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Reliability in single, double and N2R ring network structures

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Abstract—This paper studies the properties of single, double and N2R ring network structures during link errors. The structure of the network infrastructure must be redesigned in order to fulfil the requirements of services using the Internet in the future; hence, N2R structures have been suggested. N2R structures are found to be superior regarding network properties compared to the other more traditionally ring structures but the deployment of this type of structure is more complicated. Therefore, this paper suggests a deployment scheme, denoted N2R tube deployment, which is a compromise between the easy deployable double ring structure, and the better properties of the N2R structure. The properties of single ring, double ring and N2R structures have never been compared during errors in previous research. Nevertheless, this is an important part of selecting the topology of the network infrastructure for the future. This paper compares single, double, N2R and N2R tube structures when one and two errors are introduced. The results show that even when errors are introduced in the network structures, the N2R structure remain superior. Furthermore, this is also valid with a smaller margin for the N2R tube structures.

Keywords— Ring network structures, network planning, network reliability, N2R structures and network infrastructure.

I. INTRODUCTION

Recently, several new services using the Internet have been introduced which set higher requirements to the network infrastructure: Online television/video streaming requires a significant amount of bandwidth; telerobotics [1] [2] require low delays; the increasing use of the Internet for reliable services implies that the reliability of the network infrastructure must be increased [3]. There exists several other examples but those mentioned state the main challenges for the new network infrastructure: More bandwidth, lower delays and more reliable networks.

The bandwidth challenge can be addressed by replacing existing copper lines with optical fibers, which are upgradeable simply by replacing terminal equipment. The deployment of fiber optical lines is relatively expensive, mainly because of the expenses for digging ducts. Furthermore, the expected operation time of the network infrastructure is very high, which stresses the importance of choosing a suitable topology.

Reducing delays and increasing the reliability of the network infrastructure can be achieved by considering other network topologies than those typically used. This implies that it is necessary to deploy a suitable network structure

to support the end-users' demand for increasing reliability. Therefore, it is crucial to choose a suitable network structure, which guarantees the demands of the future.

Single rings (SR) are often used in network infrastructure since they make routing and restoration uncomplicated, and still have redundancy in case of failure. Recently, more advanced network structures like the double ring (DR) and the N2R structures [8] have been proposed as replacements for the SR structure. The DR and N2R structures are more complex regarding deployment and routing, but have better network properties [6], which imply higher capacity and lower delays.

In the United States, an average of 1 cable cut per year on 370km [4] of deployed¹ cable can be expected. Cable cuts are the most frequent failure in a widespread network and the most time consuming to repair [4]. The fact that it is impossible to avoid errors in networks stresses the importance of studying how the different network structures behave during errors, in order to ensure that the requirements to the networks are still guaranteed. Two basic error types can occur in the network structures: A node can fail, or a link can fail. Node errors can be caused by equipment or power failure, but usually the recovery time or time to start emergency systems is very low [4], compared to the time it takes to locate and repair a link error. Link errors are usually caused by links being dug over. These types of errors will happen randomly in the network with some probability, depending on the size of the network and the way it is deployed. This paper compares certain properties of the SR, DR and N2R network structures in scenarios where link errors occur. In case of a node error the network is divided into two separate parts since the defect node is not connected to the network anymore; hence it is not possible to evaluate the structure as a whole. Furthermore, a traffic generating element is removed from the network in case of a node error; hence, from the network's perspective the overall traffic load in the network is reduced, which reduces the impact of node errors. Therefore node errors are not evaluated in this paper.

The comparison of the network structures in scenarios with or without errors can support the selection of the network infrastructure topology of the future.

¹Deployed in both ducts and masts.

The structure of the paper is as follows: Section II “Network topologies” provides an overview of the network structures and previous research. Section III “Methods” describes the methods used to obtain the results, which are described in Section IV “Results”. Section V “Discussion” discusses and sets the results in perspective to real world applications. Furthermore, research topics are suggested. Section VI “Conclusion” concludes the paper with a brief summing up of the main findings.

II. NETWORK TOPOLOGIES

In the SR structure the nodes are placed in a ring, and neighbouring nodes are interconnected by links. Figure 1 shows a SR network structure, where nodes are denoted N_i and i denotes the node number. All links can be described as interconnecting N_i and $N_{(i+1) \bmod p}$, where p is the number of nodes in the structure, and $0 \leq i \leq p-1$. The number of nodes, p , is any positive integer larger than 2. All nodes in an SR network are connected to two other nodes; thus the nodes in the structure are of second degree. The SR structure does not scale very well since the distances in the structure increase linearly as the number of nodes increase.

