Efficient Ethernet Ring Mesh Network Design

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***Abstract*—Ethernet ring protection (ERP) is an emerging solution for carrier-grade optical Ethernet networking developed as an ITU-T recommendation. The most recent development of the ERP technique provides multi-ring protection in a mesh packet transport network. The ERP configuration and capacity planning in a ring mesh topology can be optimized in the selection of the interconnected ring hierarchy and logical loop prevention block positions. This paper reports the first investigation to understand the designing principles of protected Ethernet ring mesh networks and proposes an optimized design scheme for cost-effective and reliable ERP networking.**

***Index Terms*—Communication system fault tolerance, communication system planning, network reliability, optical communication, ring protection.**

I. Introduction

THE Ethernet has become a dominant network application with the local area networks (LANs). Recently the new development of carrier-class Ethernet has started to compete with conventional large-scale networking technologies such as SONET/SDH networks [1], [2]. Carrier-class optical Ethernet overcomes the networking limits of generic Ethernet LANs by introducing the new standards for various service-type supports, enhanced scalability, operator manageability, and reliability. Various virtual Ethernet service types with different quality of service (QoS) can be provided by the IEEE 802.1Q Standards [3], [4], and Provider Backbone Bridge-Traffic Engineering (PBB-TE) of the IEEE 802.1Qay standards provides operator-class networking for scalability with operator network management capability [3], [5]. Generic Ethernet tools for the operation, administration, and maintenance (OAM) have been introduced by the IEEE 802.1ag Standards [3] and the ITU-T Y.1731 Recommendation for operator manageability [6]. Linear and ring protection schemes using Ethernet generic functions are introduced in the ITU-T G.8031 [6] and G.8032 [8] Recommendations, respectively, to provide reliability for Ethernet services. This collective set of carrier-class optical networking will become a strong candidate to replace the legacy SONET/SDH networks in the near future. The ITU-T G.8032 Recommendation for ERP is the most recent carrier-class optical Ethernet scheme, rapidly gaining its importance in the access and enterprise networking applications [8], [9]. The ERP can provide cost-effective wide-area multipoint connectivity and highly reliable protection with guaranteed protection time less than 50 ms in a 1200-km ring with up to 16 ring nodes [8], and further optimized protection schemes have been introduced in [9]–[13]. As it is an Ethernet-generic technique based on IEEE 802.3 MAC, it is fully compatible with all other Ethernet standards. Therefore, it harmonizes well with other networks and can provide feature-rich services such as differential QoS, E-LINE, E-LAN [14], and OAM functionalities by using existing standards. In the early standard recommendation, ERP provided users with very limited functionalities and network topologies [9]. Then, it advanced in the second version of the recommendation, which can support various user commands such as manual and forced switching and protect services over complicated mesh topologies [8].

However, those advancements of ERP did not come for free; system operational principles became unique and different from other protection schemes [15], and so did the Ethernet ring network design. The issues of ring hierarchy design, capacity dimensioning, and idle-state link block positioning are either newly introduced or becoming more complicated. In this paper, therefore, we introduce an efficient Ethernet ring network design scheme in terms of reliability and cost-effectiveness based on comprehensive understandings of the ERP operation principles. The remaining part of this paper is organized as follows. In Section II, we review the operation principles of a multi-ring ERP. Then we propose a reliable and cost-effective network design in Section III, and evaluate the ERP network designs with typical network reference models in Section IV. Then, we conclude our work in Section V.

II. Principles of Ethernet Ring Protection

The loop prevention requirement is one of the fundamental attributes of generic Ethernet standards [16]. In an idle state of a protected Ethernet ring, the ERP loop prevention mechanism blocks one of ring links on each ring, forming a logical tree for the idle state, i.e., idle state tree, and that particular link block on each ring is called the ring protection link (RPL). When a failure happens on a link or at a node, the ERP loop prevention mechanism forms a new logical tree, i.e., protection state tree, by blocking the failed ring link and unblocking the RPL on the failed ring to provide protection paths.

Once a loop-free topology is guaranteed by the ERP loop prevention mechanism, every node starts to learn the new topology to route user demands. It can be achieved by source address learning, where the source address and receiver port number of a received Ethernet packet are recorded into the Ethernet packet filtering database (FDB). A consistent set of FDBs of all Ethernet ring nodes can provide routing in the loop-free topology [16]. When a topology change happens due to failures, an Ethernet ring network should clear all FDB information (FDB flush) of all nodes, and reacquire the

