Optimized Ring Identification for an Arbitrary Network Topology and Traffic Matrix

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Abstract—**An optimized algorithm is presented to embed a mesh of rings network in an arbitrary network topology to provide the necessary transport capacity for a given traffic pattern. The network can be characterized by a three-layer model. The first layer defines the ring configuration, the second the connection allocation and the third the connections among the rings. Rings are constructed systematically from faces. It is assumed that a ring provides a full-meshed network with a certain capacity between every node pair. Simulated annealing (SA) is used to optimize the mapping to best fit the traffic demands. For the objective function certain parameters can be considered. It is possible to incorporate boundary conditions, e.g. the maximum number of nodes in a ring in this function. The algorithm is tested on the basis of the COST 239 Pan-European case study as an example.**

Keywords— **ring identification, regular topology, embedding, mesh of ring**

I. Introduction

In transport networks, SDH (Synchronous Digital Hierarchy) or SONET (Synchronous Optical Network) represent the classic transport protocol. On the physical level, wavelength-division multiplexing (WDM) is used for the point-to-point connections to satisfy the demand for transport capacity.

For these networks, ring structures are often used due to their robustness against failures and their simple management. Also, all-optical realizations are feasible due to the simple routing in a ring.

Normally, the design of a communication network for a given topology and traffic matrix is connection-based, i.e. the routing will be computed for every connection. In a second step, the necessary transport capacity is provided. In general, this results in sub-optimal solutions when rings are aspired for the realization. Therefore, in this work a structure-based approach is used: the network will be built up from rings and on the resulting network, the routing is performed.

The mapping of the real-world topologies and the traffic demand on regular structures is a challenging task due to the many degrees of freedom. Jäger proposed a mapping for the all-optical network Gridconnect [1] which has the disadvantage of high computational complexity [2]. In [3], an interesting approach using a genetic algorithm to embed the Manhattan Street Network [4] in a network has been investigated. A survey on virtual topology design algorithms can be found in [5].

The aim of this work is to propose an optimized semi-heuristic algorithm with rather low complexity for the mapping of arbitrary topology and traffic pattern on a mesh of rings. This is a continuation of the work which has been presented in [6]. To justify the approach, an implementation of the algorithm using the C++ library LEDA [7] has been carried out and the "Pan-European Network" of the COST 239 project has been used as a test-scenario.

No particular realization of a ring will be considered here. The ring network is treated as a black box which provides a full-meshed network with a certain transport capacity between the node pairs. For the same reason, protection has been neglected even though this is the main reason to introduce rings.

The algorithm has been developed having the design of a long-haul network in mind. In principle, it is not restricted to that purpose and can be used for all kind of networks where a lot of connections have to be provided e.g., even for computer interconnections. In this case, the objective function has to be adapted to meet the intended design goals.

The structure of the paper is as following. First, a multi-layer graph model is introduced. The ring configuration layer and a systematic way to construct rings out of smaller pieces is presented. Then, the resulting effective graph and the ring connection layer are explained. The routing on the ring connection layer is discussed and compared to a direct routing on the virtual network layer. For the optimization, "Simulated Annealing" (SA) is used. The results for the Pan-European Network are analyzed for different maximal ring sizes. The short summary at the end includes an outlook on further work.

II. Multi-layer graph model

For the description of the network, a three-layer graph model is used (see Fig. 1). The lower layer, referred to as ring configuration layer, contains the real network nodes and the real fiber topology. The actual configuration is a set of rings: each ring consists of a set of nodes and edges of the network.

The second layer is the virtual network layer. It describes the effective, logical topology which results from the set of rings of the lower layer. Here, for every connection request of the traffic matrix, a path through this logical network has to be found.

The third layer is the ring connection layer. The routing between rings is done on this layer. It contains a simplified representation of the connections among the rings in the actual configuration.

The general aim is to minimize the ring configuration and the routing on the virtual network with respect to a given objective function so that all traffic demands are fulfilled and the boundary conditions, e.g. the capacity per link, are not violated.

In the example in Fig. 1, a configuration with four rings on a given network topology is depicted. The other two layers contain the resulting effective graph and the ring connections, respectively.

