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Comparing the Reliability of Regular Topologies on a Backbone Network. A Case Study.

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Abstract The aim of this paper is to compare the reliability of regular topologies on a backbone network. The study is focused on a large-scale fiber-optic network. Different regular topological solutions as single ring, double ring or 4-Regular grid are applied to the case study, and compared in terms of degree, diameter, average distance, economical cost and availability. Furthermore, other non-quantitative parameters such as expandability, embeddability and algorithmic support are introduced.

Key words regular topologies, backbone, grid, N2R, double ring, comparison, availability study.

1 Introduction

The use of regular topologies in backbone networks has been studied in detail in the past with satisfactory results [1]. Furthermore, year after year, users and companies demand more and more bandwidth, lower delay and higher network availability [2] [3].

Communication networks play an important role in many social and economic activities. Interruptions in data transmission and exchange, even for a short period of time, can suspend critical operations and lead to a significant loss of revenue. Furthermore, new emerging services as telemedicine and e-health care will increase even more, the necessity of designing more and more reliable networks [4].

Even though protocols are being developed to ensure reliability [5], the physical network structures limit the level of reliability that can be offered: two nodes can only communicate if there is a physical link between them.

Traditionally, rings have been used as alternatives to tree structures. Rings offer connectivity in case of any single failure. However, given the expected demands of availability, this is likely to become insufficient in near future. More information about redundancy in ring topologies can be found in [6] and [7].

This document studies the applicability of different regular topologies as backbone for a regional network. The access technology -in this regional network- was a combination of FTTH and WiMAX technologies.

Both qualitative and quantitative parameters are used in the comparison, e.g. connectivity number, economical cost, availability, support to topological routing, etc. The main goal is to evaluate how these regular topologies perform as solutions for backbones, and compare them to single ring solutions, paying special attention to two key parameters: the economical cost and the availability that they can provide.

The three main reasons for analyzing regular topologies are:

1. It is possible to define and document well-known parameters and metrics which ease the network characterization. Besides, based on well-known metrics, it is easy to compare dif-

ferent topology designs in a proper way.

2. Topological routing. Based on regular topologies it is possible to define topological routing techniques which allow faster communication, faster restoration, and the reduction of routing overhead within the network. [9]

3. Expandability and upgradability. It is easier to add links to improve the network performance or to add nodes in order to expand it (in an organized way). [10]

The organization of the paper is as follows: Section 2 introduces the different topologies. Section 3 presents the case study and briefly explains the current situation of the IT infrastructure in Denmark. Then, in section 4 the methodology is described. Section 5 shows the results of the study. Finally, sections 6 and 7 contain the conclusion and future work lines respectively.

2 Introduction to regular topologies

- Single Ring. A single ring network, is a topology in which each node connects to exactly two other nodes, forming a circular pathway for signals: a ring (Fig. 1).

- Double Ring. It consists of dividing the nodes of the network in 2 groups, and connecting them using a ring for each group. Then, each node of the outer ring must be linked with its peer of the inner one. Double rings are simple 3-regular topologies, which offer easy routing, restoration and protections schemes, but suffer from large distances [11]. (Fig. 2)

- N2R. The N2R topology (Fig. 3) is a type of generalized Double Ring (DR) topology. It consists of two rings, denoted inner ring and outer ring. Hence, the number of nodes in the N2R structure is any positive even integer larger or equal to 6. These rings each contain the same number of nodes (p). The inner ring links do not interconnect physically to neighbor nodes.