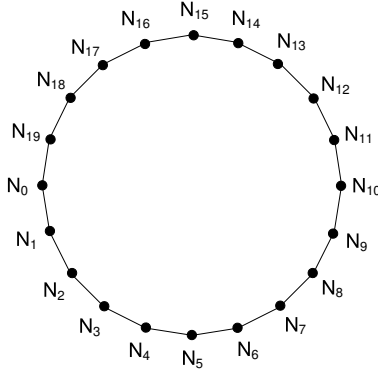


Fig. 1. Single ring network structure with 20 nodes.

The DR structure consists of two rings denoted inner ring and outer ring. These rings each contain the same number of nodes (p); hence the number of nodes in the structure is any positive even integer larger or equal to 6. The rings are interconnected by links between each corresponding pair of nodes in the inner and outer ring. Figure 2 shows a DR network structure, where nodes in the inner ring are denoted I_i and nodes in the outer ring are denoted O_i . Links in the inner ring interconnect I_i and $I_{(i+1) \bmod p}$, where p denotes the number of nodes in each ring and $0 \leq i \leq p-1$. Links in the outer ring are described in the same way: O_i and $O_{(i+1) \bmod p}$. Links interconnecting the two rings, also denoted cross links, are described by interconnecting I_i and O_i . The DR network is a third node degree network structure.

The N2R network structure is another type of generalized DR structure, where inner ring links do not interconnect physically neighbour nodes. The number of nodes in the N2R structure is any positive even integer larger or equal to 6.

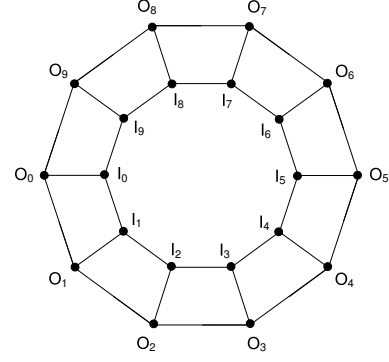


Fig. 2. Double ring network structure with 20 nodes.

Figure 3 shows an N2R structure, where inner ring nodes are denoted I_i and outer ring nodes are denoted O_i . Links in the outer ring and the links interconnecting the two rings can be described in the same way as the DR structure, but links in the inner ring are interconnecting I_i and $I_{(i+q) \bmod p}$, where q is a positive integer. To avoid forming two separated networks in the inner ring, q must fulfil $\gcd(p, q) = 1$ (Greatest Common Divisor), also q is evaluated from 1 to $p/2$.

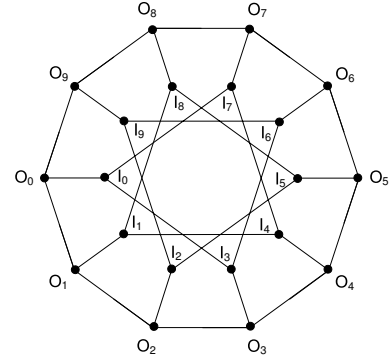


Fig. 3. $N2R(10,3)$ ring network structure.

Another similar type of $N2R(p, q)$ structure is denoted $N2R(p, q', r)$ where r denotes the number of hops between nodes in the outer ring. The $N2R(p, q', r)$ structures have isomorphic $N2R(p, q)$ structures [5] which have identical network properties. Results obtained in the $N2R(p, q)$ structure will thus be valid for the $N2R(p, q', r)$ case too. Because of this equivalence, $N2R(p, q', r)$ structures will not be studied separately in this paper.

Since q is a variable, a number of different N2R structures with the same number of nodes can be created. The N2R structures that will be evaluated in this paper will for each value of p be chosen with the lowest possible diameter [6]. If more structures have equally low diameters, optimization is done according to the lowest possible average distance. If this gives more possibilities, the smallest value of q is chosen. This optimization creates structures with the lowest maximum delay, and then fiber usage is minimized.

