Paper

Developing a Ring-Based Optical Network Structure with Glass-Through Nodes

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Abstract—**An important issue in designing optical transport networks (OTN) is security. The concept of 1+1 protection requires to connect each origin-destination(OD)-pair by at least two node-disjoint paths. In the case of a single edge or node failure, the connection of all OD-pairs is maintained under 1+1 protection. On a ring, 1+1 protection is given naturally. Moreover, on rings, the routing effort is typically decreasing. These observations motivate the investigation of ring structures for OTN. When developing a ring structure for telecommunication networks, several subtasks can be identified. Rings have to be designed, OD-pairs have to be assigned to rings, communication among rings has to be defined, a proper flow routing has to be chosen, and rings have to be dimensioned regarding flow capacity. In this paper, we address the first two issues, namely generation of rings and assignment of OD-pairs to rings. Our approach allows to distinguish active and non-active (glass-through) nodes in OTN. Active nodes are equipped with active routing hardware that weakens the optical signal and has impact on feasible ring lengths. Non-active nodes do not influence the optical signal. Although a consideration of active/non-active nodes is important in ring design, only a few references address this issue. We propose an algorithm for generating random ring candidates. Moreover, we present a mathematical model for the assignment of OD-pairs to rings subject to a feasible choice of active nodes. We test our methods using a case of Deutsche Telekom.**

Keywords—*active nodes, interring traffic, optical transport network, ring network design.*

1. Introduction

We consider the development of optical transport networks (OTN) based on ring structures. This research has been motivated by a case of Deutsche Telekom and it has been carried out in cooperation with Deutsche Telekom and T-Systems, Darmstadt, Germany. The ring-based approach is motivated mainly by two facts. In telecommunication networks, the rings provide a stable environment. On a ring, each origin-destination(OD)-pair is connected by two node-disjoint paths. We say, 1+1 protection is ensured. In the case of a single node failure all connections are maintained, i.e., network stability is enhanced by 1+1 protection. Secondly, routing efforts are usually decreasing in rings due to the generally given node degree of two.

Physically, this node degree is realized by *optical add drop multiplexer* (OADM). These hardware devices are located at ring nodes and have basically two tasks: the connection of two edges within a ring and the communication to external sources, i.e., sending and receiving of data from outside the ring. Using OADMs, a ring can be connected to an external network, or, two rings can be linked.

Ring creation is subject to physical limitations. In general, we assume the ring length to be non-bounded. However, the number of nodes on a ring is limited and depends on the ring length. The longer a ring, the less nodes are feasible, as each node and its established hardware does weaken the optical signal. However, we do not have a signal weakening in the case of glass-through nodes, i.e., nodes where the fiber is directly linked without interconnection by active hardware. Thus, in order to compute feasible ring lengths, we have to distinguish *active* and *non-active* (glass-trough) nodes.

A node has to be active if the node creates demand itself, i.e., if it is part of an OD-pair. Active hardware is required to send information from that node to the ring. Moreover, there is a second reason for a node to be active. Due to the physical limitations regarding ring size, typically a set of rings will have to be established to cover all demands in telecommunication networks of realistic size. In the case of multiple rings, communication among rings might be requested. This leads to the discussion of *interring* traffic. Two rings can be connected via joint active nodes using the installed OADMs. Thus, even if a node does not create demand, it might be active to act as interface between two rings, i.e., interring traffic is routed via this node. Note that two rings have to be connected by at least two active nodes as otherwise 1+1 protection would be violated by the single *transit node*.

We consider cost only regarding purchase and installation of equipment. Maintenance is not considered in our approach. The hardware cost arising for equipment of an OTN network is twofold. First, the cost appears for the optical fiber to be installed and it depends on the ring length. Second, active hardware has to be established dependent on the number of active nodes in the network. Moreover, nodes that act as interface for interring traffic require additional hardware that enables the connection of two OADMs on different rings.

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Summarizing, we address the following optimization problem. Given the physical layer of an optical fiber network consisting of nodes and edges, as well as traffic demand for certain OD-pairs, generate a cost-minimizing ring-based network structure containing active and non-active nodes, such that all demand is satisfied.