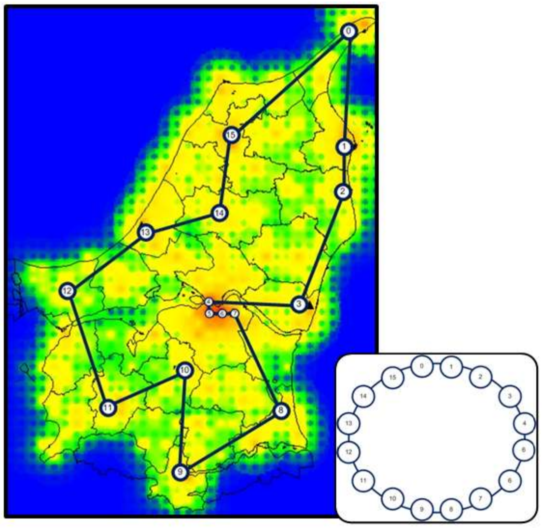


Fig. 1. Single Ring Topology

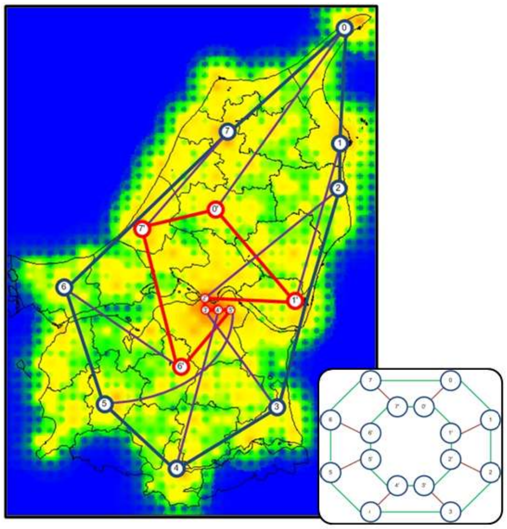


Fig. 2. Double Ring Topology

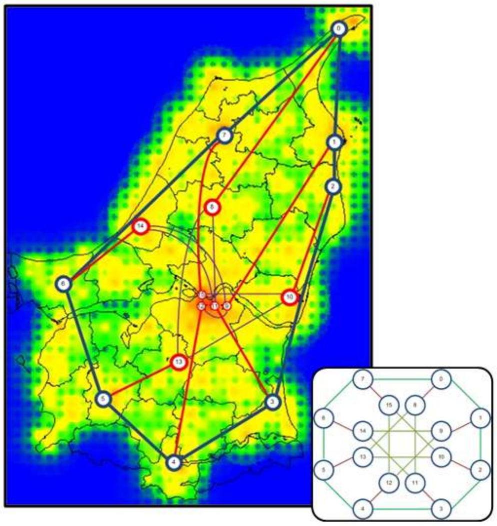


Fig. 3. N2R Topology

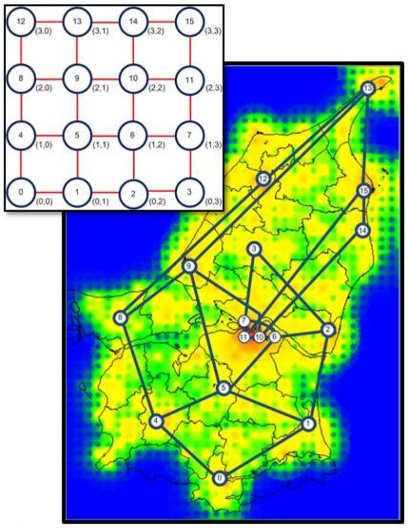


Fig. 4. 4-Regular Grid Topology

The 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 node Ii and node I(i+p)modq, 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 [8].

- Grid. A 4-regular Grid topology (Fig. 4) consists of linking the nodes in such a way that the final result is a grid. Final structure S must be modeled with node set N and line set L. Let dimx and dimy be prohibitive integers. Every node in N is associated with a pair of coordinates (x,y) such that $0 \leq$ dimx and $0 \leq$ dimy, and every coordinate pair is associated to a node. Furthermore, no two nodes are associated to the same pair of coordinates. Consequently, there are exactly (dimx+1)(dimy+1)nodes in S. If a node u is associated to a coordinate pair, (x_u, y_u) we write u=(x_u, y_u) to ease the notation [12].

3 Case Study

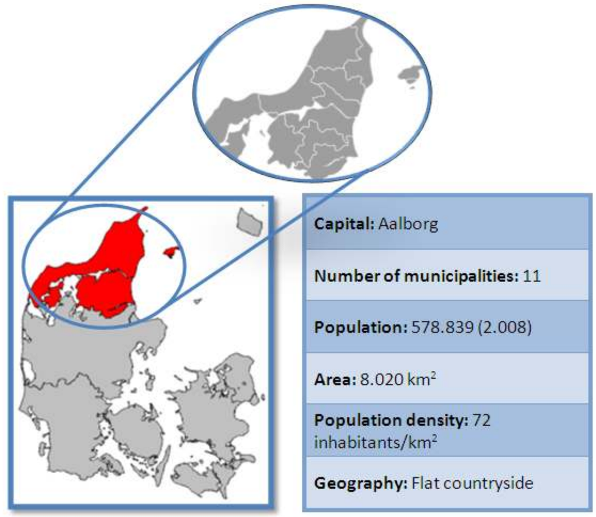
Northern Jutland is the northern region of Denmark and it is also the less populated one. Its largest city is Aalborg, the fourth largest one in Denmark, with a population of 100.731 inhabitants in 2007. (Fig. 5)

Northern Jutland covers an area of 8.020 km2, which means that its population density is about 72 inhabitants per sqkm, the lowest one in the country [16].

The current situation of the IT Infrastructure in Denmark is quite similar to the average situation in other developed countries in terms of bandwidth and FTTH deployment [19] [17]. (Fig. 6) Despite the fact that Denmark is leading (in Europe) with respect to broadband availability and penetration (Fig. 7), the main technology used in the last mile is still xDSL [17].

Important backbone networks are already deployed, but there is a bottle neck in the access networks of those users located far from their central offices (local loop) [17].

This bottleneck is due to the bandwidth limit of the traditional copper lines (Fig. 8). The replacement of the old access network based on copper wires from POTS (Plain Old Telephone Service), to new genera-



Capital: Aalborg

Number of municipalities: 11

Population: 578.839 (2.008)

Area: 8.020 km^2

Population density: 72 inhabitants/km^2

Geography: Flat countryside

Fig. 5. Region of Northern Jutland, Denmark

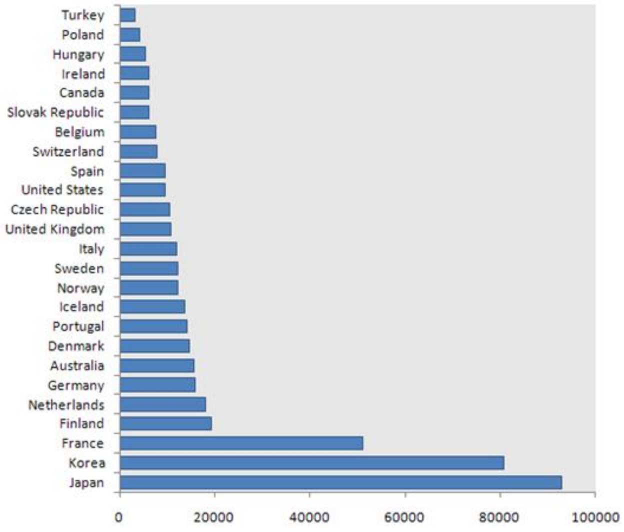


Fig. 6. Average advertised broadband download speed, [kbps], Data extracted from OECD [17], September 2008