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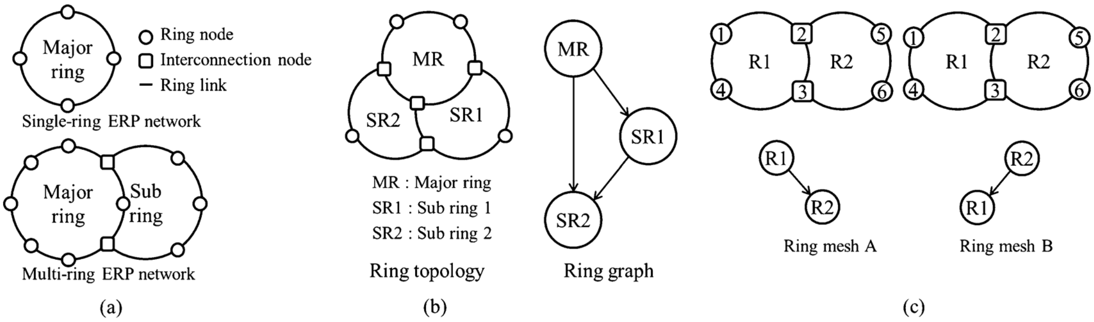


Fig. 1. ERP system architecture. (a) ERP system configurations, (b) Ring topology hierarchy and the corresponding ring graph representation, (c) Different ring hierarchy designs over an identical multi-ring mesh topology.

FDB information by the source address learning. During this period, the Ethernet packets with destination addresses not yet known to the FDB are broadcast over the network to guarantee destination reachability. This broadcasting behavior forms a transient traffic surge referred to as flooding, which can degrade network performance. This phenomenon is rigorously studied in our previous works [11], [12] in terms of link utilization and end-to-end delays.

The main functions of the ERP scheme standardized by the ITU-T G.8032 Recommendation consist of the management of the RPL for loop prevention and protection switching, detection and notification of a failure, and signaling for FDB flush [8], [9]. The G.8032 ERP Recommendation also provides interconnected multi-ring protection. When multi-rings are interconnected to form a ring mesh with a proper loop prevention scheme, the network maintains overall a tree in the idle or protected state. Hence, ERP replaces the conventional Ethernet spanning tree protocol (STP) of the Ethernet bridge. The ERP provides protection switching within the guaranteed switching time of 50 ms while the STP reconfiguration time takes as long as a few seconds. In the following subsections, we investigate on ERP network architecture and operation principles in details.

A. ERP Network Architecture

Basic elements comprising an ERP network are an Ethernet ring node and a ring link. The Ethernet ring node has two ring ports to connect two immediate neighbor ring nodes via independent ring links as if people can cast the circle by hand in hand. For interconnected ring mesh topologies, special ring nodes called interconnection nodes with multiple ring ports are introduced. In an interconnection node, two ring ports are used to form a circle as the ring node, and the others are used to connect other sub rings as we will discuss in the following.

An ERP network consists of two types of interconnected rings: Major ring and sub ring. A major ring can form a stand-alone single-ring ERP network and can be expanded by sub ring interconnections to form a complex multi-ring mesh topology, which means that at least one major ring is required to form an ERP network. A sub ring has the shape of an arc or a segmented arc so that its ends are connected to two interconnection nodes of other rings, including major rings and other sub rings, for interconnections. Being connected to other rings, a sub ring has an option to have a virtual connection to close the arc to form a virtual ring.

Fig. 1(a) shows a single-ring ERP network using one major ring and its expansion with a sub ring interconnection. Sub ring attachment to an existing ERP network introduces a ring hierarchy concept in the ERP ring mesh. As for the ring hierarchy, a ‘lower ring’ which is a sub ring is attached to an ‘upper ring’ that can be either a major ring or another sub ring. We use a directed graph representation to describe a ring hierarchy. In this graph, each vertex indicates a ring, and each edge indicates the directed interconnection relation from an upper ring to its lower ring. Fig. 1(b) shows an example of a nested ring hierarchy and its corresponding directed graph. In this example, sub ring 1 is attached to the major ring, and sub ring 2 is attached to the major ring and sub ring 1, and thus the major ring is the upper ring of the other two, whereas sub ring 1 is an upper ring of sub ring 2. An important notion of the ring hierarchy is that an upper ring shares its network capacity with lower rings for the traffic into and out of the lower ring. In addition, an upper ring provides connection within its lower ring when the lower ring is bisected due to the ERP block.

In a multi-ring mesh topology, there are many possible ring hierarchies depending on which rings we choose as major rings and sub rings, and a network operator can choose one of many possible ring mesh hierarchical designs. A simple example can be found in the Fig. 1(c). In this example, the network consists of 6 ring nodes and 7 ring links. There are two ring hierarchy design candidates, ring meshes A and B. In the ring hierarchy design of ring mesh A, ring R1 is chosen as the upper major ring forming circle consisting of four links 1-2, 2-3, 3-4, and 4-1, whereas in ring mesh B, ring R1 is chosen as the lower sub ring, forming arc consisting of three links of 1-2, 3-4, and 4-1. In summary, a multi-ring mesh can have various hierarchy designs, and each has different link ownerships for protection switching and requires different capacity dimensioning.