In this work, only the ring identification and the routing in the logical network is investigated. It is assumed that for the realization of one of these rings, an efficient solution is known (e.g. the Colored Section Ring or an SDH ring). Therefore, for example, the mapping of the resulting channels to distinct wavelengths is not treated. This could be easily integrated in

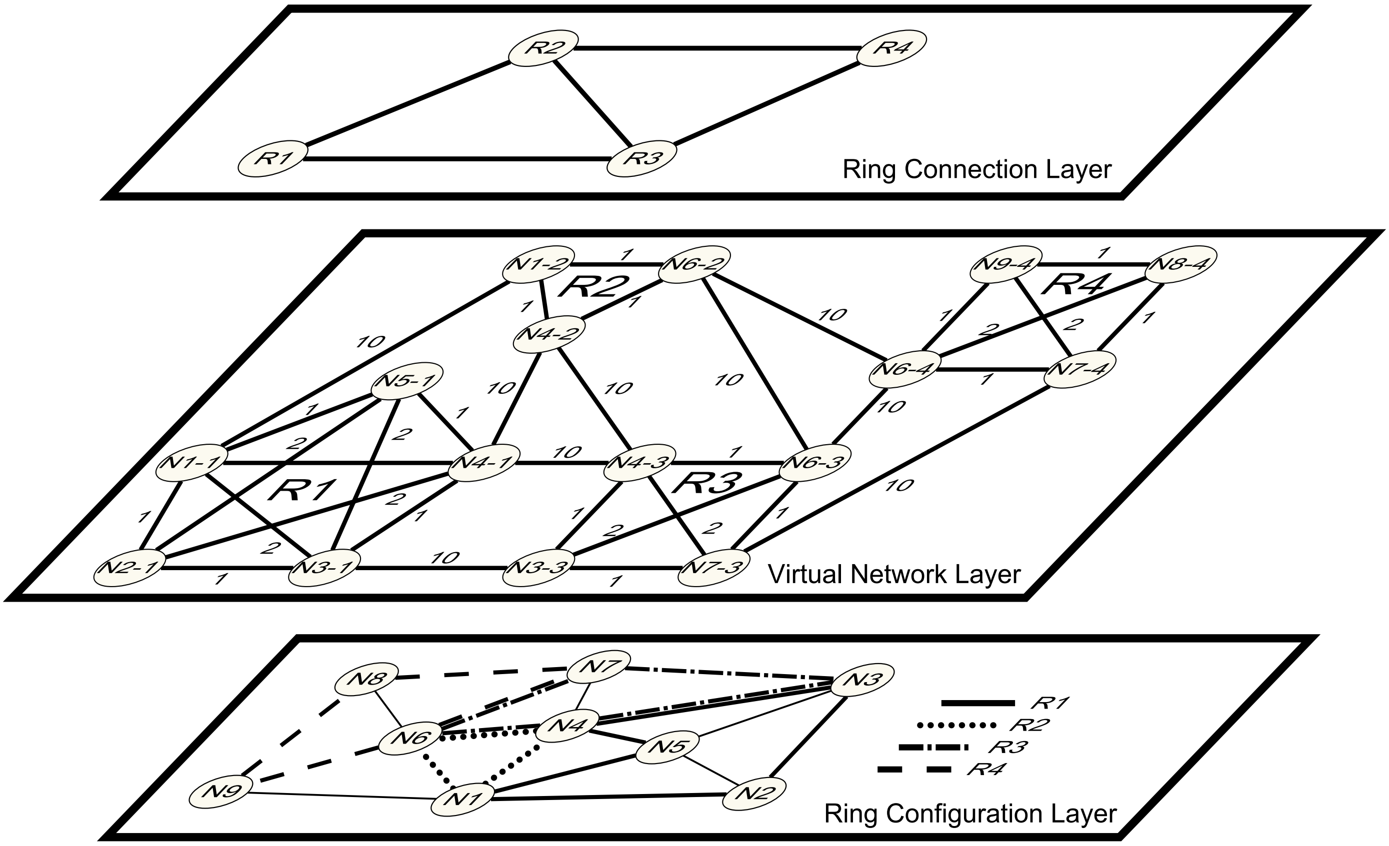

Fig. 1. Three-layer graph model.

the algorithm by adding an additional layer and using one of the known algorithms for wavelength allocation, e.g. “First-Fit” [8].