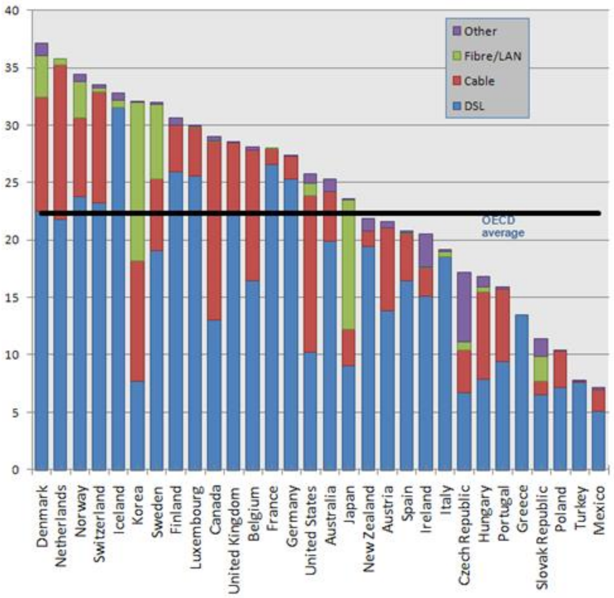


Fig. 7. Broadband penetration per 100 inhabitants, by technology, Data extracted from OECD [17], 2008

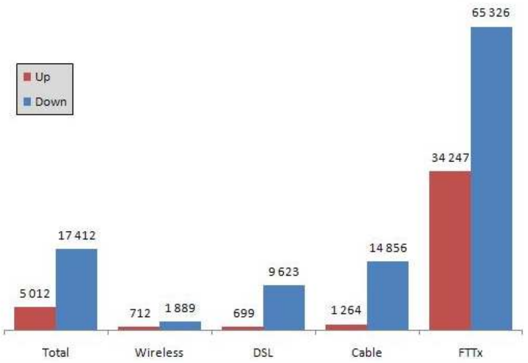


Fig. 8. Average advertised broadband speeds, by technology, [kbps], Data extracted from OECD [17], 2008

tion wired technologies (such as FTTH), that are able to provide higher transfer rates, is becoming a reality nowdays.

New generation access technologies will provide to the society the opportunity to use a new series of emergent services, such as e-health care or telemedicine. These new services will require high network availability, not only at the backbone, but also in the distribution and access networks.

4 Methodology

The aim of this section is to study the methodology applied to the case study. The methodology can be divided into three main stages:

1. The location of the nodes.
2. The general comparison of the topologies.
3. The study of the availability.

4.1 Nodes location process

The first stage in which the nodes are located in the scenario, consists of a computer assisted process that requires several iterations, due to the high number of parameters to optimize (e.g. economical cost, users distribution, network balance, etc.).

This process is divided onto three sequencial steps:

1. Step 1: Locating the nodes in the most densely areas. The first step consisted of placing the nodes in the most densely populated areas of the map. If we assume that every user will be connected using a wired technology to a node, by placing the nodes in the regions with more users density, we minimize the digging in the distribution and access networks. This digging reduction implies both lower economical cost, and faster network deployment. MAP Info Software [18] and Geographic Information System (GIS) Data, with the position of all the Network Terminals (NT) of the region, has been used to carry out this phase. MAP Info provides resources to easily create density maps from any GIS Data. Afterwards, different kinds of filters have been applied in order to point out those ”hot cells”, or areas with highest NT density, potential candidates to allocate a node.
2. Step 2: Adapting the nodes to the WiMAX distribution network. In this second step, the location of the backbone nodes suffers from minor variations in order to merge its location with those WiMAX base stations that are in a relatively short distance from them. This way, allocation expenses are reduced, and if the need arises, the backbone can be exploited not only by wired, but also by wireless access users.
3. Step 3: Final adjustments and backbone adaption. Other minor adjustements were performed in order to achieve new goals as traffic distribution. The goal was to modify the located nodes in such a way that they covered a similar number of NTs. See Eq. 1:

$$NTsperNode = \frac{TotalN.ofNTs}{Numberofnodes} \tag{1}$$

Further information about the methodology can be found in [19].

4.2 General Comparison

The second stage consists of comparing regular topologies as backbone for the case study. Each topological model is adapted to the number of nodes defined in stage 1 (16 nodes for this studied scenario). Then, the following parameters are used for the comparison:

I. Diameter. The maximum distance (number of hops) between any pair of nodes in the network. This parameter is important, because it has direct influence on the maximum delay.

II. Average distance. The average number of hops between any pair of nodes. This parameter is important, because it has direct influence on the average delay. The average distance for the secondary independent path has also been calculated. (In network planning, secondary independent path applies to the possibility of a node A, to send data to a node B, by using an alternative path, physically independent from the primary path. In other words, if a failure occurs, there exists a spare route, so the flux of data can be re-routed and the communication is not lost.)