The list of publications concerning ring network design for OTN is very extensive. See [1] for an overview on optical network design in general and [2] for a mesh-based approach. Closely related to our approach is the cycle cover problem (CCP) [3], or, ring cover problem (RCP) [4]. The CCP aims to find a least cost selection of simple rings such that for a given network all edges are covered. Variations of the CCP are the bounded cycle cover problem (BCCP) [5], the constrained cycle cover problem (CCCP) [6], and the lane covering problem [7]. The BCCP treats problems where the number of edges in a ring is bounded, whereas in the CCCP the number of edges as well as the flow capacity in rings is limited. For the lane covering problem, only a subset of edges in the graph has to be covered. The main difference to our model is that in the CCP and its variants, a cover of *edges* is required. This is due to the fact that for the CCP, network flows have been already fixed in a preprocessing step. Thus, demand is given on the network edges and has to be met by the ring selection. In our setting, however, flows are not fixed in advance. Thus, our demands are still given with respect to OD-pairs. Consequently, we require to cover and connect demand nodes only. In fact, we do not even need to cover all network nodes, but only active ones.

There are a lot more approaches on ring network design, see, e.g., [8]–[13] as a selection. However, in most references a discussion of active and non-active nodes is not considered. This includes the literature on the CCP mentioned above. The number of publications dealing with active nodes in combination with ring network design is scarce. References [14], [15] consider the location of active nodes, when rings are already given. Moreover, [16], [17] present *foundation design*, a model which allows non-active nodes on rings. In this approach, locations of active nodes, as well as the demand loaded onto the ring are already fixed for the candidate ring structures. Then, a cost minimizing set of rings is chosen by an integer programming formulation. However, there is no consideration of detailed interring flows. A survey on ring-based networks is given by [18].

In our research, we focus on a more general approach to include active/non-active nodes in OTN design. We do not predefine demand nor active nodes in a preprocessing step. Rather we combine the selection of rings with the selection of active nodes in an enhanced ring cover approach.

The paper is structured as follows. We present preliminaries on technical notations, input data and solution structure in Section 2. In Section 3 we discuss a separation of the problem into subtasks. We address the first subtask, namely random ring generation in Section 4 and proceed with the second subtask, the coverage of OD-pairs by rings, in Section 5. We finish by presenting a computational study in Section 6 and by giving concluding remarks in Section 7.

2. Problem Settings

In this section, we describe the problem settings in more details. It seems to be worthwhile to start with a short introduction to technical aspects of optical networks. An *optical transmission system* connects transmitters and receivers to an optical transmission medium. In particular, an electrical signal arriving at a transmitter is transformed to a light signal, then it is transmitted over an optical fiber edge and afterwards converted back to an electrical signal at the receiver station. To increase capacity utilization of the optical fiber, wavelength division multiplexing (WDM) is introduced. WDM is a technique that allows to send multiple signals simultaneously over one optical fiber by transferring them to light signals of different wavelength. The necessary hardware components are *optical multiplexer and demultiplexer (short: mux and demux)*, which allow electrical-optical (E-O) and optical-electrical (O-E) conversion. Whenever an optical signal is routed over a *lightpath*, i.e., a sequence of optical edges, signal routing on the traversed nodes has to be organized. Wavelength cross-connects (WXC) handle the routing at nodes. Typically, these hardware components allow to connect two, three or four edges at one node. If a higher node degree is necessary, cross-connects can be joined to systems offering a node degree greater than four. As a particular cross-connect allowing node degree two, we have OADMs. Dependent on length and type of the optical fiber, the optical signal looses power during the transmission. Whenever a certain distance between two cross-connects is reached, *amplifiers* can be used to reshape the signal. However, in this study, we exclude the consideration of this technique and focus on pure OADM installation. In terms of security, for each OD-pair, 1+1 protection has to be ensured. Origin and destination are connected by at least two node-disjoint paths. This ensures maintenance of the connection even in the case of one edge (or even one node) failure. If an OD-pair is covered by a single ring, 1+1 protection is given naturally. However, if traffic is routed over more than one ring it is necessary to ensure that the rings are disjoint. Moreover, rings have to be connected via two transit nodes, at least.