The digging expenses of deploying the crossing inner links in the N2R structures are very high. To compensate for this problem, it is possible to deploy the N2R structure, where all the fibers in the inner ring are gathered in the same fiber tube. Figure 4 shows an example of an N2R structure deployed with a tube in the inner ring. This type of structure can use the same ducts as a DR structure and is therefore almost as economic to deploy, but with the same properties as the N2R structure in an error free scenario. A problem that evolves when deploying the N2R structure with common inner ring tube is the risk of a tube being dug over, which will cause q links to fail.

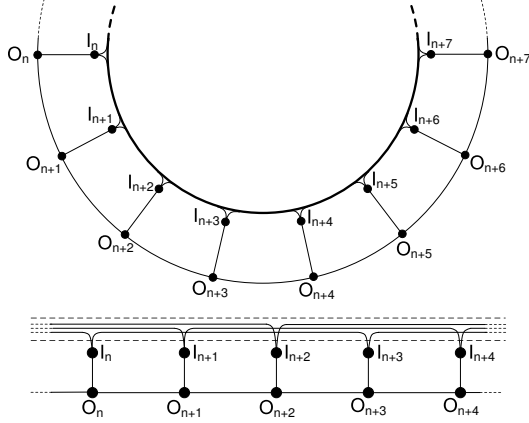


Fig. 4. Tube deployment of N2R ring network structure ($q=3$).

III. METHOD

In order to compare the properties of the different structures, a set of evaluation parameters is defined. These evaluation parameters reveal the interesting properties of the structures. The structures are evaluated on diameter, average distance (AvgDist) and the maximum traffic load on a link (MaxLinkLoad).

The diameter [7] is calculated as the maximum length of all shortest paths;

$$Diameter = \max(S_{N_i-N_j}) \quad (1)$$

where S represents the number of hops in the shortest path between node N_i and N_j , evaluated between all distinct pairs of nodes. The diameter is the maximum number of hops a data packet can travel in the network, provided that a shortest path is always used. This parameter can be used to estimate maximum delays for packets in the network, which is a critical parameter in real time applications.

The AvgDist [3] is calculated as the average distance between nodes;

$$AvgDist = \frac{\sum_{i=0}^{n-1} \sum_{j=0}^{n-1} (S_{N_i-N_j})}{(n-1) \cdot n} \quad (2)$$

where n is the number of nodes, and $S_{N_i-N_j}$ is the number of hops in the shortest path between node N_i and N_j . The AvgDist indicates the expectation of hops between any two

nodes, and can be used to estimate the average delay in the structure.

In order to evaluate the MaxLinkLoad, a traffic pattern must be defined. Using an all-to-all traffic pattern² makes it easy to identify changes caused by errors. Furthermore, it is assumed that a link error causes communication to fail completely in both directions between the interconnected nodes. The MaxLinkLoad [7] is the link which has the maximum load;

$$MaxLinkLoad = \max(L_i) \quad (3)$$

where L_i is the traffic load on a link evaluated for all links in the structure. The maximum traffic load is of particular interest during dimensioning of the network, since it specifies the required extra bandwidth which must be present in the network if the traffic must remain unaffected by the errors.

Calculations of the diameter, AvgDist and MaxLinkLoad are based on a shortest path routing scheme. In case of several shortest paths, a path selection policy is required in order to ensure even link load distribution throughout the network: Paths routing the traffic counterclockwise in the network are selected first; then paths routing traffic clockwise in the network are selected; finally paths interconnecting the rings are selected. This selection ensures that if a shortest path between two nodes in the same ring can be found, this path will be used, which will distribute the traffic in the rings more evenly. In case of errors in a structure, all paths are rerouted according to the shortest path routing policy. When the new shortest paths have been found, the structure is reevaluated.

In order to evaluate the different structures, worst and best case failures are identified for each type of error. These failures represent worst and minimal impact caused by a specific error in a specific structure. Both worst and best cases are based on calculations of AvgDist. The worst case failures can be used to dimension the network to different error scenarios.

Since two errors in a SR structure will divide it into two separate networks, SR structures will only be evaluated for scenarios where no or one error occurs. Furthermore, any link in the SR structure will cause both the worst and best case failure scenario since it causes the same impact in the structure.

For the DR structure it can be shown that an error on a cross link causes the least impact, and an error on an inner or outer ring cause the worst impact; when the previously introduced shortest path routing policy is applied. This implies that to create a worst case failure scenario with one link error, a link in the inner or outer ring must fail, and for the best case failure scenario, a cross link must fail. Worst and best case failures for two errors can easily be determined for all DR structures by following the same pattern.