B. ERP Network Loop Prevention Principle

The fundamental principle of the ERP loop prevention is that each ring maintains one of its links blocked at all times. Such ERP block is provided by an RPL block or protection switching block under a link or node failure. The RPL block used in an idle state can be a part of network planning because an RPL can be selected by the operator; other blocks happen randomly.

In an interconnected ring mesh, a ring hierarchy determines unique ownership of links among rings. Hence, a different ring hierarchy requires a different set of RPL block positions in an idle state. An illustrative example is shown in Fig. 2(a). Under

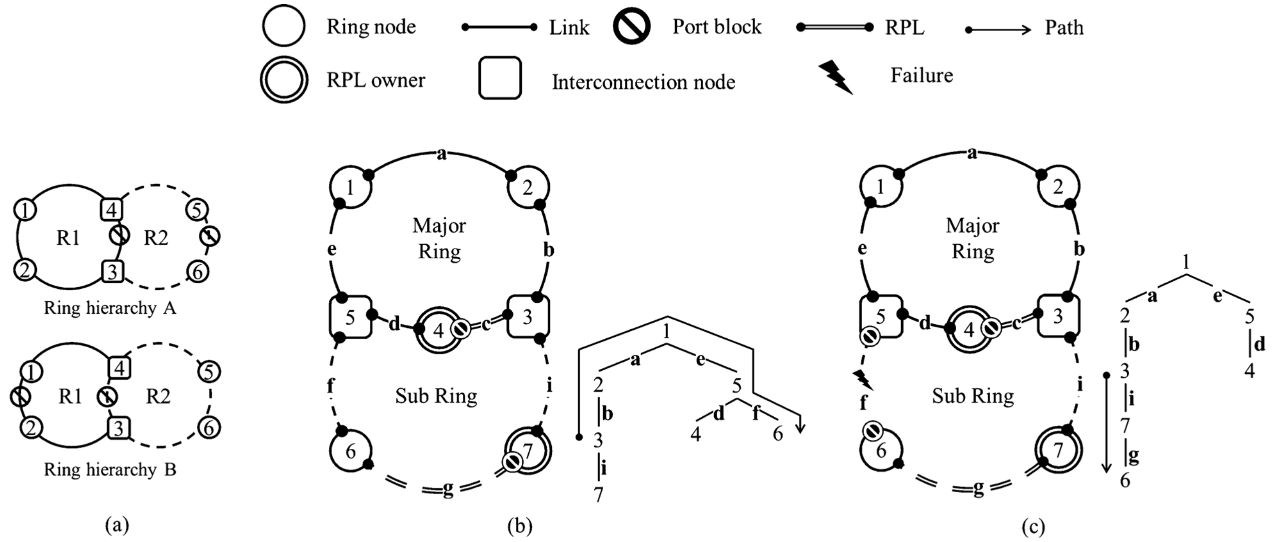


Fig. 2. Examples of ERP protection switching from an idle state (b) to a protection state (c). (a) Example sets of link positions under different ring hierarchies, (b) Idle state, (c) Protection state.

ring hierarchy A, the choice of RPL blocks on links 3-4 and 5-6 is feasible. On the other hand, under hierarchy B, it is not feasible as links 3-4 and 5-6 are conjoined in the same ring R2, and thus ring R1 has no blocks. Even though it eliminates loop formation, it is obviously a violation of the ERP switching operation principle of "one link block each ring". In order to resolve this problem, RPL blocks should be placed on links 1-2 and 2-3 in hierarchy B. Hence, RPL block positions should be chosen after a ring hierarchy choice.

Once each RPL block position is determined, the RPL block is managed by a ring node called RPL owner, which is a node adjacent to either end of the RPL. An RPL owner node blocks its port to the RPL so that no traffic is forwarded on the RPL. When the initial RPL blocks are set in a ring mesh, the topology forms a logical tree, i.e., an idle state tree. Accordingly, the path for any pair of source and destination nodes is uniquely determined. Subsequently, the Ethernet forwarding engine at every node starts to collect FDB information from the traffic by the source address learning as aforementioned. Once FDBs of all nodes finish learning, the traffic pattern reaches a steady state. This transient behavior is extensively studied and reported in [12].

In order to describe the protection switching behavior in an ERP ring mesh, consider an example shown in the Fig. 2(b). The network consists of two rings, one major ring and one sub ring, and each has its own RPL and RPL owner node. By blocking the RPLs c and g, a tree for the idle state is established as shown in the right hand side. In the tree, the user demand from node 3 to node 6 is routed though links b, a, e, and f.

ERP protection can protect a network against at most one link or node failure on each ring, as a ring inherently has a min-cut of two. Hence, we consider only the cases where each ring has at most one link or node failure. If a link failure occurs on a link other than the RPL, we no longer need to block the RPL as the failure becomes another link block that prevents loop formation. Therefore, upon detecting the link failure, the RPL owner of the failed ring unblocks the RPL to form a protection service tree. In order to illustrate this behavior, consider that a link failure happens on the link f of the sub ring in Fig. 2(c), and the ERP mechanism of the failed ring moves link block from the RPL to the failed link. As a result, a protection state tree is established as in the right hand side, and the Ethernet forwarding function reroutes user traffic from the node 3 to the node 6 through the links i and g.