Next, we provide a formal presentation of the given input data. First, we are given a directed network $G = (N, E)$. G is defined by the nodes $n \in N$ and the edges $e \in E$. Moreover, for all edges we define the edge weight $\ell(e) \geq 0$ as the physically given length of the optical fiber edge $e \in E$. Network G presents a macroscopic view on the real telecommunication network: Nodes are estates where hardware is physically installed and a single node might represent more than one hardware unit. Edges correspond to tunnels and each tunnel connects two estates. Thus, a single edge might represent more than one fiber.

Second, point-to-point demands are given for OD-pairs. We define Q to be the set of OD-pairs generating traffic. OD-pairs are symmetric, demand of equal size occurs in both directions. Moreover, demand arises as 1 Gbit and 10 Gbit traffic. Thus, for all $q \in Q$ we introduce d_q^1 and d_q^{10} to denote 1 Gbit and 10 Gbit demand, respectively.

Finally, costs are specified in terms of node cost (dependent on installed active hardware) and edge cost (dependent on edge length). More precisely, we have costs of c_e per kilometer of optical fiber and costs of c_n for each installed OADM unit. Moreover, at transit nodes, additional costs arise for each installed mux-demux, namely c_{tn1} for handling 1 Gbit flow and c_{tn10} for handling 10 Gbit flow. Note that only in this case we have to distinguish between 1 Gbit and 10 Gbit flow with respect to cost. In terms of expenses for installing OADMs or optical fiber, the hardware costs are not influenced by bandwidth.

We proceed by defining required properties of network and solution structures. A *ring* r is defined as a node-disjoint (and consequently, edge-disjoint) closed path. Different rings may share nodes and we denote a set of *candidate rings* by R. Formally, a ring r is given as sequence of its edges: $r = \{e_{r_1}, e_{r_2}, \dots, e_{r_m}\}$ where m denotes the number of edges in r. The *length of a ring* is given by

$$\ell(r) = \sum_{e \in r} \ell(e) \ . \tag{1}$$

The length of a ring (in kilometers) is in principle non-bounded, but, dependent on the number of active nodes on the ring. The more nodes are active on a ring, the smaller this ring has to be due to a weakening of the optical signal. Or, the longer a ring, the less active nodes are allowed for this ring. Given a certain ring r with length $\ell(r)$, the number of active nodes in this ring is limited and we denote the *upper bound on the number of active nodes* in r as $\bar{a}(r)$.

We distinguish active and non-active nodes in the network. A node n is active on a ring r if n contains routing hardware. The only active routing hardware to be considered are OADMs as we generally assume to have node degree of two for establishing rings. A single OADM is able to connect a node only to a single ring. Thus, if a node is active in different rings, one OADM for each of these rings has to be established at the node. On each ring, only a subset of its nodes need to be active. On the other hand, a single node which is part of several rings might be active on some rings and non-active on others.

Interring traffic becomes possible via transit nodes. At these nodes, installation of multiplexer and demultiplexer allow traffic to leave one ring and enter the other ring. To ensure the 1+1 property, each pair of connected rings has to have at least two transit nodes in common. Traffic demand of a certain OD-pair might be routed via several rings, using established transit points. Due to connection of rings via transit points, it appears that flow is using only some parts of a ring. Thus, the edges of a single ring may carry different loads. This has to be respected when dimensioning the rings.

3. Solution Approaches

Solving the described problem includes a number of different subproblems. Rings have to be designed, active and transit nodes have to be chosen and a proper flow routing has to be established. These decisions have to be taken under the light of maintaining feasibility with respect to ring lengths, bandwidth and 1+1 protection. Clearly, these issues do influence each other. For instance, the ring design has impact on a feasible choice of active nodes, or, the choice of transit nodes influences the flow routing. However, to handle this complex problem it will be inevitable to divide the task into smaller portions. We propose the following partitioning into subtasks.

1. Generation of a *candidate ring set R* based on the physically given optical fiber network layer. Each ring is given as a sequence of its edges. Additional ring information like ring length $\ell(r)$ and upper bound on active nodes $\bar{a}(r)$ can be derived throughout the ring generation process.