Since q varies for each N2R structure, it is not trivial to determine the worst and best case failures for a structure in a given error scenario. This implies that worst and best case failures must be calculated for each error scenario. Since

²Every node in the network transmits a traffic unit to all other nodes in the network.

calculation time for large network structures is high, worst and best case failures of the largest structures in this paper are estimated based on worst and best case failures found by calculating smaller N2R structures.

For N2R tube structures, an error on a tube in the inner ring will cause the worst case failure scenario, since this causes q links in the inner ring to fail. The best case failure scenario in an N2R tube structure can be found as an error on an outer link or a cross link, and the impact will be the same as for the N2R structure. Both assumptions are also valid for two errors.

Because of the computational complexity of finding worst and best cases, only a subset of 15 structures between 6 and 200 nodes are evaluated.

IV. RESULTS

The simulations have shown how the properties of the network structures are affected when errors are introduced. Figures 5, 6 and 7 show AvgDist, Diameter and MaxLinkLoad respectively when one error is introduced in the structures. The graphs show the evaluation parameters for all possible one link errors in the structures, and represent this by a shaded area. The upper bound of this area is the worst failure scenario, and the lower bound is the best case failure scenario³. For the N2R tube structure the best case failure scenario is the same as for the N2R structure; hence, the area which shows the possible impact of errors in the N2R tube structure is represented by the best case failure of the N2R structure and the worst case failure of the N2R tube structure.

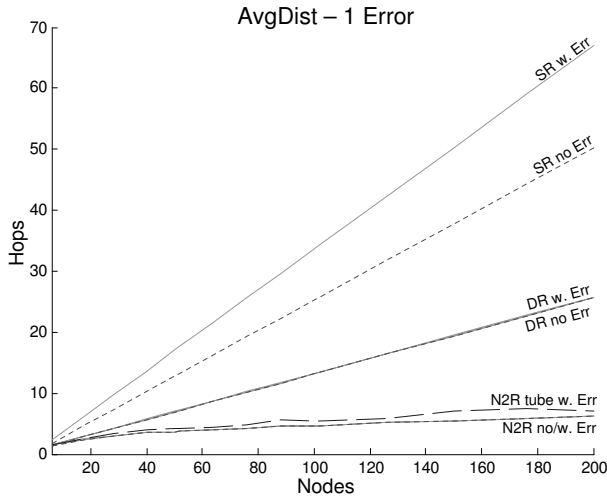


Fig. 5. Comparing AvgDist during one link error in SR, DR, N2R and N2R tube structures.

Figure 5 shows that the impact caused by an error in the SR structure increases the AvgDist compared to the error free scenario and is linearly dependent on the size of the structure. For the DR the increase caused by an error is very small, which is also the case for the N2R structure. For the N2R tube structure a small increase in AvgDist is noticeable, but AvgDist is still significant smaller than for the SR or DR structures.

³Best illustrated on Figure 7.

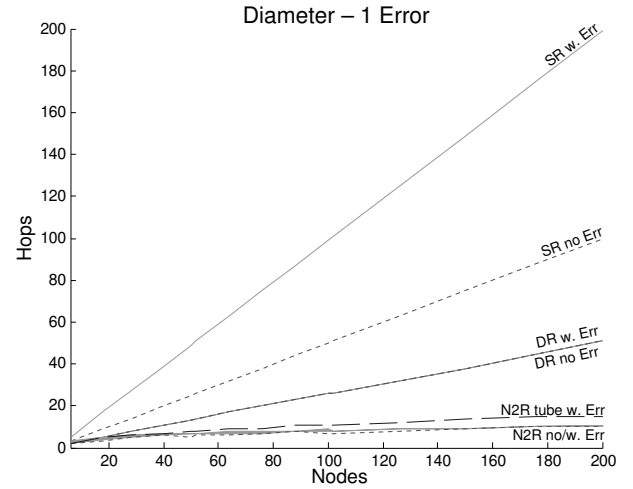


Fig. 6. Comparison of the diameter for the SR, DR, N2R and N2R tube structures during one link error.

Figure 6 shows the same tendencies as Figure 5, but since the SR structure is broken when an error occurs, the diameter increases to approximately the double. The diameters for the DR and N2R structures are particularly affected by the link error. For the N2R tube structure only a small increase in the diameter is noticeable.

