) q_j(a,v) (b)}.
\]

The average number of links used for a call from \( V_\mu \) to \( V_\nu \) is

\[
D(a,v) = \frac{m(a,v)}{d_j(a,v) q_j(a,v) (b)}.
\]

where \( d_j(p,v) \) is the length of the connecting path \( y_j(p,v) \), Let \( d(p,v) \) be the offered traffic from \( V_\mu \) to \( V_\nu \). Then, for the entire calls, the traffic carried by each link is

\[
C = \frac{N}{N-1} \frac{N}{N-2} \cdots 1 D(a,v) a(a,v)/n.
\]

where \( n \) is the number of links in the network. As link blocking probability is uniformly \( b \), the load offered to a link is

\[
a = c/(1 - b)
\]

\[
= \frac{N}{N-1} \frac{N}{N-2} \cdots 1 D(a,v) a(a,v) / (1 - b).
\]

Consequently, once we prescribe the allowable connecting paths, we can get the load offered to a link as a function of \( b \). Much study has been made on the relation between load and link block-

\[
\text{Fig. 2 Regular Tetrahedron-type Network}
\]

\[
\begin{align*}
\text{V}_1 & \quad \text{V}_2 \\
\text{X}_1 & \quad \text{X}_2 \\
\text{X}_3 & \quad \text{X}_4 \\
\text{V}_3 & \quad \text{V}_4
\end{align*}
\]
If traffic is uniform, blocking probability of any link is estimated to be \( b \). Then,

\[
q_1(1, 2) = (1 - b) \quad \qquad q_2(1, 2) = b (1 - b)^2
\]

\[
q_3(1, 2) = 2 b^3 (1 - b) + b^4 (1 - b)^2 \quad \qquad q_4(1, 2) = b^6 (1 - b)^4
\]

Therefore, probability that connection between \( V_1 \) and \( V_2 \) will be succeeded is

\[
P(1, 2) = 1 - p(1, 2)
\]

\[
= b - b (1 - b)^2 - 2 b^2 (1 - b)^2 - b^3 (1 - b)^3 - 2 b^4 (1 - b)^4.
\]

The average number of links per call from \( V_1 \) to \( V_2 \) is

\[
D(1, 2) = (1 - b) + 2 b (1 - b)^2 + 2 b^2 (1 - b)^3 + 4 b^3 (1 - b)^4 + 6 b^4 (1 - b)^5.
\]

As the network has a symmetrical structure, \( p(\mu, \nu) = p \), \( g(\mu, \nu) = g \) and \( d(\mu, \nu) = d \) for \( \mu, \nu = 1, 2, 3, 4 (\mu \neq \nu) \). Furthermore we assume that the traffic between every pair of the stations is the same, namely,

\[
a(1, 2) = a(2, 3) = a(3, 4) = a(4, 1) = a(1, 3) = a(2, 4) = a.
\]

Then,

\[
c = \frac{2}{K} \left( \frac{1}{K} a \right) = 6 a.
\]

Therefore system equations are

\[
\begin{align*}
\frac{a}{1 - b} &= D \\
\frac{b}{K} &= \frac{2}{K} \sum_{i=1}^{K} a_i^{1/1}
\end{align*}
\]

Fig. 3 End-to-end Blocking Characteristics of Regular Tetrahedron-type Network (K = 100)

Fig. 4 End-to-end Blocking Characteristics of Regular Octahedron-type Network (K = 100)

Fig. 5 End-to-end Blocking Characteristics of Regular Hexahedron-type Network (K = 10 and K = 100)
Thus we can get the values of a and b by means of digital computation.

4. RESULTS AND DISCUSSIONS

Flexible routings in three kinds of regular polyhedron-type network shown in Fig. 1 were analyzed. Followings are the results.

4.1 END-TO-END BLOCKING PROBABILITY

Figs. 3 through 5 are the plots of the end-to-end blocking probabilities against to the load offered to the entire network. In the figures, the load is defined such as:

\[ L = \sum_{i}^{N} \epsilon (\mu, \nu) \alpha (\mu, \nu), \]

where \( \epsilon (\mu, \nu) \) is the offered traffic and \( \epsilon (\mu, \nu) \) is the length of the regular connecting path between the stations \( V_{\mu} \) and \( V_{\nu} \). The symbol \( \lambda_{1}, \lambda_{2}, \lambda_{3}, \ldots \) indicates a restriction on the path selection in the flexible routing, where \( \lambda_{1} \) is the length of the largest detour allowable to connect two stations with the distance \( l \). The symbol SIMPLE indicates a simple network where no alternate path is used.