2. An *extended ring cover problem under consideration of active nodes* has to be addressed. Given the ring candidates, choose a cost-minimizing subset of rings together with active nodes such that all OD-pairs are covered by rings. Interring traffic is not yet considered. That is, OD-pairs have to share a common ring. The limitation of the ring length might lead to feasibility problems if long distances have to be covered for some OD-pairs. Thus, for the extended ring cover, OD-pairs where no common ring is existing in the candidate set are excluded from consideration. These cases are postponed and addressed through a repair approach, see item 5.

3. Redefine the ring structure by allowing *interring traffic* to obtain cost savings. Interring traffic becomes possible for all *adjacent* rings, i.e., rings that share at least two nodes. Interring traffic allows to cover a single OD-pair by a set of connected rings instead of covering it by a single ring.

4. Given the ring structure, choose a proper *ring dimensioning* such that traffic demand is covered by the provided ring capacities. This includes to determine a proper flow routing.

5. *Repair and improvement*. Check for non-covered OD-pairs. Utilize repair methods such as generation and adding of new, suitable rings. Interring traffic can be introduced for this purpose. Moreover, establish improvement techniques, e.g., by shifting nodes between neighbored rings or by generating new rings based on experience on what a "good" ring is.

This comprehensive list of subproblems illustrates the complex nature of the problem. Addressing the complete problem within a single one-step solution procedure looks not

very promising for this setting. Rather we focus on a multi-step method that handles separately the subtasks described above. In the remainder of this paper, we investigate the first two issues, namely items 1 and 2. The remaining issues are left for future and ongoing work.

4. Ring Generation

The ring generation process is a preprocessing step that provides a set of candidate rings as input data for the subsequent optimization procedures. These rings are only given by their edges and do not carry any information on active nodes nor demand.

We follow the approach presented by [4]. In this reference, there is a suggestion for a ring generator based on the fundamental set of rings, resulting from a spanning tree in the network. By joining rings taken from the fundamental set, this method allows to generate all rings in a network. However, the number of rings in a network is growing exponentially and, for realistic settings, a complete enumeration would exceed the computational limits of subsequent optimization processes. Thus, we focus on a random approach that generates a selection of rings.

Next, we present the approach of [4] in more details. Given a network, generate an arbitrary spanning tree T (not necessarily minimal). Such a spanning tree consists of $|N| - 1$ edges. Thus, we have $p = |E| - |N| + 1$ remaining edges in $E \setminus T$. Moreover, whenever an edge $e \in E \setminus T$ is added to the spanning tree T, the resulting 1-tree does contain a unique ring. It is easy to see that for each of the p edges in $E \setminus T$ we obtain a new ring. Thus, p different rings can be obtained from one spanning tree T. The resulting set of rings is called a *fundamental set of rings*. Two rings r_1 and r_2 can be combined into a new subgraph $\bar{r}$ by the following procedure. Include all edges into $\bar{r}$ that are contained in exactly one of the two rings, either r_1 or r_2. Leave away all other edges of r_1 and r_2, i.e., all edges that appear in

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Algorithm 1 : Ring generator

Require: Fiber network $G = (N, E)$, number of iterations k

Ensure: Set of rings R
1: Set $R := \emptyset$
2: Set number of rings per iteration: $p := |E| - |N| + 1$
3: **for** $i = 1, \dots, k$ **do**
4:    Generate a random spanning tree T in G
5:    **for** j = 1, $\dots$, p **do**
6:       Set $e :=$ jth edge in $E \setminus T$.
7:       Set $r :=$ unique ring in $T \cup \{e\}$, see Algorithm 2
8:       **if** $r \notin R$ **then**
9:          $R := R \cup \{r\}$
10:      **end if**
11:    **end for**
12: **end for**
13: Output: R

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both rings. The resulting subgraph $\bar{r}$ might be not a ring. However, it can be shown that all rings of the network can be generated using one fundamental set of cycles and generating all combinations.

As we are not interested in obtaining the complete set of rings in G, we propose the following approach. Generate an arbitrary number of random spanning trees. For each of these trees, build the fundamental set of rings as described above. Add these rings to the candidate ring set R unless they are not already stored in R.