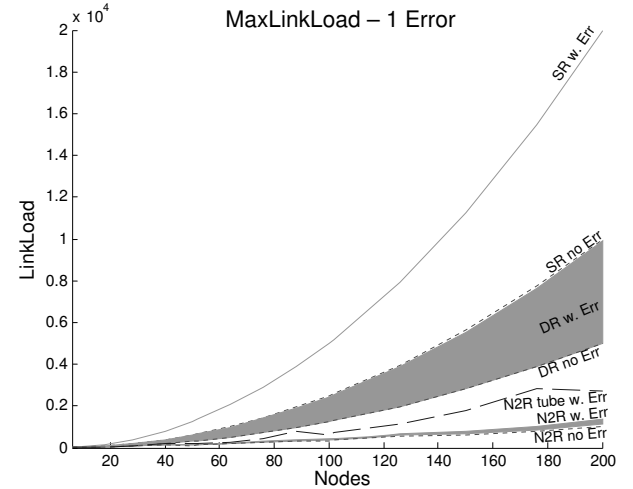


Fig. 7. MaxLinkLoad in SR, DR, N2R and N2R tube structures during one link error.

Figure 7 shows that the MaxLinkLoad is much more affected by the error than AvgDist and Diameter, because a broken link will imply that other links will be heavily loaded due to the shortest path routing policy. Since the link load on cross links in the DR structure is smaller compared to the link load on other links, the increase in MaxLinkLoad depends more on the location of the error. This is also the case for the N2R tube structures where an error on an inner ring tube will imply higher impact on the structure than an error on a cross or outer link. For the N2R structure it is not significant where

the link error happens.

Two errors in the SR structure will cause it to separate into two parts which makes comparison of the evaluation parameters impossible; hence, the SR structure is not evaluated for two errors.

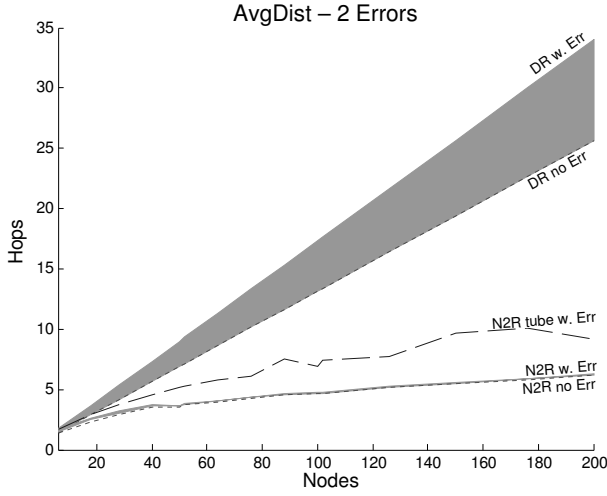


Fig. 8. Comparison of the AvgDist in the DR, N2R and N2R tube structures during two link errors.

Figure 8 shows that the introduction of two link errors causes the AvgDist of the DR structure to increase linearly when the number of nodes in the structure increase. The figure also shows that AvgDist depends on where the errors occur in the DR structure. Two errors cause the AvgDist of the N2R tube structure to increase depending on the value of q , which also explains the fluctuations in AvgDist for the N2R tube structure. However, the AvgDist in the N2R tube structure is significant smaller than the AvgDist of the DR structure. The impact of two link errors does not causes the AvgDist of the N2R structure to increase noticeable, thus the AvgDist of the N2R structure remain considerable lower than in the two other structures.

Figure 9 shows that the diameter of the DR structure remains almost unaffected when two best case errors occur. When two worst case errors occur in the structure the diameter increases significantly. The diameter of the N2R tube structure depends on the calculated q value for the different structures. A large q value will cause the diameter of the N2R tube structure to increase more than for structures with smaller q values. The impact on the N2R structure is significantly smaller compared to the DR and N2R tube structure.

Figure 10 shows that the MaxLinkLoad also depends on where errors occur in the structures. For the DR structure two best case errors will cause almost no increase in MaxLinkLoad, while two worst case errors will cause high impact. For the N2R tube structure the MaxLinkLoad with two worst case errors will approach the MaxLinkLoad for the DR structure. Two worst case errors do not cause the MaxLinkLoad in the N2R structure to increase significant compared to the other structures.