III. Connectivity number (Degree). The number of neighbors of each node. This parameter is important, because it has direct influence on the reliability of the network. If e.g. a node has degree 2, it means that it is connected to two other nodes in the network. Thus, two simultaneous fails (one in each link) should occur in order to become isolated from the network. If the node had degree 3, three simultaneous fails should occur, and so on.

IV. Economical cost. An estimation of the overall fiber deployment cost. This estimation has been realized using GIS Data and Map Info software. Distances between nodes have been calculated using (Geographic Information System) GIS data, and multiplied by the approximate cost of deploying 1 meter of fiber [19].

Moreover, some extra qualitative parameters defined in the SQoS evaluation framework, and presented in 2004 at the Information Technology and Telecommunication Conference [20], have been discussed. Due to their non-quantitative nature, they have not been directly included in the numerical comparison:

V. Algorithmic support. For example, topological routing support.

VI. Embeddability. This parameter is important when implementing graph structures in the real world. Some structures are easier to embed than others; this depends highly on physical conditions. Planar structures are relatively easier to embed. Fig. 4 shows an example of embeddability: the N2R topology embedded in the considered scenario.

VII. Expandability. The graph structures have different properties with respect to support SQoS parameters. An expansion of these structures can degrade these properties if not expanded correctly. Some structures, especially planar ones, are easier to expand than the non-planar ones.

4.3 Availability Estimation

The third stage consists of studying the availability of each of the considered solutions.

Availability is the probability that a system is available for use at a given time, or in other words, the ratio of the total time a functional unit is capable of being used during a given interval to the length of this interval. [21]

Before focusing on how to calculate it, some parameters should be introduced:

- MTBF. Mean Time Between Failures (MTBF) -also known as Mean Time To Fail (MTTF)- is the average time between failures of hardware modules. It is the average time a manufacturer estimates before a failure occurs in a hardware module.

- MTTR. Mean Time To Repair (MTTR), is the time taken to repair a failed hardware module. In an operational system, repair generally means replacing the hardware module. In our optical fiber network context, MTTR could be viewed as the mean time to replace the segment of fiber that has been damaged.

Network availability can be calculated in several ways. In this study we have chosen two different approaches as availability indicators:

- Approach 1: It considers the whole network as a unique system. We have calculated the availability as the possibility of loosing the connectivity between any pair of nodes within the network. In other words, if between any pair of nodes the communication is lost, the whole system is considered as unavailable.

- Approach 2: It calculates the availability from a node perspective. We have calculated the probability of a node to be totally isolated from the rest of the backbone. This means that we calculate, for every node, which is the possibility of a simultaneous fail in each of the links that connects it to its neighbours. This situation will be less common than the handled in the first approach, but also more critical, because the affected node will be unable to communicate not with some, but with any of the other nodes of the network.

Fig. 9. Availability in Series

Network Availability is calculated by modeling the system as an interconnection of parts in series and parallel [21]. The following rules are used to decide if components should be placed in series or parallel:

- If failure of a part leads to the combination becoming inoperationable, the two parts are considered to be operating in series.
- If failure of a part leads to the other part taking over the operations of the failed part, the two parts are considered to be operating in parallel.

4.4 Availability in series

As stated above, two parts X and Y are considered to be operating in series, if failure of either of the parts results in failure of the combination. The combined system is operational only if both Part X and Part Y are available. From this it follows that the combined availability is a product of the availability of the two parts. The combined availability is shown by the Eq. 2:

$$A = A_x \times A_y \tag{2}$$

4.5 Availability in parallel

As stated above, two parts are considered to be operating in parallel if the combination is considered failed when both parts fail. The combined system is operational, if either is available. From this it follows that the combined availability is 1 - (both parts are unavailable). The combined availability is shown by the Eq. 3:

Fig. 10. Availability in Parallel

$$A = 1 - [(1 - A_x)(1 - A_y)] \tag{3}$$

4.6 Calculating the availability of individual components

MTBF (Mean Time Between Failure) and MTTR (Mean Time To Repair) values are estimated for each component. Once MTBF and MTTR are known, the availability of the component can be calculated using the following formula (Eq. 4):

$$A = \frac{MTBF}{MTBF + MTTR} \tag{4}$$

4.7 Assumptions and data

Due to ubiquitious deployment, optical networks are prone to failures. While a considerable effort has been devoted to improve the physical protection of underground and underwater cables, fiber cuts occur at a significant rate. According to the US Federal Communications Commission (FCC), metro networks annually experience 13 cuts for every 1000 miles of fiber (0.81 cuts per 100 km per year), while long haul networks experience 3 cuts for every 1000 miles of fiber (0,19 cuts per 100km per year). [22]

In this study 0,8 errors per year per 100km of ditch has been considered as appropiate rate for the worst case calculations, while 0,5 errors per 100km per year has been considered as rate for the average calculations.

Repairing a cable typically takes up to 14 hours, but it may take as long as 100 hours in extreme cases. [22]

The following list contains the input parameters used for the availability estimation:

- $MTBF_1$ = 0,5 errors/year per 100km of ditch in average cases.
- $MTBF_2$ = 0,8 error/year per 100km of ditch in the worst case.
- $MTTR_1$ = 12 hours to fix a failure in average cases.
- $MTTR_2$ = 100 hours to fix a failure in worst cases.
- Fails in the nodes have not been considered. The probability of having fails in the nodes hardware compared to the probability of having fails in the fibers has been studied before and can be considered negligible. [23] [24].
- In the case of Grid topologies, corner nodes are the worst case for the availability study, because they are connected to the rest of the network using only 2 independent paths.