Algorithm 2 : Detect unique ring in subnetwork

Require: $T \cup \{e\}$ containing one unique ring

Ensure: Unique ring r
1: Set $\bar{T} := T \cup \{e\}$
2: Set $\bar{N} :=$ set of nodes adjacent to $\bar{T}$
3: Set $\bar{G} = (\bar{N}, \bar{T})$
4: Set $N^1 := \{n \in \bar{N} :$ node degree of n w.r.t. $\bar{G}$
5:                   equals one $\}$
6: Set $E^1 := \{e \in \bar{T} :$ edge e adjacent to a node $n \in N^1\}$
7: **while** $N^1 \neq \emptyset$ **do**
8:    $\bar{T} := \bar{T} \setminus E^1$
9:    $\bar{N} := \bar{N} \setminus N^1$
10:    Update N^1 and E^1
11: **end while**
12: Output: $r := \bar{T}$

A formal description of the ring generator is presented in Algorithm 1. In this procedure, step 7 needs further specification. How to detect a unique ring in a network $T \cup \{e\}$? We propose the following simple approach, see Algorithm 2. Check the node degree of each node in $\bar{T} := T \cup \{e\}$. As long as there are nodes with node degree one, remove from $\bar{T}$ each of these nodes together with the single adjacent edge. The procedure terminates with the unique ring.

Note that for each ring r obtained through Algorithm 1 we do already have the information on ring length $\ell(r)$ by Eq. (1) and on the maximal number of active nodes $\bar{a}(r)$.

5. Ring Cover Problem

In a second stage, based on the set of candidate rings R, an *extended ring cover problem under consideration of active nodes* (RCP-A) is addressed. RCP-A is the following. Given a set of OD-pairs as well as a set of candidate rings, choose a cost-minimizing set of rings together with active nodes such that each OD-pair $q \in Q$ shares (at least) one ring, where origin and destination of q are active.

Note that the RCP-A is related to the general CCP and its variants BCCP, CCCP, and lane covering. However, there are two main differences between these models. First, it is possible in RCP-A, to distinguish active from non-active nodes, which is not the case for the CCP and its variants. Second, in the CCP demand is already given for the edges, i.e., the flow routing has been already carried out

in advance. In RCP-A, demand is still given for OD-pairs, routing of flow is not fixed.

The RCP-A requires that each OD-pair is covered by (at least) one ring. So far, we do not give the possibility for joining rings and for interchanging traffic between them. The advantage of this approach is obvious: 1+1 protection is ensured naturally. Nonetheless, we might run into troubles if there are OD-pairs that can not be covered by one single ring due to limitations in ring length. Moreover, this approach might be costly as it is likely that we end up with a large number of rings. To deal with the first issue, we recommend a repair algorithm that generates suitable rings, see item 5 in Section 3. Finding such rings is possible for each OD-pair q, unless there is just a single path connecting the origin and destination of q. In this case, 1+1 protection cannot be established and the considered OD-pair has to be treated separately. Addressing the second issue, we refer to item 3 in Section 3. Interring traffic will allow to serve a single OD-pair using a set of adjacent rings. Algorithmic approaches following item 3 will potentially reduce the number or rings and generate a leaner ring network structure.

For each OD-pair q, let nodes $o(q)$ and $d(q)$ denote the origin and destination of q, respectively. Recall that $\bar{a}(r)$ is the upper bound on active nodes on a ring r. Furthermore, let $n^Q = |Q|$, $n^R = |R|$, and $n^N = |N|$ be the number of OD-pairs, rings and nodes, respectively. We denote by the $n^Q \times n^R$-matrix B the relation between OD-pairs and rings. More precisely, let $b_{qr} = 1$ if ring r is able to cover OD-pair q, i.e., if nodes $o(q)$ and $d(q)$ are adjacent to edges $e \in r$. Finally, let $n^Q(r)$ be the number of OD-pairs that ring r is potentially able to cover, i.e., $n^Q(r) = \sum_{q=1}^{n^Q} b_{qr}$.

The following logical tests will serve as a preprocessing step to clean up the input data for the mathematical model.

- For all $r \in R$, check whether r covers at least one OD-pair, i.e, if $n^Q(r) \geq 1$. If not, ring r can be diminished.

