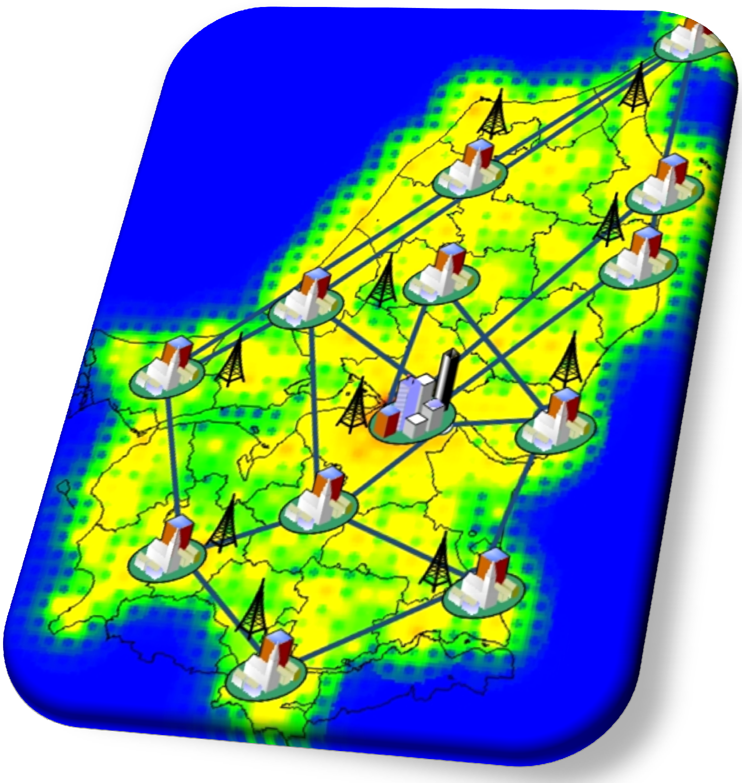
2008

Design of a new IT Infrastructure for the Region of Nordjylland

The Backbone Network



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Abstract

This master thesis concerns a design of a backbone for a new IT Infrastructure for the region of Nordjylland. The first chapter contains an analysis of the current situation of the IT Infrastructure in the area and fixes the aims of the project. After that, chapters 2 and 3 study the projection of population and bandwidth demand respectively. Both statistics are basic in the network planning process. Next, chapter 4 deals with the location of the nodes. The methodology used for deciding the number of nodes and its placement are explained in detail. Chapter 5 compares different topologic solutions in terms of degree, average distances and economical cost and decides which one fulfills better the initial requirements. Chapter 6 proposes a strategic deployment plan for the designed network. Chapters 7 and 8 analyze the traffic and the availability of the network respectively. Chapter 9 tries to quantify the necessary economical investment in the backbone. Finally, chapter 10 contains the conclusion and presents some future work lines.

Dedicated with affection to my family and friends:

Your support has been essential since the day I started my engineering studies

Preface

This document is written at the Department of Electronic Systems at Aalborg University and documents a final thesis made by Sergio Labeaga in Network Planning & Management line between February 4th and June 4th 2008.

The project concerns the *Design of a new IT Infrastructure for the Region of Nordjylland.* It has been divided in two different parts. The first one deals with the access network and it is presented in (Sevilla, 2008). The second one deals with the backbone network and is discussed in the present document.

Special effort has been paid to separate the initial assumptions and the methodology from the final results. Thus, applying the same methodology to other input data (e.g. other region) or adjusting the assumptions should not suppose any inconvenience. Illustrations are other of the aspects that have been specially detailed. Many diagrams, tables and graphs support the text with the objective of clarifying the reading.

Paragraphs including chapter conclusions or main decisions have been highlighted in italics. Thus, a fast overview of the project can be achieved only reading these parts.

The report has been written in Microsoft Word 2007. The figures are made in Microsoft Visio 2007. For the management of the data Microsoft Excel 2007 and MapInfo Professional 7.5 has been used.

Any questions regarding this project can be directed to slabeaga@gmail.com

Aalborg, Denmark, June, 2008

Content

1. Introduction

In this chapter the motivation and the project objectives are explained. After it, the region of Nordjylland and the situation of the current IT Infrastructure are described. Finally, some initial assumptions are introduced.

1.1 Motivation

Information technologies have a profound impact on a variety of bussiness applications and help to improve the quality of service and lower the costs. Technology has changed the nature of competition in all bussinesses (Aaby & Discenza, 1995). The use of technology can give an organization a competitive advantage. In addition, technology is an essential ingredient in the strategic plan of the organization.