4.8 Availability Algorithm for Approach 1

Focusing on our first approach, the next procedure has been followed in order to calculate the average availability of the network:

1. Estimating the average $MTBF_{1st}$. $MTBF_{1st}$ denotes the average $MTBF$ for the first independent path (primary path). This estimation is calculated by multiplying the average number of hops (of the primary path) by the average link distance by the $MTBF_1$ parameter (Eq. 5):

   $$MTBF_{1st} = hops \times dist. \times MTBF_1 \tag{5}$$

2. Estimating the average $MTBF_{2nd}$. $MTBF_{2nd}$ denotes the average $MTBF$ for the second independent path (secondary path). This estimation is calculated by multiplying the average number of hops (of the seconddary path) by the average link distance by the $MTBF_1$ parameter (Eq. 6):

   $$MTBF_{2nd} = hops \times dist. \times MTBF_1 \tag{6}$$

3. Using $MTTR_1$ as $MTTR$ value.
4. Using $MTBF_{1st}$ and $MTBF_{2nd}$, as MTBF for the first and second path, respectively.
5. Applying the calculated parameters into the equation 4, in order to obtain the availability for both primary, and secondary path.
6. Calculating the final availability as the parallel of the first and the second independent path.

The availability of the network considering the worst case situation is calculated as follows:

1. Estimating the average $MTBF_{d1}$. $MTBF_{d1}$ denotes the average $MTBF$ for the longest first independent path (worst case), that corresponds to the diameter. This estimation is calculated by multiplying the diameter (of the primary path) by the longest link distance by the $MTBF_2$ parameter (Eq. 7):

   $$MTBF_{d1} = diam. \times Mdist. \times MTBF_2 \tag{7}$$

2. Estimating the average $MTBF_{d2}$. $MTBF_{d2}$ denotes the average $MTBF$ for the longest second independent path, that corresponds to the diameter of the second independent path. This estimation is calculated by multiplying the diameter (of the secondary path) by the longest link distance by the $MTBF_2$ parameter (Eq. 8):

   $$MTBF_{d2} = diam. \times Mdist. \times MTBF_2 \tag{8}$$

3. Using $MTTR_2$ as $MTTR$ value.
4. Using $MTBF_{d1}$ and $MTBF_{d2}$, as MTBF for the first and second path, respectively.
5. Applying the calculated parameters into the equation 4, in order to obtain the availability for both primary, and secondary path.
6. Calculating the final availability as the parallel of the first and the second independent path.

4.9 Availability Algorithm for Approach 2

Focusing on our second approach, the next procedure has been followed in order to calculate the average availability of every topological solution:

1. Estimating the $MTBF$ for each link. This estimation is calculated by multiplying the link distance by the $MTBF_1$ parameter.
2. Using $MTTR_1$ as $MTTR$ value.
3. Calculating the availability of every node. The availability of every node will be calculated as the availability of all its links in parallel.
4. Calculating the average (Eq. 9):

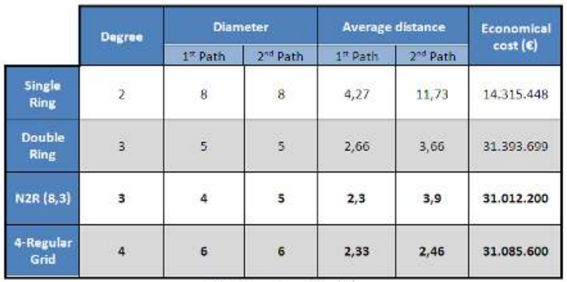
$$\bar{A} = \frac{\Sigma A_i}{N} \tag{9}$$

where A_i is the availability in the node i, and N is the total number of nodes.

The availability of the node placed in the most critical situation has been calculated as follows:

1. Estimating the $MTBF$ for each link. This estimation is calculated by multiplying the link distance by the $MTBF_2$ parameter.
2. Using $MTTR_2$ as $MTTR$ value.
3. Calculating the availability of every node. The availability of every node will be calculated as the availability of all its links in parallalel.
4. The final output result will correspond to the node with minor availability result "worst case".

5 Results



	Degree	Diameter		Average distance		Economical cost (€)
		1st Path	2nd Path	1st Path	2nd Path	
Single Ring	2	8	8	4,27	11,73	14.315.448
Double Ring	3	5	5	2,66	3,66	31.393.699
N2R (8,3)	3	4	5	2,3	3,9	31.012.200
4-Regular Grid	4	6	6	2,33	2,46	31.085.600

Fig. 11. General Topological Comparison

Fig.11 summarizes the results obtained after applying the selected topologies to the case study scenario. The first column shows the degree of each topology. In the single ring, double ring and N2R cases it is simple to obtain the degree, because they are completely regular topologies. However, in the case of 4 regular Grid, it is not so trivial because the topology is not completely regular. Internal nodes have degree 4 (valued showed by the table), whereas the nodes in the sides have degree 3, and the ones at the corners only degree 2. In our case study, with 16 nodes, the average degree is 3.

As it was commented in Sec. 4, the degree has a direct influence on the network reliability, because it limits the number of independent physical paths.