Following properties of the flexible routing are observed from the figures. Under the light load condition, the blocking probability can be reduced nearly to zero by means of flexible routing (normal state). On the contrary, under the heavy load condition, the blocking probability in the flexible routing system rather increases than that in the simple network (congested state). Furthermore, the transition from the normal state to the congested state is very abrupt in the flexible routing system. This tendency becomes more remarkable as the restriction on path selection becomes small and finally the value of the offered load just as the network encounters the congestion is different from that just as the network is recovered from it, i.e., the former becomes larger than the latter. Therefore, once congestion occurs, it does not disappear immediately even if the load is lessened thereafter. Thus the characteristic curve draws the hysteresis loop. When this characteristics is remarkable, such a possibility is induced that the congestion may occur even if the load is considerably light. This is a disadvantage in the network operation.

Comparing the Figs. 3 through 5, the properties above mentioned become more remarkable as the network structures more approach to that of mesh-type network and as \( K \), the number of trunks in each link, becomes larger.

4.2 NETWORK EFFICIENCY

The network efficiency is defined here as the ratio of effective load actually handled in the network to the network capacity. It is slightly different from the efficiency of link, since the links may be used redundantly by the flexible selection of detours. The mathematical expression of the network efficiency is given by

\[ e = \frac{1}{nK} \sum_{\mu=1}^{N} \sum_{\nu=1}^{N} \epsilon (\mu, \nu) \alpha (\mu, \nu) \left( 1 - B (\mu, \nu) \right) \]

where \( \epsilon (\mu, \nu) \alpha (\mu, \nu) \left( 1 - B (\mu, \nu) \right) \) is the effective load between the stations \( V_{\mu} \) and \( V_{\nu} \), and \( nK \) is the network capacity because there are \( n \) links each of which includes \( K \) trunks.

Fig. 6 shows the relations between the network efficiency and the load in the regular hexahedron-type network for the case where \( K=10 \) and \( K=100 \). The relations were obtained by calculating the formula (15) after reading the values of the end-to-end blocking probability and those of the load from the diagrams in Fig. 5.

Fig. 6 has disclosed the followings: In general, the network efficiency increases monotonously with the increase of load. In such a network, however, that the very large detour is allowed, the network efficiency rather decreases with the increase of load in the congested state. This is because that the number of used links per call increases by use of such large detour and the network cannot afford to connect so many calls in the congested state. Thus the flexible routing allowing very large detour is disadvantageous under the heavy load condition.

When \( K \) is small, the network efficiency does not so decrease even if the large detour is allowed. Therefore, it is concluded that the flexible routing is very effective from the viewpoint of the efficiency as well as the service quality.
4.3 HYSTERESIS CHARACTERISTIC

As mentioned in preceding sections, the hysteresis characteristics appear when the large detour is used. It follows that the network does not encounter the congestion till the load increases up to a certain level, but the congestion does not easily disappear even if the load decreases, once the network encounters the congestion.

The occurrence of such phenomena is due to the mathematical fact that the system equations (14) have two or more solutions. The equations (14) are plotted in Fig. 7, where the curves A's correspond to the first equation depending on the parameter \( \alpha \), and the curve E corresponds to the second equation. It is noted that the slope of curves A's is steeper than that of curve B at the right side of the curves, since the number of used links increases near here by use of the large detour. Curves A's are shifted upward as the parameter \( \alpha \) increases. As shown in Fig. 7, there exist three intersections of curves A and E at a certain value of \( \alpha \). In the figure, \( \alpha = \alpha_2 \) is this case and curves \( A_2 \) and E have three intersections \( C_2 \), \( C_2 \), and \( C_2 \). When \( \alpha \) is small, curves \( A_1 \) and E have only one intersection \( C_1 \) existing at the smaller value of b. Hence the network remains in the normal state. On the other hand, when \( \alpha \) is sufficiently large, there exists one intersection \( C_3 \) of the curves \( A_3 \) and E at the larger value of b. Hence the network is in the congestion.

The occurrence of hysteresis phenomena can be explained in physical, as follows. Under a certain load condition, it is possible to imagine two cases:

1. The case where a lot of detours are used and the blocking probability of each link is so greatly increased that the network falls into congestion; and
2. The case where most of calls are handled with the regular connecting paths and the used link is not so many that the network remains in the normal state.

In the former case, the newly offered calls are apt to be blocked in the regular path and then to overflow to the detour. Thus the network tends to be more congested. In the latter case, on the contrary, the blocking probability of each link is so small that the regular path is almost always available. Therefore, overflow to the detour seldom occurs and the network retains the normal condition. As found from these considerations, once the network is in the normal (or congested) state, it tends to retain the same state under some special load conditions.