A. The ring configuration layer

A map is a graph for which the reversal information for every edge is defined. An embedding of a graph is a drawing, where no edge is drawn across a node, images of distinct edges do not cross, and multiple edges between two nodes are embedded in the same manner. A map for which an embedding in the plane exists, is a planar map. A famous theorem of Kuratowski states [9] that every non-planar map contains a subdivision of either a Kuratowski sub-graphs K_5 (complete graph of degree 5) or $K_{3,3}$ (complete bipartite graph with 2×3 nodes). There exist algorithms to find such subgraphs efficiently and to test planarity. By successive removing edges, the graph may be converted in a planar map. This problem is related to graph-drawing and is NP-hard. In the following, always a planar map is assumed. Details on graph theory may be found in [10].

In graph theory, there exists the combinatorial and geometrical concept of a face. A face is a list of edges. To construct a face, one starts at a node, follows the edges, and takes at every node the preceding outgoing edge to the next node until one returns to the starting node (see Fig. 2). It is possible to decompose every planar map into faces with a computational complexity which increases linearly with the number of edges in the graph.

These faces are the building blocks for rings and form a basis for the space of cycles in a graph. Every face is a ring in the network. By the addition of a neighbor face to a ring, the ring may be enlarged. On the other hand, to shrink the ring, one of the faces which share an edge with the border of the ring has to be removed. Some caution has to be taken for both operations. In some special cases, the result is no longer a ring. In Fig. 3, an example for such a configuration is shown. The dashed face can’t be added to the original ring (solid line and black nodes), because the result would not be a ring. However, the addition of the dot-dashed face is possible.

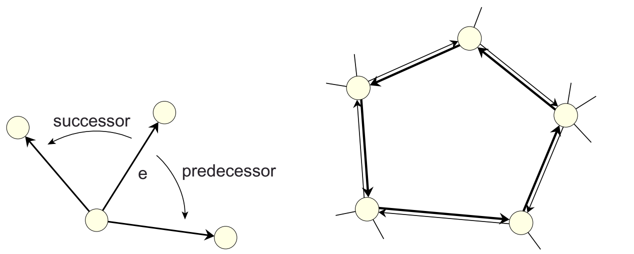

Fig. 2. On the left side, the definition of the successor and predecessor of the edge e is displayed. On the right side, the constructed face and its edges are marked with thick lines.

By using the face concept, it is possible to construct rings in a systematic way with low complexity. Every ring is described by a set of faces. The removal of the last face of a ring destroys the ring. On the other hand, the addition of one face to an empty set creates a new ring.

One configuration of the ring layer stands for a set of rings, or in other words, a mesh of rings with distributed interfaces.

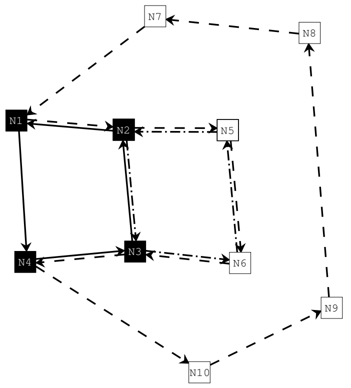

Fig. 3. Problem which may occur when enlarging a ring (solid line and black nodes) by a face.

For a given node configuration and edge topology, all faces may be computed. On the other hand, it is possible to use a triangulation algorithm of the plane for the generation of a triangular mesh when only the nodes and their positions are given to get a starting topology. At the end, some of these links may not be used.

B. The virtual network layer

The ring configuration provides an effective network topology for the connections. Every ring in the lower layer is translated into a complete graph of the virtual network layer. In a complete graph, a direct link exists between every node. Nodes which belong to several rings, create multiple copies in the effective graph, where all copies are connected by a bridging link.

In the example in Fig. 1, the network nodes $N1-1$ and $N1-2$ are the two virtual copies of network node $N1$ in the rings $R1$ and $R2$, respectively.

For the simulation, it is assumed that every ring link has a capacity of four connections. This is e.g. the case for a traffic matrix with granularity of STM-16 ($2.5\,\mathrm{Gbit/s}$) and a ring technology which offers STM-64 ($10\,\mathrm{Gbit/s}$) channels. The connections could be multiplexed using SDH/SONET technology. The bridging links are not limited in the number of connections they can carry.