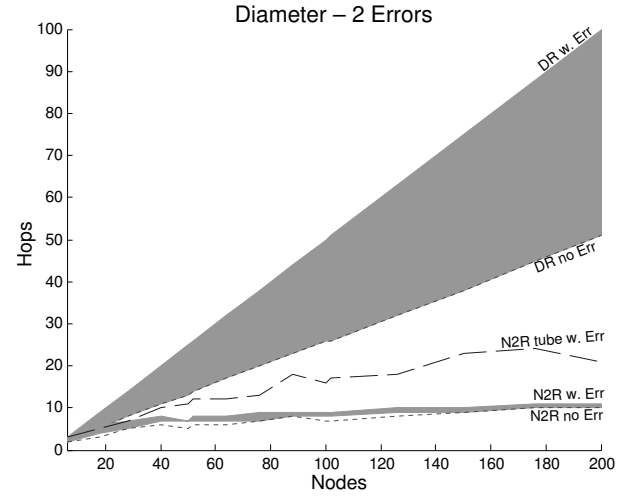


Fig. 9. The diameters in the DR, N2R and N2R tube structures during two link errors.

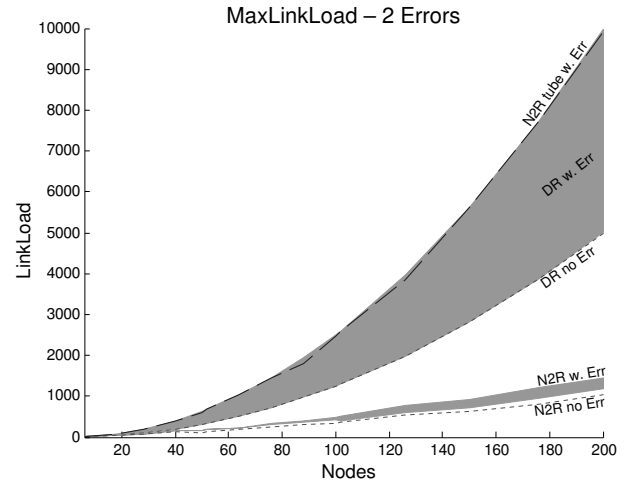


Fig. 10. The MaxLinkLoad during two link errors in the DR, N2R and N2R tube structures.

The figures indicates that the N2R and N2R tube structures scale better than the SR and DR structures, since the evaluation parameters for the N2R and N2R tube structures increase considerable less than for the SR and DR structures when the number of nodes in the structures increases.

Figure 11 shows a comparison of the increase in the evaluation parameters, due to the introduction of one or two worst case failures, compared to the error free scenario. The figure shows the average impact of all simulated structures, represented relative to the SR error free scenario. This comparison also shows that the N2R structure has better properties than the other structures even when errors are introduced. The N2R tube structure can compete with the DR structure with one error in the structures. With two errors in the N2R tube structure the AvgDist and Diameter are still far better than in the DR structure, but the MaxLinkLoad will approach that of the DR structure in the worst case failure scenario.

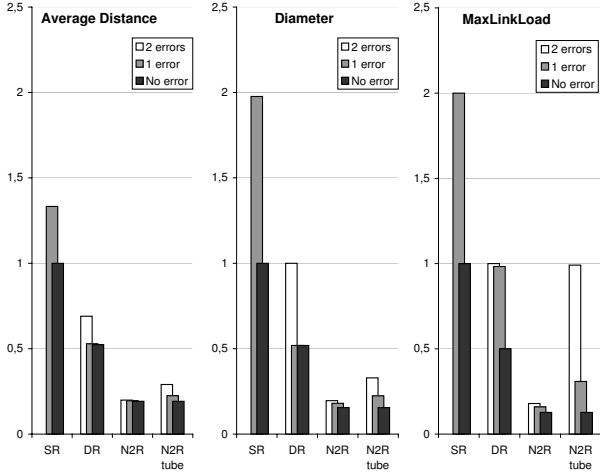


Fig. 11. Comparison of averaged evaluation parameters for all simulated worst case failure scenarios.