- For all $q \in Q$, check whether an OD-pair q is covered by at least one ring, i.e., if $\sum_{r=1}^{n^R} b_{qr} \geq 1$. If not, shift the OD-pair q into a pool of *uncovered OD-pairs* (to be treated later).

The mathematical description of RCP-A is the following. There are three classes of variables. Variables x_{qr} indicate that an OD-pair q is covered by a ring r, y_{nr} indicate that a node is set active on a ring (i.e., hardware that connects n to r is established at n), and z_r indicate that a ring r is used, i.e., if some OD-pair is assigned to r. More precisely we have

$$x_{qr} = \begin{cases} 1, & \text{if OD-pair } q \text{ is assigned to ring } r, \\ 0, & \text{otherwise;} \end{cases}$$

$$y_{nr} = \begin{cases} 1, & \text{if node } n \text{ is active on ring } r, \\ 0, & \text{otherwise;} \end{cases}$$

$$z_r = \begin{cases} 1 & \text{if ring } r \text{ is chosen,} \\ 0 & \text{otherwise.} \end{cases}$$

We establish a set of constraints that ensure a proper interaction of the variables and ensure feasibility.

1. Each OD-pair has to be assigned to exactly one ring:

$$\sum_{r=1}^{n^R} b_{qr} x_{qr} = 1 \ , \quad \forall\, q = 1, \dots, n^Q. \qquad (2)$$

2. If any OD-pair is assigned to a ring r, r has to be chosen.

$$z_r n^Q(r) \geq \sum_{q=1}^{n^Q} x_{qr} \ , \quad \forall\, r = 1, \dots, n^R. \qquad (3)$$

3. If an OD-pair is assigned to a ring r then the origin and destination of that OD-pair have to be active on r.

$$x_{qr} \leq y_{o(q)r} \ , \quad \forall\, q = 1, \dots, n^Q, \ r = 1, \dots, n^R, \quad (4)$$

$$x_{qr} \leq y_{d(q)r} \ , \quad \forall\, q = 1, \dots, n^Q, \ r = 1, \dots, n^R. \quad (5)$$

4. Do not violate the maximal number of active nodes per ring.

$$\sum_{n=1}^{n^N} y_{nr} \leq \bar{a}(r) \ , \quad \forall\, r = 1, \dots, n^R. \qquad (6)$$

Regarding the objective function, we address a minimization of total cost given by the sum of cost for optical fiber (dependent on ring length) and cost for the installation of OADMs (dependent on the number of active nodes).

$$\min c_e \sum_{r=1}^{n^R} \ell(r) z_r + c_n \sum_{n=1}^{n^N} \sum_{r=1}^{n^R} y_{nr}. \qquad (7)$$

Alternative objectives might be discussed. For instance, more detailed cost values c_{nr} could be introduced to model costs for OADMs in dependency of the ring. Another approach could be to remove the hard constraint of covering all OD-pairs, see Eq. (2), and punish violation of (2) by introducing a corresponding term to the objective function. Thus, the selection of expensive rings could be avoided by accepting uncovered OD-pairs.

6. Computational Results

We tested our approach on a real world instance provided by Deutsche Telekom. The input fiber graph $G = (N, E)$ consisted of $|N| = 8,349$ nodes and $|E| = 12,397$ edges. In addition, a total number of $n^Q = 5,132$ OD-pairs has been given; 2761 nodes have a positive demand.

The numerical test included three phases. First, a ring generation has been carried out, see Algorithm 1. Afterwards the resulting data has been cleaned up by the logical tests described in Section 5. Finally, the adjusted candidate ring set has been fed into the mathematical model to

solve RCP-A. The ring generator has been coded in C++ and compiled with the GNU compiler selection gcc 4.3 on a Pentium 4 1.3 MHz Linux workstation with 1 GB of RAM. The mathematical model has been implemented and solved using ILOG OPL 4.2.

Table 1
Results of the ring generator phase

Spanning tree	Newly generated unique rings	Total number of unique rings
1	4049	4049
2	2754	6803
3	2303	9106
4	1990	11096
5	1876	12972

The generation of rings by Algorithm 1 provided a set R of candidate rings with a total of $12,972$ unique rings out of $k = 5$ different spanning trees. Computational time was less than five minutes (wall-clock time). The detailed description of the five iterations produced by the ring generator is summarized in Table 1. With increasing number of spanning trees, the probability to produce duplicate rings is increasing and consequently, the number of new unique rings is decreasing.