In this section, we investigated architecture and operation principles of the ERP ring mesh with representative examples, and here we can have the following three important observations. First, protection switching changes topology. Accordingly, the traffic pattern change requires different link capacities for different protection states. In order to provide guaranteed protection, every link should be installed for the maximum traffic amount in all possible protection states including the idle state. Second, due to the ERP operation principle, each ring hierarchy defines uniquely which link block belongs to which ring, and also requires different link capacities for protection. Third, RPL positions determine link loads in the idle state. Hence, we can choose RPL positions in such a way to minimize idle-state link loads, and hence we can maximize protection reserve capacities for the support of unprotected best-effort traffic as an additional service.

III. Efficient Design of Ethernet Ring Network

Designing a protected ERP ring becomes a unique problem because of the nature of hierarchy design and RPL arrangement of multiple rings. The optimal hierarchy design has a minimum cost for protected service provisioning, while the optimal RPL arrangement can maximize the best effort service capacity in the idle state. Here, we introduce a concise dimensioning strategy for protection capacity dimensioning, cost-effective ring hierarchy designs, and optimal RPL positioning.

A. Protection Capacity Dimensioning

Capacity dimensioning is an important and fundamental issue in network designs. A network should have 1) a large enough capacity to serve the given user demands and at the same time

2) a minimized capacity under the constraint of cost. In dimensioning link capacity for protected packet services, we consider two classes of services: guaranteed and best-effort services. In order to differentiate the two services, the guaranteed service traffic is handled with higher priority than the best-effort service traffic. The guaranteed service is protected in a way by being preemptive in taking available network capacity while the best-effort traffic can be discarded when network capacity is short. The goal of our ERP ring mesh planning consists of the following concerns:

1) For a given guaranteed service demand, the protection link capacity dimensioning is minimized, and
2) For a given protection capacity dimensioning, the capacity of the best-effort service in the idle state is maximized.

The second goal for a maximum best-effort service is a unique and novel concept that is introduced due to the degree of freedom in the assignment of RPL positions in an ERP ring mesh.

In the process of capacity dimensioning, we can find the minimum capacity requirements for guaranteed services [17]. As we discussed in Section II, link loads change on protection switching, and therefore, the capacity requirement of a link is determined by the maximum link traffic of guaranteed services under all possible choices of the ring mesh hierarchy and the block position on every ring, considering the block as all possible protected failure, i.e., a single failure each ring. The combination of these two variables generates a quite different optimization search space from that of a conventional mesh protection problem. Then, as the next step, the maximum available capacity for best-effort services is analyzed, which is a protection link capacity reserve in the idle state after granting the guaranteed service. Hence, the minimization of the idle-state link traffic for a given guaranteed traffic by an optimal choice of the RPL position of each ring maximizes the amount of protection capacity reserve. Here, we provide a guideline of capacity dimensioning of an ERP ring mesh.

To begin with, we define network parameters in a network graph of $\boldsymbol{G}(\mathbf{V}, \mathbf{L})$ as follows. Let $\mathbf{V}$ and $\mathbf{L}$ be the sets of all nodes and bidirectional physical links, respectively, in the network, such that $\mathbf{V} = \{v \,|\, v = 1, 2, \ldots, V\}$ and $\mathbf{L} = \{l \,|\, l = 1, 2, \ldots, L\}$, where V and L are the total numbers of nodes and links, respectively. Each link is either blocked or unblocked depending on the RPL arrangement or failure. Let $\mathbf{S}_k$ be a binary link state vector, such that

$$\mathbf{S}_k = \{S_{k,l} | S_{k,l} = 1 \text{ for blocked link; otherwise}, 0, l \in \mathbf{L}\} \quad (1)$$

indicates the link states whether or not the link block is set. Then, $\boldsymbol{S} = \{\mathbf{S}_k \,|\, k = 1, 2, \ldots K\}$ is the set of all possible K different link block states that comply the constraint of one block each ring. Remind that a block is the representation of RPL block, block due to a link and node failure, or other protection switching block. Each link block state vector $\mathbf{S}_k$ uniquely determines forwarding paths and the corresponding link loads for a given user traffic demand because each $\mathbf{S}_k$ constructs a tree topology according to the ERP ring mesh operation principle. The link load on link l is the total amount of user traffics on the link for a certain block state of $\mathbf{S}_k$, which is denoted by $\lambda_l(\mathbf{S}_k)$. Let C_l and W_l be the capacity and optimization weight of link l, respectively. Our objective of capacity dimensioning is

$$\min_{\mathbf{S}_k} \sum_{l=1}^{L} C_l W_l \quad (2)$$

subject to

$$C_l \geq \lambda_l(\mathbf{S}_k) \quad \text{for all } k \in \{1, 2, \ldots, K\}. \quad (3)$$

The optimization weight W_l can represent the cost of link l, such as the length of the link. For the evaluation of (3), we assume user demands are given and apply exhaustive search for $\mathbf{S}_k$. Then, one can find the maximum load on link l, $\lambda_l(\mathbf{S}_k)$ for the optimal $\mathbf{S}_k$, and it determines the link capacity requirement of C_l. In this way, C_l can reserve enough protection capacity for guaranteed services under all possible topologies.