V. DISCUSSION

Studies of the ring network structures have clarified differences in the properties of the structures, with and without errors introduced in the networks. Link errors are the worst kind of errors which can occur in a network structure as discussed in the introduction. The repair time of a link error is probably longer than a node error since the spot where the cable has been cut must be identified. Furthermore, digging and splicing the fibers take a while. Therefore link errors are considered as the worst error type which can occur in the network structure. This assumption may not be valid in all kinds of situations, e.g. fire in a node may cause the repair time of the node error to take longer time to correct than a link error. The fact that the defective node does not load the network during the repair time, justifies the assumption of link errors causing the worst impact on the network structures.

In this paper maximum two link errors are introduced in the DR and N2R structures. There is a risk that more than two errors may occur in a network structure. The risk of link errors increases with the physical distances of the network, the number of nodes in the network, the digging activities in the area in which the cables are deployed and other parameters. For the majority of deployed networks it is unlikely that more than two errors occurs in the network at the same time or within the repair time period. Since N2R structures can be deployed as very large networks, it can be necessary to study the impact of more than two errors, to evaluate the reliability of very large N2R networks.

The evaluation parameters used in the results section are always worst case failures; hence, the parameters of the network structures in normal operation are smaller compared to those found in this paper. In dimensioning the network the worst case parameters must be evaluated in order to give guarantees during errors.

The results obtained in this paper are based on shortest path routing. This type of routing scheme can introduce some

problems when errors occur in the structure since certain links can be heavily loaded. The traffic distribution in the structures can be balanced by allowing paths that violate the shortest path routing scheme. A routing scheme which also take link traffic load into account will distribute the traffic more equally, which will reduce the extra capacity necessary to handle the traffic in case of errors in the structure. A routing scheme that handles the routing in the structure as discussed must also handle restoration within a short period of time to avoid heavily decreased network performance. In the simulations a complete rerouting of the network is conducted before calculating the evaluation parameters; hence, the results do not take the restoration into account.

The N2R tube structure is cheaper and more practical to deploy than the ordinary N2R structure; since the digging expenses equal those of a DR structure, although the network properties equal those of the N2R structure. This paper reveals that one error in an N2R structure deployed in tubes does not imply considerable worse properties. Introducing two errors in the N2R tube structure imply that the MaxLinkLoad approaches the MaxLinkLoad of the DR structure where two worst case errors have been introduced; the AvgDist and the diameter remain considerable lower than those of the DR structure; hence, the N2R structure deployed in tubes remains preferable.

In the $N2R(p, q)$ structure the q values is calculated for every $N2R(p, q)$ structure by minimizing AvgDist and diameter, which implies that the q values can be relatively high. To reduce the fiber cost and minimize the impact of link errors, it is often possible to find a compromise between low q values, AvgDist and diameter. A tube error will cause q links to fail, as reducing q will also imply less impact on the network structure when errors occur. Furthermore, the physically deployment of the N2R tube structure can be optimized by using the $N2R(p, q', r)$ structure instead of the $N2R(p, q)$ structure, which also reduces the cost and complexity of the deployment. For most structures it is possible to find an $N2R(p, q', r)$ structure which has the exact same network properties as an $N2R(p, q)$ with the same number of nodes, where $r + q' \cong q + 1$ and $r \cong q'$. This structure will distribute the q fibers in the inner ring of the $N2R(p, q)$ structure to the outer and inner ring of the $N2R(p, q', r)$ structure. The main advantage of using the $N2R(p, q', r)$ structure is that the number of fibers cut in case of a link error is reduced, but also the interconnection of nodes in the unaffected ring will cause the $N2R(p, q', r)$ structure to perform better in case of a tube link error than the $N2R(p, q)$ tube structure. Since every $N2R(p, q', r)$ structure is isomorph to an $N2R(p, q)$ structure [5] the theoretically calculations can in error free scenarios be conducted on the simpler $N2R(p, q)$ structure while the physically deployment is achieved using the $N2R(p, q', r)$ structure.

Further topics of research include advanced routing and restoration in the N2R structures. Also, the physically deployment of the N2R structures is a topic for further research.

VI. CONCLUSION

The task of choosing a suitable topology for the network infrastructure of the future requires careful studies and considerations. The results in this paper show that N2R structures are preferable regarding low delays, high bandwidth and reliability also when errors occur; however, the physical deployment of N2R structures are unrealistic. The N2R tube deployment is a more realistic structure to physically deploy with the same network properties in an error free scenario as the N2R structure. When deploying N2R tube structures it is of great importance that the $N2R(p, q', r)$ structure is considered, since the impact on the structure in case of errors is reduced.

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