Regarding the diameter, single ring shows the worst results due to its structure: To reach an opposite node in a single ring, it is necessary to cover half of it. The most valuable topology in this area is N2R. A diameter of 4 for the first independent path, and 5 for the second, shows to be the most advanced solution. Notice that despite Grid has in the inner nodes degree 4, the average topological degree in our case study is 3, so diameter results are not better than in other degree 3 solutions. Even the double ring presents better results in this aspect. A possible solution to improve the results of the Grid, is to upgrade it to a "Torus" network. This has been studied in [19].

The average distance is the parameter that emphasizes the difference between the topologies the most. Thus, we see that the simplest topology has very low results compared to the rest. 11,73 is the average distance for the secondary path using single ring, while the worst secondary path average distance result among the rest of topologies, corresponds to N2R and is only 3,9. N2R is the most favorable topology taking the first independent path into account. However, if we also consider the second one, Grid is the referable solution.

The economic cost is favorable to the single ring. As reflected in the last column of Fig. 11, the economic cost is similar in all the advance topologies.

Regarding the non-quantitative parameters, 4 regular grid is the most interesting topology because of its well-known properties to support topological routing and expandability.

All the studied topologies are based on planar structures. In general, if we compare planar vs. non-planar topologies (e.g. Torus), the embeddability of the first group is higuer. Focusing on the studied topologies, Single Ring presents the most favorable embeddability properties, while Grid shows up as the worst case. This is due to the difficulty to find enough physical independent paths -typically roads- to construct a Grid topology on the real world.

Fig. 12, 13, 14, 15 and 16 contain the results from the availability study. Both the average and the worst case results are shown in every topology. Notice that they have been highlithed in the last row of each table.

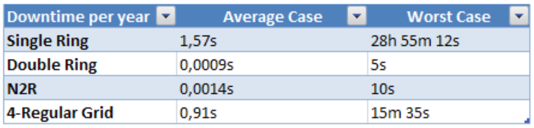
In the first approach (Fig. 12) only the first two independent pahts have been taking into account due to the level of complexity that implies calculating the necessary parameters (average number of hops and diameter) for the 3th (and 4th in the Grid topology) independent paths. Therefore, the availability differences between the degree 2 topologies (Single Ring) and the degree 3 topologies (Double Ring and N2R) are not significant.

According to the results from the second approach, single Ring performs good on average with results over five 9's, but not good enough in worst case conditions, where it shows much worse results than the rest of the compared topologies (only two 9's).

With similar results, Double Ring and N2R topologies arise as the most robust solutions. Both average results and worst case results, accomplish the five 9's high availability criteria.

Finally, 4-Regular Grid topology achieves up to seven 9's on average, and four 9's for the worst case.

Next, Figure 17 summarizes -according the second approach- the availability parameter as the downtime in a year scale:



Downtime per year	Average Case	Worst Case
Single Ring	1,57s	28h 55m 12s
Double Ring	0,0009s	5s
N2R	0,0014s	10s
4-Regular Grid	0,91s	15m 35s

Fig. 17. Downtime during a year

6 Conclusion

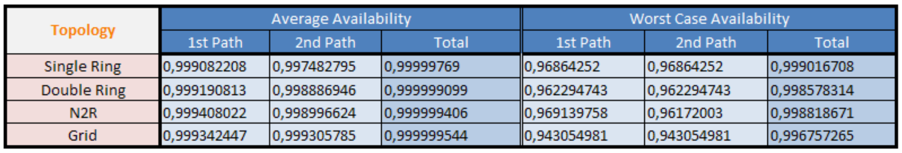
This paper has emphasized the importance of high-available backbones for new Internet applications and services.

A comparison framework has been shown. Besides, high reliable regular topologies have been compared to traditional solutions as single ring. Finally, the results of the study have been analyzed achieving the following conclusions:

1. Single ring topology is a really economical solution, but it is also the most limited one in all the studied features. Its large diameter, its lower average distance, and mainly its low degree (that limits the availability), may force it to be non-recommendable for next generation networks. Furthermore, we cannot guarantee high availability ($\geq$ 0,99999) for all the nodes conditions.

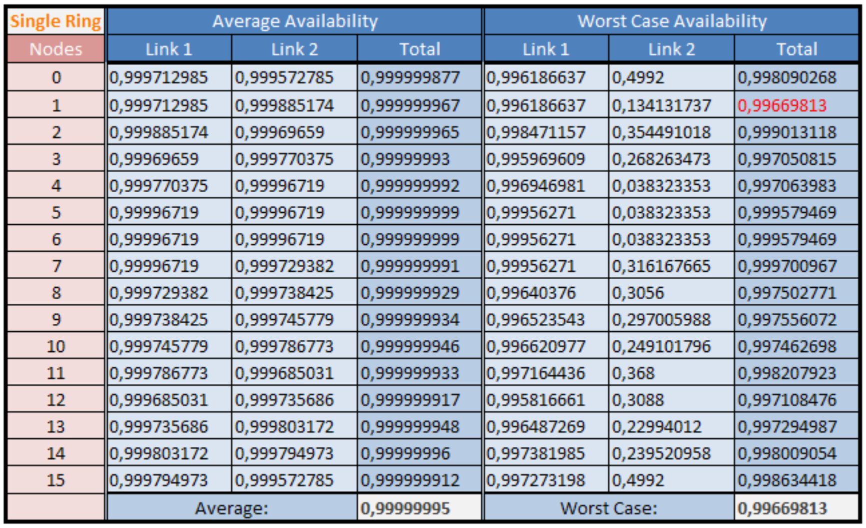
2. Focusing on degree 3 topologies, it has been proved that N2R obtains better results (in terms of average distances and diameter), than standard double ring. Regarding the availability, both have obtained results over five 9s.