For the routing, it is necessary to assign a distance to every link. Here, the inter-ring distance is the number of nodes which are passed in the real network topology and the distance for the bridging links is chosen as $d_{bridge} = 10$ in the examples. This takes into account that changing the ring results in a demultiplexing and a multiplexing operation, which is rather expensive. In general, the value of d_{bridge} depends on the ratio between the cost for bandwidth and the cost for multiplexing or demultiplexing, and may even be a function of the network size.

Considering a concrete realization of the rings, it is necessary to incorporate the transmission properties of the physical links into the design process. Therefore, a simple hop-count for the distances in the virtual network is not appropriate in this case. Due to the abstraction from the physical layer, no transport properties are considered in this work.

For every connection request of the traffic matrix, a connection has to be assigned on the effective graph. Since there is the abstraction of the distinct realization of one ring, this is trivial for connections which can be handled within a direct channel of the ring. For the remaining ones (in the following referred to as “hop connections”), a minimization of the path-length is aspired.

Possible paths, e.g. the ten shortest paths, through the network for every node pair may be computed with one of the standard algorithms [11]. In case that the start or the end node belongs to several rings, all virtual copies of it are treated in the same way. This has been the approach used in [6]. The disadvantage of this method is that the virtual network layer contains normally much more nodes and edges than the actual network. In this case, the main computational time during the optimization process is spent for the calculation of the routing on this layer. Consequently, a third layer has been introduced which contains only the connections among the rings. This permits a fast calculation of the routing.

C. The ring connection layer

In this layer, every ring in the configuration is represented by one node. When there is a network node which belongs to two or more rings, an edge between the corresponding ring nodes is added. The routing for ring connections is computed using this representation. The paths for the virtual network layer for the hop-connections can be deduced from the paths in the connection ring layer.

In the example under consideration, for a path from $N2-1$ to $N8-4$, the ring path $R1-R3-R4$ may be expanded in four different ways:

```
N2-1,N3-1,N3-3,N7-3,N7-4,N8-4
N2-1,N4-1,N4-3,N7-3,N7-4,N8-4
N2-1,N3-1,N3-3,N6-3,N6-4,N8-4
N2-1,N4-1,N4-3,N6-3,N6-4,N8-4
```

Thus, the complexity to calculate the routing can be significantly reduced. For a network with n network nodes, the virtual network layer contains $n_{vnl} = \bar{c}_r \cdot N$ nodes, with $\bar{c}_r \geq 1$ being the mean number of rings to which a network node belongs or, in other terms, the mean ring connectivity (a connected graph is assumed). In contrast, the ring connection layer, consists of only $n_{rcl} = n_{vnl}/\bar{n}$ nodes, with $\bar{n}$ being the mean average ring size. A similar reduction holds also for the number of edges. The typical computational complexity of a shortest path algorithm is usually $\mathrm{O}(n \cdot m + n^2 \cdot \log n)$, where m is the number of edges in the graph. Therefore, the running time is reduced by a factor of $\bar{n}^2$, which is typically $\bar{n}^2 \approx 50 \ldots 100$. In addition, the amount of storage to hold the routing table is drastically reduced because only the paths for the ring connections have to be stored. For the routing within a ring, only the direct link between the two ring nodes is investigated.

The drawback of this simplification is that inter-ring routing has been neglected. When e.g. not the necessary capacity on the direct link is available for the transit in $R3$ from node $N3-3$ to $N7-3$, a multi-hop solution is not considered. Therefore, the direct routing on the virtual network layer may use slightly fewer resources.

The capacity for the hop-connection requests on the virtual connection layer are assigned in random order. For every request, starting with the shortest possible path, it is checked if enough capacity remains on all links. If this is the case, a solution has been found, otherwise the next longer possible path is examined. When there is no possible routing found among the computed possible paths, the connection is added to a special list of not-fulfilled connections. It is possible to route this traffic manually in the standard connection-oriented style.

Due to the fact that the granularity of the ring connections is higher than that of the traffic matrix, also the grooming of the different connections can be solved.