As an example, assume that there is a single-ring network consisting of four ring nodes, as shown in Fig. 3. User demands are given in the upper right-hand side table. In this example, the lengths of all links are the same, and thus we set $W_l = 1$ for all l. Then, we have $\mathbf{V} = \{1, 2, 3, 4\}$, $\mathbf{L} = \{1, 2, 3, 4\}$, and there are eight possible link state vectors that protect the ring from a single link or node failure: $\mathbf{S}_1 = \{1, 0, 0, 0\}$, $\mathbf{S}_2 = \{0, 1, 0, 0\}$, $\mathbf{S}_3 = \{0, 0, 1, 0\}$, $\mathbf{S}_4 = \{0, 0, 0, 1\}$, $\mathbf{S}_5 = \{1, 0, 0, 1\}$, $\mathbf{S}_6 = \{1, 1, 0, 0\}$, $\mathbf{S}_7 = \{0, 1, 1, 0\}$, and $\mathbf{S}_8 = \{0, 0, 1, 1\}$. Here, a node failure corresponds to two adjacent link failures, so that $\mathbf{S}_5$ through $\mathbf{S}_8$ indicate node failures. If we assume that $\mathbf{S}_1$ is the link block arrangement for the idle state, then each link load corresponding to S_1 is $\lambda_l(\mathbf{S}_1)$, and from (2), the minimum traffic load dimensioning for the idle state is achieved by

$$C_l^{(1)} = \lambda_l(\mathbf{S}_1) \quad (4)$$

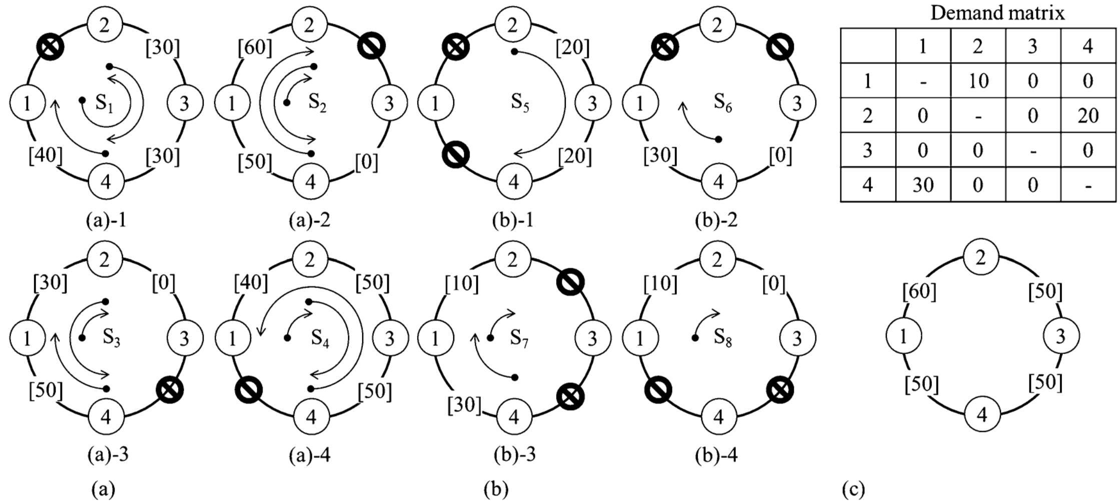
Fig. 3(a) and (b) shows network capacity requirements for link or node failure scenarios. If we plan link capacities for the minimum requirement for the idle state (4), then it would not be survivable because there exist certain link l and link block state $\mathbf{S}_x$ such that $C_l^{(1)} < \lambda_l(\mathbf{S}_x)$. This observation makes a requirement that the capacity of link l is determined by the maximum of $C_l^{(k)}$'s, and we can derive a protected capacity dimensioning as

$$C_l^* = \max_{k \in \{1, 2, \ldots, K\}} \{\lambda_l(\mathbf{S}_k)\}, \quad (5)$$

which is the solution for (2) with all $W_l > 0$, because the capacity of each link is determined independently from the weight as there is only one unique routing for each flow in a tree topology. Since (4) is the capacity requirement for the idle state, $C_l^* - C_l^{(1)}$ is considered as the capacity reserve for protection, which is available for best-effort services.

Fig. 3(c) is an example of the protection capacity dimensioning for a 4-node single ring network. It shows links 1-2, 2-3, 3-4, and 4-1 should have a capacity of 60, 50, 50, and 50, respectively, to provide protection switching.