Table 2
Rings chosen for the candidate ring set

	Min	Max	Av.	Stdev
Number of nodes	3	80	10.49	10.33
Ring length [km]	3	2182	186.54	277.79

Table 2 provides statistical information about ring length and number of nodes of rings created throughout the ring generation phase. Moreover, Fig. 1 illustrates the frequency of rings with a given number of nodes per ring.
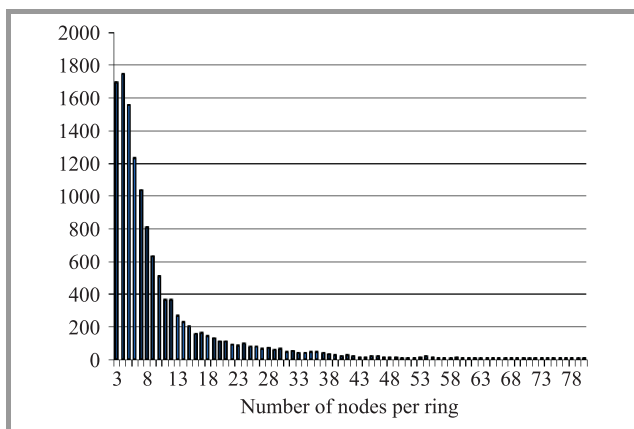
Fig. 1. Ring generation solution: frequency of rings by number of nodes.

In a second step, we clean up the candidate ring set R and the set of OD-pairs Q by logical tests. An OD-pair $q \in Q$ can be covered, i.e., assigned to a ring, only if there exists at least one ring $r \in R$ such that both origin and destination $o(q)$ and $d(q)$ are located on ring r. Moreover, we consider only rings that are able to cover at least one OD-pair.

In our experiments, 2002 rings had to be removed from R by logical preprocessing. We obtained a reduced candidate ring set $R' \subseteq R$ with $|R'| = 10,970$. In addition, the set of OD-pairs needed to be adjusted. We ended up with a reduced set of OD-pairs $Q' \subseteq Q$ of size $|Q'| = 4,420$. We defined the *level of coverage* of a candidate ring set R with respect to a set of OD-pairs Q as $cov(R,Q) = |Q'|/|Q|$. For our test instance, we achieved $cov(R,Q) = 0.86$.

Finally, the implementation of RCP-A, see Eqs. (2)–(7), is the last phase of our computational test. RCP-A aims to detect a feasible and cost minimizing ring cover. The input data is given by the candidate ring set R and the set of OD-pairs Q'. We stopped the solver after a computational time of around one week and took the best feasible solution found so far. Note that optimality of this solution is not proved. The feasible solution contained 784 rings and 1048 active nodes. An active node was active on 2.3 rings at an average.

Table 3
Rings chosen by RCP-A

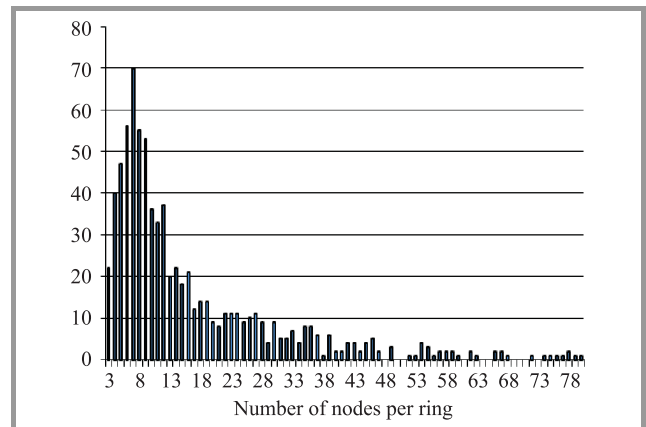|	Min	Max	Av.	Stdev
Number of nodes	3	80	16.50	14.50
Number of active nodes	2	7	3.07	1.39
Share of active nodes	0.03	1.00	0.30	0.20
Ring length [km]	5	2128	305.90	369.99

Fig. 2. RCP-A solution: frequency of rings by number of nodes.