For simplicity, protection against link or node failure has not been investigated. Though it is straightforward instead of handling only one path between the node pairs for every connection, to take a combination of working and protection paths into account, to provide $1 + 1$ protection. This is only important for the connections passing through several rings because, normally, the ring management will provide inter-ring protection.

III. Objective function

For the optimization process, the evaluation of the configuration is of crucial importance. Here, the design strategy for the network has to be incorporated.

In this work, the cost for a configuration C_{cfg} is composed of two parts:

$$C_{cfg} = C_r + C_p. \tag{1}$$

The first contribution comes from the cost C_r of the realization for the configuration. Here, the sum of the lengths of all connections plus a constant C_{ring} for every ring is used

$$C_r = \sum_{p \in R_p} d(p) + n_r \cdot C_{ring}, \tag{2}$$

where R_p denotes the set of routed paths and n_r the number of rings in the configuration. In the example, $C_{ring} = 100$ has been chosen. The distance for the path p (as defined in subsection II-B) is denoted as $d(p)$.

The second contribution to C_{cfg} are penalties C_p for the violation of some boundary conditions. Here, for every connection which could not be routed, a penalty of $p_{nc} = 1000$ is added. Rings which exceed the imposed ring-size r_{max} are punished with a constant $p_{rs} = 1000$ plus $p_{an} = 1000$ for every additional node

$$C_p = \sum_{np \in R_{np}} p_{nc} + \sum_{\substack{r \in R_{cfg}, \\ n(r) > n_{max}}} \left(p_{rs} + p_{an} \cdot (n(r) - n_{max}) \right). \tag{3}$$

Here, R_{np} is the set of the node-pairs for which no connection has been found, and R_{cfg} denotes the set of rings of the configuration. The function $n(r)$ returns the number of nodes in the ring r.

The bandwidth utilization is not considered explicitly. The provisioning of more transport capacity is being charged only by the costs for an additional ring C_{ring}. For the optimization of the bandwidth utilization, an additional factor for the unused channels of the rings has to be included in Equation (2). It is simple to incorporate in the same way any other design criteria, e.g. the maximum diameter for a ring.

The values for the costs and the penalties have been chosen more or less arbitrarily. They depend on the preferences for the design of the network. With the chosen one as an example, the results are reasonable. A general rule is that penalties are much larger than configuration costs. The final configuration should have $C_p = 0$, otherwise one of the boundary conditions is violated and the outcome of the optimization process is of no use.

IV. The optimization process

Due to the high degrees of freedom in network optimization problems, it is impossible to compute all configurations to find the optimum solution. Therefore, one has to rely on approximation methods. One very well-known method which has proved in this class of problems is "Simulated Annealing". Any other known optimization method like taboo-search or genetic optimization, which are not trapped in local minima, could be used as well.

As a starting configuration, all faces of the graph are computed and assigned as a ring to the set of rings. The translation in an effective network graph, the building of the ring connection layer and the routing on this network is done as described above.

In every step, a neighbor configuration is derived from the actual configuration. One of the following operations is chosen at random to derive the neighbor configuration:

- adding one face to one of the rings,
- creating a new ring with a random face,
- deleting a face of a ring (when there are no faces left in the set of faces of the ring, the ring is destroyed),
- changing the order in which the hop connections are assigned.

When connections cannot be fulfilled, it is favorable to add transport capacity by either creating new or by enlarging existing rings. Therefore, as long as there are such unfulfilled requests, the probability for the first two derivations of a neighbor configuration is increased. This helps to converge to the final configuration, and the optimization procedure requires fewer steps.

The objective function for the actual configuration and the neighbor configuration are compared. When the cost for the neighbor configuration C_{ncfg} is lower than for the actual configuration C_{cfg}, it is accepted in any case. Otherwise the worse neighbor configuration is accepted if

$$r < \exp\left(-\frac{C_{ncfg} - C_{cfg}}{T} \right), \tag{4}$$

with $r \in [0, 1]$ being a random number with uniform distribution. This prevents to be trapped in a local minimum of the objective function. T is a state variable of the optimization process which is referred to as the temperature. In the beginning, T is chosen such that more or less every configuration is accepted. It is lowered in the following steps for that in the final phase of the optimization procedure, only better configurations with lower cost are accepted. Here, an exponential cooling has been chosen for T.