5. FURTHER ANALYSIS OF HYSTERESIS CHARACTERISTIC

5.1 MODEL OF THE NETWORK

In this paragraph, a mesh-type network model with \( N \) switching stations, shown in Fig. 8, is considered to quantitatively study the hysteresis characteristic appearing in the network to which the flexible routing technique is applied. Since it is of mesh-type, the total number of links is,

\[ n = \frac{N(N - 1)}{2} \]

![Fig. 8 Mesh-type Network with N Stations](image)

Now we shall here assume that the following case:

1. There is the same traffic between any pair of stations;
2. The regular connecting path is the straight link connecting the originating and the destinatting stations; and
3. For alternate connecting paths, all the paths with length 2 are allowable (there are \( N \)-2 alternate paths for each call in this case). That is, the tandem connection with 3 or more links is not allowable.

According to assumptions (2) and (3), every connecting path is independent each others since any path does not contain the same link.

Under these assumptions, the load offered to each link is uniform on the average even if alternate paths are used. Therefore, it could be considered that all the link blocking probabilities are same and equal to b.

5.2 ANALYSIS

It is comparatively easy to analyze this network because every connecting path is independent each others. Let's denote the traffic volume offered to each link by \( a \), and the link blocking probability by \( b \). And put

\[ s = 1 - b \]

Then, for the connection of a call,

- the probability that the 1st path is available
- the probability that the 1st path is not available and the 2nd path is available
- the probability that the 1st and 2nd paths are not available and the 3rd path is available

and so on.
Hence the probability that the connection succeeds is derived as follows:

\[ P = s + b s^2 + b (1-s^2) s^3 + b (1-s^2)^3 s^4 + \ldots \]

\[ \ldots + b (1-s^2)^N s^N \]

\[ = s + b \left( 1 - (1-s^2)^N \right) \]

Then the end-to-end blocking probability is obtained such that

\[ B = 1 - P = 1 - \left( s + b \left( 1 - (1-s^2)^N \right) \right) \]

Since the average number of used links per call is

\[ s + 2 b \left( 1 - (1-s^2)^N \right) \]

the total traffic volume carried by all the links in the network is

\[ C = \frac{N(N-1)}{2} a \left( s + 2 b \left( 1 - (1-s^2)^N \right) \right) \]

where \( d \) is the traffic flow between each pair of the stations. The traffic volume offered to each link is then,

\[ c = C / n = a \left( s + 2 b \left( 1 - s^2 \right) N^{-2} \right) \]

on the average. Therefore, the traffic volume offered to each link is obtained as follows:

\[ a = \frac{c}{1-b} = a \left( 1 + \frac{2 b}{s} \left( 1 - (1-s^2)^N \right) \right) \]

Furthermore, Erlang's equation B holds between a and b such as

\[ b = \frac{a^K}{K!} \left( \frac{K}{a} \right)^{a^{-1}} \]

Equations (16) and (17) must hold simultaneously. Then, we can get the values of a and b as the solution.

5.3 RESULTS

The analysis has been made, hereinbefore, for various values of the number of stations, N, and the number of trunks, K, in each link. As the result of analysis, a characteristic curve of the end-to-end blocking probability having a hysteresis loop, for example, was obtained as shown in Fig. 9.

In this diagram, \( W_1 \) is a load just as the congestion disappears and \( W_2 \) a load just as the congestion appears. The difference between \( W_1 \) and \( W_2 \) roughly indicates the approximate shape of the hysteresis loop.

![Hysteresis Diagram](image)

Fig. 9 Illustration of Typical Blocking Characteristic

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6. CONCLUSIONS

The behaviors of some symmetrical networks have been analyzed and discussed for the case where flexible routing technique is introduced. The major results are followings.

1. The flexible routing is advantageous under the light load condition in the sense that the call loss can be reduced to extremely small, while it is disadvantageous under the heavy load condition. Thus the flexible routing is recommendable in such a light loaded network where the extremely high service quality is required.

2. It is not so significant to make an extremely large detour even under the light load condition.

3. The flexible routing is very advantageous in a network where the connection between stations is composed of comparably small number of trunks, i.e., \( K \) is small.

4. The congestion occurs quite abruptly when the large detour is allowed. It is disadvantageous for safe and stable operation of the network.
There would appear a sort of hysteresis characteristic in the relation between the load and the appearance/disappearance of the congestion. That is, the congestion once occurred will not disappear even if the offered traffic decreases down thereafter.

Thus it is concluded that the flexible routing is advantageous under a certain condition, even if the traffic distribution is uniform on the average. But paying attention to the abrupt occurrence of congestion, such a network management as the suppression of flexible routing based on a careful traffic supervision is necessary.

It attributes to the use of simple network models that the properties of the flexible routing have been quantitatively clarified. Although the actual network has more complicated structure, the fundamental properties are the same as those obtained here. It is desired that the results will contribute to further studies of routing problems and network designs.

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