3. 4-Regular Grid presents a similar cost than N2R. Its diameter is longer than in N2R, but on the other hand, the average distance for the second independent path is shorter. Also the scalability -it is easy to change the 4-Regular mesh into a triangular one, or to expand it as showed in [9]- and the possibility of using topological



Topology	Average Availability			Worst Case Availability		
	1st Path	2nd Path	Total	1st Path	2nd Path	Total
Single Ring	0,999082208	0,997482795	0,99999769	0,96864252	0,96864252	0,999016708
Double Ring	0,999190813	0,998886946	0,999999099	0,962294743	0,962294743	0,998578314
N2R	0,999408022	0,998996624	0,999999406	0,969139758	0,96172003	0,998818671
Grid	0,999342447	0,999305785	0,999999544	0,943054981	0,943054981	0,996757265

Fig. 12. Approach 1: Availability Results



Single Ring	Average Availability			Worst Case Availability		
Nodes	Link 1	Link 2	Total	Link 1	Link 2	Total
0	0,999712985	0,999572785	0,999999877	0,996186637	0,4992	0,998090268
1	0,999712985	0,999885174	0,999999967	0,996186637	0,134131737	0,99669813
2	0,999885174	0,99969659	0,999999965	0,998471157	0,354491018	0,999013118
3	0,99969659	0,999770375	0,99999993	0,995969609	0,268263473	0,997050815
4	0,999770375	0,99996719	0,999999992	0,996946981	0,038323353	0,997063983
5	0,99996719	0,99996719	0,999999999	0,99956271	0,038323353	0,999579469
6	0,99996719	0,99996719	0,999999999	0,99956271	0,038323353	0,999579469
7	0,99996719	0,999729382	0,999999991	0,99956271	0,316167665	0,999700967
8	0,999729382	0,999738425	0,999999929	0,99640376	0,3056	0,997502771
9	0,999738425	0,999745779	0,999999934	0,996523543	0,297005988	0,997556072
10	0,999745779	0,999786773	0,999999946	0,996620977	0,249101796	0,997462698
11	0,999786773	0,999685031	0,999999933	0,997164436	0,368	0,998207923
12	0,999685031	0,999735686	0,999999917	0,995816661	0,3088	0,997108476
13	0,999735686	0,999803172	0,999999948	0,996487269	0,22994012	0,997294987
14	0,999803172	0,999794973	0,99999996	0,997381985	0,239520958	0,998009054
15	0,999794973	0,999572785	0,999999912	0,997273198	0,4992	0,998634418
	Average:		0,99999995	Worst Case:		0,99669813

Fig. 13. Approach 2: Single Ring Availability Results

Double Ring	Average Availability				Worst Case Availability			
Nodes	Link 1	Link 2	Link 3	Total	Link 1	Link 2	Link 3	Total
0	0,999712985	0,999412615	0,999572785	0,999999999927977	0,996186637	0,992224532	0,99433366	0,999999832
1	0,999712985	0,99988515	0,99966104	0,999999999988827	0,996186637	0,998470835	0,995499347	0,999999974
2	0,99988515	0,999427668	0,999563161	0,999999999971286	0,998470835	0,992422392	0,994206691	0,999999933
3	0,999427668	0,999738425	0,999698691	0,999999999954892	0,992422392	0,996523543	0,995997418	0,999999895
4	0,999738425	0,999751407	0,999593275	0,999999999973552	0,996523543	0,996695556	0,994604074	0,999999938
5	0,999751407	0,999685031	0,999608333	0,999999999969333	0,996695556	0,995816661	0,994802884	0,999999928
6	0,999685031	0,999435194	0,99964598	0,999999999937021	0,995816661	0,992521352	0,995300259	0,999999853
7	0,999435194	0,999572785	0,9996761	0,999999999921845	0,992521352	0,99433366	0,995698516	0,999999818
8	0,999412615	0,999698691	0,999804128	0,999999999965334	0,992224532	0,995997418	0,997394672	0,999999919
9	0,999698691	0,999774001	0,99966104	0,999999999976918	0,995997418	0,996995057	0,995499347	0,999999946
10	0,999774001	0,999967193	0,999563161	0,999999999996761	0,996995057	0,999562748	0,994206691	0,999999992
11	0,999967193	0,999967193	0,999698691	0,999999999999676	0,999562748	0,999562748	0,995997418	0,999999999
12	0,999967193	0,999967193	0,999593275	0,999999999999562	0,999562748	0,999562748	0,994604074	0,999999999
13	0,999967193	0,99981166	0,999608333	0,999999999997580	0,999562748	0,997494626	0,994802884	0,999999994
14	0,99981166	0,999638451	0,99964598	0,999999999975893	0,997494626	0,995200744	0,995300259	0,999999943
15	0,999638451	0,999804128	0,9996761	0,999999999977062	0,995200744	0,997394672	0,995698516	0,999999946
	Average:			0,999999999970845	Worst Case:			0,999999818