One process of SA is used for changes of the routing and topology. To improve the results, a two-step procedure

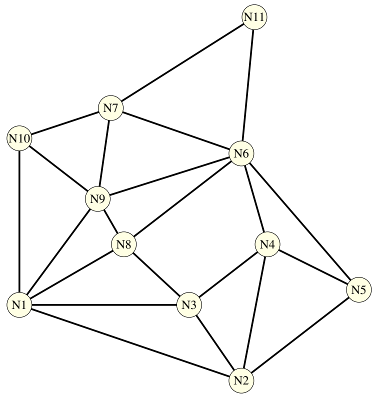

Fig. 4. Fiber topology according to the COST 239 case study for a Pan-European Network.

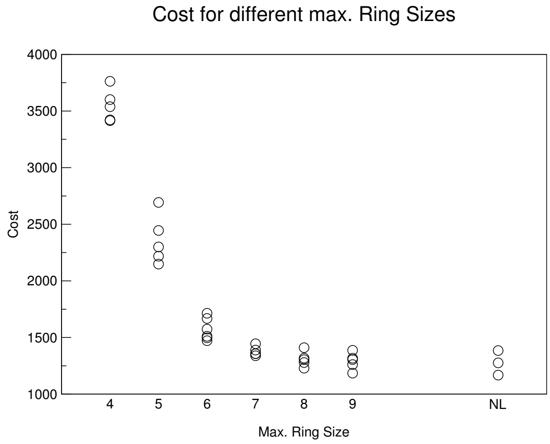

Fig. 5. Configuration cost for different maximum ring sizes.

may be favorable where one SA process optimizes the ring-configuration and a second SA tries to minimize the resulting routing of the connections.

V. A CASE STUDY FOR THE "PAN-EUROPEAN NETWORK" OF THE COST 239 PROJECT

In the framework of the European project COST 239, several case studies for a Pan-European network have been performed [12]. In Fig. 4, the given fiber topology and in Tab. I the corresponding traffic matrix are depicted. For the example, a granularity of $2.5\,\mathrm{Gbit/s}$ per connection has been assumed. The presented algorithm has been implemented in `C++` using the library for discrete math and graphs `LEDA` and tested using the COST 239 scenario as a test example. All parameters of the objective function (distances, capacities, penalties) have been chosen as described before. In total 348 connections have to be established.

One typical outcome for the resulting ring configuration is

```
Ring #0:  (N6 N8 N3 N2 N1 N10 N7 N11)
Ring #1:  (N8 N6 N5 N2 N3 N1 N9)
Ring #2:  (N7 N11 N6 N4 N3 N2 N1 N10)
Ring #3:  (N5 N2 N1 N10 N9 N7 N11 N6)
```

The optimization process has needed 615 steps to find the final configuration with only 4 rings. It has a total cost of 1217.

Most of the connections may be handled by the rings and only 10 hop-connections are necessary. The ring connectivity factor is $\bar{c}_r = 2.82$ and the mean ring-size $\bar{n} = 7.75$ is close to the imposed maximum of $\bar{n}_{\max} = 8$.

In Fig. 5, the cost for the resulting ring configuration is depicted function of the maximum ring size imposed. The label "NL" indicates that there has been no limit in the size of a ring. For every parameter set, five realizations have been calculated to estimate the variations among different outcomes. As expected, with increasing ring size, the cost for the realization decreases. For rings larger then 8 nodes, the results are similar, and further improvement may not be achieved. This is because there are only 11 nodes present in the COST 239 network. The variation among the different realization cost is of the order of $15\,\%$ and may be decreased by a slower lowering of the temperature during the optimization process.

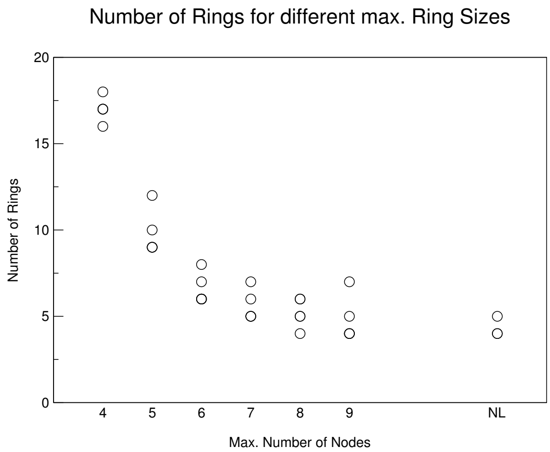

Fig. 6. Number of required rings for different maximum ring sizes.