When multiple link or node failures occur, a network can be segmented and not all user demands can be served. Hence, a multiple-failure instance introduces a decreased amount of



	1	2	3	4
1	-	10	0	0
2	0	-	0	20
3	0	0	-	0
4	30	0	0	-

Fig. 3. An example of the protection capacity dimensioning procedure for protection: User demands are given in the table in the upper-right. The numbers in the brackets in (a) and (b) indicate the traffic loads λ_l of the links for different block positions. The bracketed numbers in (c) shows the capacity dimensioning to provide protected services considering all possible positions of blocks and failures. (a) Single-link failure scenarios, (b) Single-node failure scenarios, (c) Reliable capacity dimensioning.

traffic load, and dimensioning by (5) is enough to cover traffic loads under a multiple failure condition.

B. Interconnected Multi-Ring Hierarchy Optimization

In the previous section, we introduced a protected link capacity dimensioning method for single-ring network protection. In this section, we investigate the ring hierarchy design for a mesh Ethernet ring network where various hierarchy candidates are available.

Let $\mathbf{R}$ denote a set of rings forming a ring mesh network, such that $\mathbf{R} = \{\mathrm{R}_r \,|\, r = 1, 2, \ldots, R\}$, where R is the total number of rings. A directed graph $\boldsymbol{H}(\mathbf{R}, \mathbf{E})$ describes an arbitrary ring hierarchy design, where vertices $\mathbf{R}$ and directed edges $\mathbf{E}$ represent rings and their directed interconnection relations as the vertices and edges respectively, as aforementioned in Fig. 1(c). For a given $\mathbf{R}$, many different choices of $\mathbf{E}$ exist. Hence, we can consider a set of $\boldsymbol{H}$ that includes all possible hierarchy design graphs such that $\boldsymbol{H} = \{H_z(\mathbf{R}, \mathbf{E}_z) \,|\, z \in \mathbf{Z}\}$. $\mathbf{Z} = \{1, 2, \ldots, Z\}$, where Z is the total number of possible hierarchy designs.

The ring hierarchy design rule uniquely determines link ownerships. Therefore, a set of links belonging to ring r for given hierarchy design H_z is denoted as $\mathbf{L}_r^z$, then $\mathbf{L}_x^z \cap \mathbf{L}_y^z = \emptyset$ for $x \neq y, x, y \in \mathbf{R}$ which means that every link belongs to only one ring, and $\bigcup_{r=1}^{R} \mathbf{L}_r^z = \mathbf{L}$ for all $H_z \in \boldsymbol{H}$. The corresponding link state vector of (1) is modified as $\mathbf{S}_k^z$, which represents the k-th link state vector under hierarchy design H_z. Furthermore, the set of all possible link state vectors under H_z is denoted as $\boldsymbol{S}^z = \{\mathbf{S}_k^z \,|\, k = 1, 2, \ldots, K_z\}$.

Let's assume that there is a mesh ring network consisting of two rings of six ring nodes and seven links, as shown in Fig. 4. We have $\mathbf{V} = \{1, 2, 3, 4, 5, 6\}$, $\mathbf{L} = \{1, 2, 3, 4, 5, 6, 7\}$, $\mathbf{R} = \{1, 2\}$, and $\boldsymbol{H} = \{\boldsymbol{H}_1, \boldsymbol{H}_2\}$. $\boldsymbol{H}_1$ and $\boldsymbol{H}_2$ are ring hierarchy designs whose major rings are Ring1 and Ring2, respectively. Then, we have $\mathbf{L}_1^1 = \{1, 3, 4, 6\}$ and $\mathbf{L}_2^1 = \{2, 5, 7\}$ for $\boldsymbol{H}_1$, and, likewise, $\mathbf{L}_1^2 = \{1, 3, 6\}$, and $\mathbf{L}_2^2 = \{2, 4, 5, 7\}$ for $\boldsymbol{H}_2$. Now, we elect the RPLs of each ring under $\boldsymbol{H}_1$.

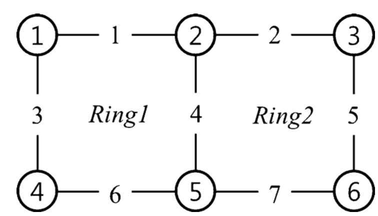


Fig. 4. Example of interconnected multi-ring network.