See Table 3 for statistical information on the extended ring cover solution regarding the chosen rings. For an illustration of frequencies of rings with given number of nodes and given number of active nodes, see Figs. 2 and 3, respectively.

On average, longer rings with more nodes have been selected by RCP-A than given by the random candidate ring generator. Regarding active nodes, the solution de-
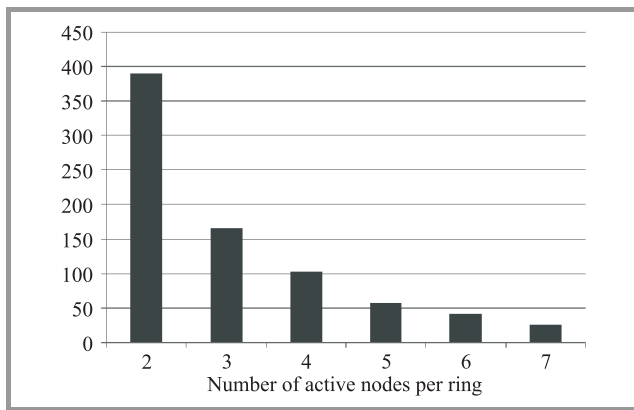
Fig. 3. RCP-A solution: frequency of rings by number of active nodes.
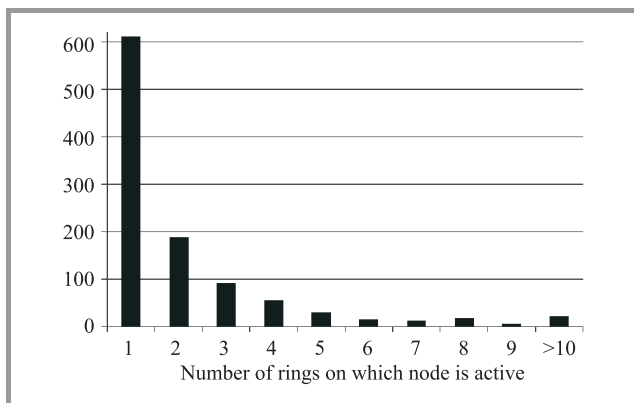

Fig. 4. RCP-A solution: frequency of nodes by number of assigned rings.

livered 2,409 out of 126,888 potential active-node/ring assignments. These assignments refer to unique 1048 active nodes. The majority of these nodes are assigned only to one ring, see Fig. 4. At maximum, one node has been assigned to 39 rings.

7. Conclusion

We investigated two stages of OTN ring network design, namely the generation of rings and the assignment of OD-pairs to rings. The consideration of active and non-active nodes has been included into our approaches. We proposed an algorithm for random generation of candidate rings. Moreover, we presented a mathematical model for assigning OD-pairs to rings such that active nodes are chosen accordingly. While recent discussion on protection also considers issues beyond 1+1 (like 1:n, m:n, see, e.g., [19]) our research addresses important issues with real-world relevance. We tested our approaches using data of Deutsche Telekom, yielding a 86% coverage of OD-pairs by pure rings without interring traffic.

A next step would be to redefine the network structure obtained by RCP-A by enabling interring traffic. The aim is to reduce the number of rings and to obtain a leaner network structure. Moreover, OD-pairs that have been sorted out before RCP-A, as coverage by a single ring was not possible, could now be covered by a set of joined rings. For this matter, satisfaction of 1+1 protection has to be carefully checked. In particular, it has to be ensured that the flow is routed via node-disjoint rings to maintain node-disjoint paths. Putting the ideas forward to more general protection mechanisms could be another step.

Moreover, there is a need to develop the repair and improvement techniques. For instance rings of the candidate set could be merged to create new rings to include uncovered OD-pairs. In addition, the shifting of nodes between existing rings could lead to improvement methods. Finally, a proper ring dimensioning is dependent on a flow routing. A distinction of 1 GBit and 10 GBit demands should be addressed there. This line of research could also re-consider older work making the case for partitioning the overall network design problem into subproblems (see, e.g., [20]). This may also support the idea of solving one model for OD pairs that can be on a common ring and another for pairs that must route traffic over multiple rings.

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