The corresponding number of rings for the different realizations is shown in Fig. 6. With increasing ring size, less rings are necessary to accommodate the traffic demands.

With larger rings, it is possible to satisfy more connections in the rings (circles and left axis) and to require less hop-connections (stars and right axis), as can be seen in Fig. 7. For rings larger then 7 nodes, most of the connections can be handled by inter-ring connections.

The typical running time on an Athlon 1000 PC is around $5\,\mathrm{min}$ compared to approximately one hour when the routing is performed on the virtual network layer. Therefore, the treatment of networks with up to 100 nodes seems to be feasible.

In comparison, when routing is performed directly on the virtual graph, the resulting configuration cost has been between 1174 and 1295 for a maximum ring size of 8 nodes, whereas by routing on the ring connection layer, the realization cost has been between 1229 and 1410 and requires therefore about $5\,\%$ more resources.

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11
N1	0	12.5	15	2.5	5	27.5	12.5	2.5	17.5	25	2.5
N2	12.5	0	15	2.5	7.5	22.5	5	2.5	5	7.5	2.5
N3	15	15	0	2.5	7.5	27.5	7.5	2.5	7.5	7.5	2.5
N4	2.5	2.5	2.5	0	2.5	5	2.5	2.5	2.5	2.5	2.5
N5	5	7.5	7.5	2.5	0	22.5	2.5	2.5	2.5	5	2.5
N6	27.5	22.5	27.5	5	22.5	0	20	5	15	20	7.5
N7	12.5	5	7.5	2.5	2.5	20	0	2.5	10	12.5	2.5
N8	2.5	2.5	2.5	2.5	2.5	5	2.5	0	2.5	2.5	2.5
N9	15	5	15	2.5	2.5	15	10	2.5	0	10	2.5
N10	25	7.5	7.5	2.5	5	20	12.5	2.5	10	0	2.5
N11	2.5	2.5	2.5	2.5	2.5	7.5	2.5	2.5	2.5	2.5	0

TABLE I

TRAFFIC MATRIX FOR THE COST 239 CASE STUDY FOR A PAN-EUROPEAN NETWORK IN UNITS OF Gbit/s.

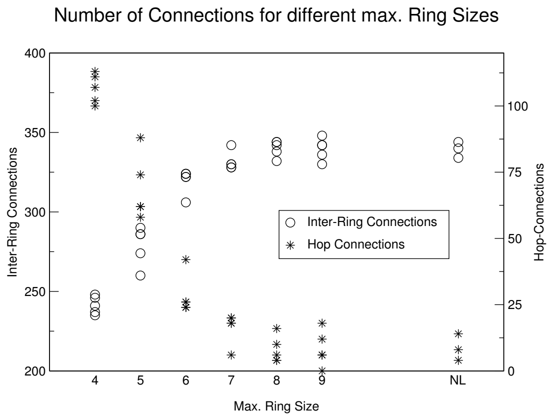

Fig. 7. Inter-ring and hop connections for different maximum ring sizes.

VI. CONCLUSIONS AND OUTLOOK

A three-layer graph model with a ring configuration layer, an effective network layer and a ring routing layer has been presented. Using faces as building blocks allows for a systematic and efficient description of the ring configuration. The allocation of the connection for the actual traffic demands takes place on the resulting effective network. The computation of the routing can be significantly speeded up by introducing the ring connectivity layer and by performing the routing of the hop-connections on this layer. SA is used to optimize the ring configuration with respect to an objective function. Boundary conditions can be incorporated in this function. Therefore, it is possible to map an arbitrary network topology and traffic demand on a mesh of rings network. The algorithm has been tested with the COST 239 Pan European Case study. Only 400-700 steps are necessary to find a good realization for this network.

A specific realization of the rings has not been treated until now. The method can be easily extended to incorporate an additional layer for the wavelength paths. This would enable, e.g. an optimization with respect to the number of necessary wavelengths or the treatment of the wavelength allocation problem.

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