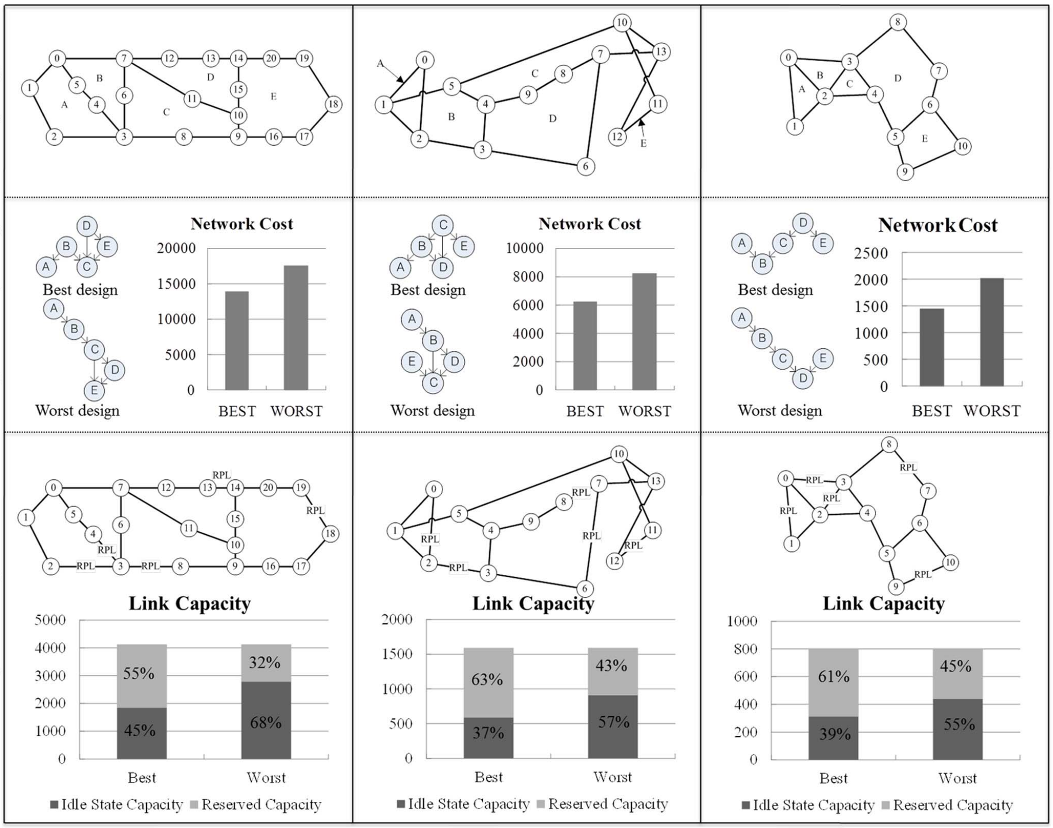
In order to understand the semantics and notations better, we investigate a trial case. For example, we elect links 4 and 5 as the RPLs of ring 1 and ring 2 under H_1 respectively. Then, the corresponding link state vector of the idle state is $\mathbf{S}_1^1 = \{0, 0, 0, 1, 1, 0, 0\}$. However, as we discussed in the Section II, it does not comply with the ERP rule of one block per ring under $\boldsymbol{H}_2$, and hence $\mathbf{S}_1^1 \notin \boldsymbol{S}^2$ because $\mathbf{L}_2^2$ has two blocks, while $\mathbf{L}_1^2$ has no block.

In general, different ring hierarchy designs require different link capacity dimensioning. Since the sets of supported link block states $\boldsymbol{S}^i$ and $\boldsymbol{S}^j$ are different for $i \neq j$, i.e., for different ring hierarchy designs $\boldsymbol{H}_i \neq \boldsymbol{H}_j$, the required capacities of $\max_k\{\lambda_l(\mathbf{S}_k^i)\}$ and $\max_k\{\lambda_l(\mathbf{S}_k^j)\}$ can be different. Then, the objective function for an optimal ring hierarchy design to minimize the network cost is straightforward as follows:

$$z^* = \arg\min_{z \in \mathbf{Z}} \underbrace{\left[\sum_{l \in \mathbf{L}} \overbrace{\max_{k \in \{1,2,\ldots,K\}} \{\lambda_l(\mathbf{S}_k^z)\}}^{\text{required capacity}} \times \overbrace{W_l}^{\text{cost weight}} \right]}_{\text{network cost}}. \tag{6}$$

Then the optimal hierarchy is $\boldsymbol{H}_{z*}$, and from (5), the corresponding capacity requirement for protected service dimensioning is given as

$$C_l^* = \max_{k \in \{1,2,\ldots,K\}} \{\lambda_l(\mathbf{S}_k^{z^*})\}. \tag{7}$$



(a) (b) (c)

Fig. 5. Ethernet ring network design examples of well-known network reference models. The best and worst graphs of H(R,E) are presented in the raw of ring hierarchy designs. (a) ARPA2, (b) NSFNET, (c) COST239.

In the application of this model, the actual cost weight can be considered.