Fig. 14. Approach 2: Double Ring Availability Results

N2R	Average Availability				Worst Case Availability			
Nodes	Link 1	Link 2	Link 3	Total	Link 1	Link 2	Link 3	Total
0	0,999712959	0,999572785	0,999412606	0,999999999927969	0,99433366	0,99618629	0,992224404	0,999999832
1	0,99988515	0,999712959	0,999510465	0,999999999983862	0,99618629	0,998470835	0,993512035	0,999999962
2	0,999427657	0,99988515	0,999698691	0,999999999980194	0,998470835	0,992422244	0,995997418	0,999999954
3	0,999738425	0,999427657	0,999520049	0,999999999928146	0,992422244	0,996523543	0,993638317	0,999999832
4	0,999751432	0,999738425	0,999490942	0,999999999966901	0,996523543	0,996695885	0,993254905	0,999999923
5	0,999685031	0,999751432	0,999461836	0,999999999957866	0,996695885	0,995816661	0,992871789	0,999999901
6	0,999435182	0,999685031	0,999432731	0,999999999899083	0,995816661	0,992521194	0,992488969	0,999999765
7	0,999572785	0,999435182	0,999403629	0,999999999856097	0,992521194	0,99433366	0,992106444	0,999999665
8	0,999751407	0,999600804	0,999412606	0,999999999941709	0,994703469	0,996695556	0,992224404	0,999999864
9	0,999924656	0,999698691	0,999510465	0,999999999988887	0,995997418	0,998996342	0,993512035	0,999999974
10	0,99966857	0,999774001	0,999698691	0,999999999977431	0,996995057	0,995598922	0,995997418	0,999999947
11	0,999751407	0,999721283	0,999520049	0,999999999966746	0,9962965	0,996695556	0,993638317	0,999999922
12	0,999924656	0,999969861	0,999490942	0,999999999998844	0,999598295	0,998996342	0,993254905	0,999999997
13	0,999600804	0,99966857	0,999461836	0,999999999928798	0,995598922	0,994703469	0,992871789	0,999999834
14	0,999698691	0,999721283	0,999432731	0,999999999952361	0,9962965	0,995997418	0,992488969	0,999999889
15	0,999774001	0,999969861	0,999403629	0,999999999995938	0,999598295	0,996995057	0,992106444	0,99999999
	Average:			0,999999999953177	Worst Case:			0,999999665

Fig. 15. Approach 3: N2R Availability Results

Grid	Average Availability					Worst Case Availability				
Nodes	Link 1	Link 2	Link 3	Link 4	Total	Link 1	Link 2	Link 3	Link 4	Total
0	0,999738425	0,999728156			0,999999928892327	0,99618629	0,992224404			0,999970346
1	0,999738425	0,999673394	0,999748009		0,999999999978472	0,99618629	0,998470835	0,993512035		0,999999962
2	0,999673394	0,999678186	0,999758962		0,999999999974665	0,998470835	0,992422244	0,995997418		0,999999954
3	0,999678186	0,999766356			0,999999924810032	0,992422244	0,996523543			0,999973656
4	0,999728156	0,999800725	0,999685031		0,999999999982938	0,996523543	0,996695885	0,993254905		0,999999923
5	0,999748009	0,999800725	0,999570048	0,999759647	0,999999999999995	0,996695885	0,995816661	0,992871789	0,996804763	0,999999901
6	0,999758962	0,999759647	0,999961645	0,999995206	0,999999999999999	0,995816661	0,992521194	0,992488969	0,999936077	0,999999765
7	0,999766356	0,999961645	0,999967193		0,999999999999706	0,992521194	0,99433366	0,992106444		0,999999665
8	0,999685031	0,999735686	0,999407885		0,999999999950706	0,992224404	0,996695556	0,994703469		0,999999864
9	0,999570048	0,999735686	0,999691191	0,999245775	0,999999999999974	0,996695556	0,9962965	0,993512035	0,990036347	0,999999921
10	0,999995206	0,999691191	0,999995206	0,999548834	0,999999999999999	0,9962965	0,995997418	0,995997418	0,994017738	0,999999941
11	0,999967193	0,999995206	0,999447566		0,999999999999913	0,995997418	0,998996342	0,993638317		0,999999974
12	0,999407885	0,999572785			0,999999747039809	0,998996342	0,999598295			0,999999597
13	0,999245775	0,999572785	0,999570732		0,999999999861683	0,999598295	0,996995057	0,992871789		0,999999991
14	0,999548834	0,999570732	0,99988289		0,999999999977319	0,996995057	0,995598922	0,992488969		0,999999901
15	0,999447566	0,99988289			0,999999935304647	0,995598922	0,994703469			0,99997669
	Average:				0,999999970985761	Worst Case:				0,999970346

Fig. 16. Approach 4: 4-Regular Grid Availability Results

routing is valued but also difficult to quantify. Availability is high on average terms, but not as good as degree 3 topologies in worst cases, due to the critical situation of the corner nodes.

7 Future Work

Creating an objective evaluation framework, in which each parameter had a scale to be evaluated (including the non-quantitative ones). The solution with higher average ranking would be selected. Networks could be classified so that a framework could be constructed, based on a combination of technical and business-model parameters.

Improving the approach 1 in the availability study: Including the third independent path (or even 4th where correspond) in the calculations, in order to emphasize the difference between topologies of different degree.

Extending the availability study (approach 2) to the nodes including the availability of them: Despite the erors in the hardware are not common, power supply fails, and other external factors could be considered. Thus, networks managers could decide if it is more efficient to invest in node redundancy, or in creating new independent paths in order to improve at a certain level the availability of their networks.

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