C. RPL Position Optimization

Once the protection capacity dimensioning is achieved, we find RPL positions that can minimize the guaranteed service traffic in the idle state so that the capacity reserve can be maximized. By maximizing the reserved capacity, 1) the network service becomes more resilient to transient burst traffic in the idle state, 2) and the best-effort service capacity can be maximized. The capacity reserve is calculated by the difference between capacities given by (4) and (5) for $\boldsymbol{H}_{z*}$. The working bandwidth of $\lambda_l(\mathbf{S}_k^z)$ is the only variable, and therefore, we can easily maximize reserved bandwidth by minimizing working bandwidth of an idle state. In searching optimal RPL block states, all link block states due to node failures are excluded. Let $S_{\text{Link}}^{z^*}$ be a subset of block states excluding node failure cases, then the object function of optimal RPL positioning is given by

$$k^* = \arg \min_{S_k^{z^*} \in S_{\text{Link}}^{z^*}} \left\{ \sum_{l \in L} \lambda_l \left(S_k^{z^*} \right) \right\}. \tag{8}$$

The RPL positions are determined by $\mathbf{S}_{k^*}^{z^*}$. Note that the cost weight is not considered because the selection of RPL positions does not change network capacity investment.

IV. Performance Evaluation

In order to evaluate the impact of optimization for ring hierarchy and RPL selection, we investigate mesh ring network designs for well-known network reference models including ARPA2, NSFNET, and COST239 and evaluate capacity dimensioning efficiency in terms of cost, which is

$$\sum_{l=1}^{L} C_l^* W_l. \tag{9}$$

An ERP model can be directly applied to the ARPA2 network since it originally forms a ring mesh topology (Fig. 5(a)). However, NSFNET and COST239 require selection of rings out of mesh topologies as they do not explicitly form ring mesh topologies. Hence, we define heuristic ring mesh topologies for NSFNET and COST239, as shown in Fig. 5(b) and (c), respectively, in reference to their minimum cost spanning trees and Hamiltonian cycles [18]. The optimality of ring mesh topology selection is left out of the scope of this paper.

Each example of the network in Fig. 5 consists of five rings labeled as A, B, C, D, and E, and has a different interconnection pattern. As aforementioned, ring hierarchy designs are described by directed graphs where vertices and directed edges correspond to rings and interconnection relations, respectively. In order to determine the optimal ring hierarchy $\boldsymbol{H}_{z*}$, the protection capacity dimensioning by (5) and the ring optimization by (6) are applied to all network examples. We assume a uniform user demand that every pair of two nodes has identically one unit of bidirectional traffic. The geometric distance between nodes is used as the cost weight for the link. In order to investigate the difference between the best and worst ring hierarchies, we evaluate the cost for all possible ring hierarchies. As a result, the middle row of Fig. 5 presents the best- and worst-ring hierarchy costs in each network model calculated by (9), which shows that the best ring hierarchy design reduces network costs typically by around 25% compared with the worst one in all three networks. For example, for the best ring hierarchy design for ARPA2 ring D is a major ring which has two sub rings C and E, and, likewise, ring B is another major ring with two sub rings A and C, as shown in the middle row of Fig. 5(a). The result also shows that in general the skewed ring hierarchy designs tend to require higher network costs. This procedure determines the network resource dimensioning including link and node capacities.

As the next procedure to determine optimal RPL positions, we apply the idle-state capacity optimization in addition to the optimal hierarchy designs found in the previous procedure using (8). The optimal RPL positions maximize the best effort service capacity in idle states, using the protection capacity reserve. The resulting working- and reserved-capacity comparisons for the best and worst selections of RPL positions are presented in the bottom row of Fig. 5. Results show that an optimal RPL positioning can provide typically around 60% of the total link capacity for the bandwidth reserve that can be allocated to best-effort services while the worst one does only around 40%.

V. Conclusions and Future Works

An Ethernet ring protection network is a brand-new reliable packet transport technology that was introduced by ITU-T as the G.8032 Recommendation. In this paper, we reviewed the principles of the operation of a single ERP ring and interconnected ERP ring mesh. We have also developed, for the first time, an Ethernet ring mesh network design principle based on comprehensive understandings of the ERP network and system operation principles. Protection switching varies link loads due to the displacement of Ethernet blocks; therefore, each link capacity should be provisioned in such a way to support maximum link loads of all possible topologies by protection switching. Different ring hierarchy designs of an interconnected ring mesh have different capacity requirements. We showed that optimization of an interconnected ring hierarchy can minimize network cost by 25% in typical reference network models.

Once a network capacity is determined, the idle (working) state block positions, or the positions of the RPLs, can be optimized to allow the maximum reserved capacity. The reserved capacity is helpful to increase reliability in terms of packet loss performance in the case of sudden bursts of user demands and can be also used for best-effort services. By choosing appropriate RPL positions that minimize link loads in the idle state, we can allow upto 60% for reserved capacity in typical network models.

For future researches, investigations on ring topology optimization are anticipated. The main challenge in this research subject is finding an optimal logical ring graph from a mesh network. Since each ring can protect only one link or node failure, a ring mesh can be protected against more faults if it consists of a larger number of logical rings; however, more capacity is required as more links are used. Moreover, capacity requirements and network costs can vary for the same number of rings. All these considerations make ring topology decisions complex.

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