Healthcare organizations are implementing electronic medical records, upgrading hospital informations systems, setting up intranets for sharing information, using public networks to distribute health-related information, and providing remote diagnostics via telemedicine (Raghapathi, 1997).

Customers want faster Internet conections. They want more video channels, movies “on demand” and new services as interactive gaming and virtual reality, that telcommunications and computer companies are now beginning to offer. (Speta, 2000).

It is clear that new information systems have a powerful potential to improve the functioning of all organizations. However, that potenial can only be realized if information systems can be successfully developed and implemented (Paul, Pearlson, & McDaniel, 1999).

Yet one historic technological barrier to these services remains: the phone lines. While computer operating speeds have greatly and rapidly increased, the capacity of the connections to individual computers in homes and small businesses will remain unchanged unless other technology was used. The heart of the matter are traditional copper lines, the ends of the true communications network that reaches every business and residence, simply do not have enough transmission capacity to deliver these services to individual customers.

Videoconference, telemedicine, domotic, HD[1] television, among other emerging services, force the task of replacing (as soon as posible) the old acces network for a new one, based on technologies able to provide higher bandwidth as e.g. FTTH.

The planning and construction of a new generation IT[2] infrastructure for the region of Nordjylland could be an important supporting point in the replacement process of the old local loop[3], which would open final subscribers the possibility of using all these new services.

[1] High Definition.
[2] Information Technology.
[3] It is the physical link or circuit that connects from the demarcation point of the customer premises to the edge of the carrier, or telecommunications service provider, network.

1.2 Project objectives

The main objective of this project is to design a new Triple Play[4] telecommunication network for the region of Nordjylland. The project is divided in two different parts: the access network that is discussed in (Sevilla, 2008) *and the backbone network, in which this project is focused.*

The network should be able to work as backbone for a WiMAX access network in short-term and also for a FTTH access network in long term. The design of the backbone network is a delicate process because of the influence of many factors and the necessity of achieving a trade-off between them. The backbone must carry out the following requirements:

- ***Cover more than 95% of the Network Terminals (NTs)***. The network must not be projected only from a commercial point of view. It must be assured than most of the NT, independently from their location, have access to the new IT infrastructure.
- ***Availability higher than 99,999%.*** The network must be highly reliable. The operation of critical services as telemedicine or videoconference must be assured. The standard availability required by most of the telecommunication providers for optical fiber communications is five 9s (Grover, 2003).
- ***Reduced cost***. This objective forces the planning task to find cost-effective solutions to all the previous requirements.
- ***Scalability***. The network must be completely scalable. Nowadays future services demands are difficult to predict and by this reason the network must be as dynamic and scalable as possible. It must be prepared for future improvements without the necessity of modifying the deployed model.
- ***Balanced traffic between nodes***. Nodes load and also traffic between them must be evenly shared. This way scalability and availability goals will be easier fulfilled (Hermann, 2003)**.**

1.3 Project methodology

Following tasks are pretended to be realized:

1. Nodes location **(Figure 1)**. According NTs distribution and taking into account WiMAX projected infrastructure (Sevilla, 2008), economical and geographic factors, the best place to locate the nodes will be discussed.
2. Study of the topology **(Figure 2)**. Linking the nodes is probably the most critical part. It will be necessary to achieve a trade-off between reliability, scalability and low cost.
3. Deployment plan. Guidelines about the network construction and priorities will be discussed.
4. Traffic study. The traffic in each link will be estimated.
5. Availability study. The time when the network will be inactive during a year will be checked. This way it is possible to verify if the network fulfils the availability five 9s requirement or not.
6. Budget. The total cost of the network will be calculated.

[4] Term for the provisioning of three different services: High-speed Internet access, television and telephone.

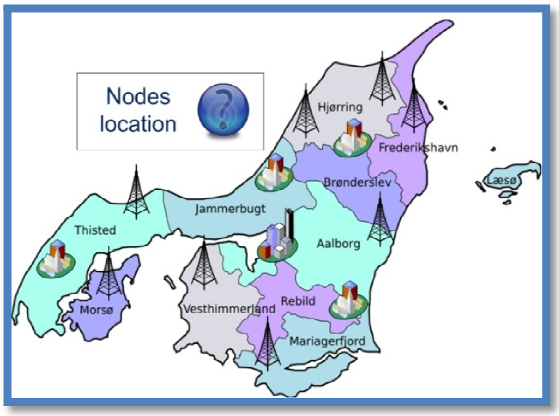


Figure 1: Nodes Location

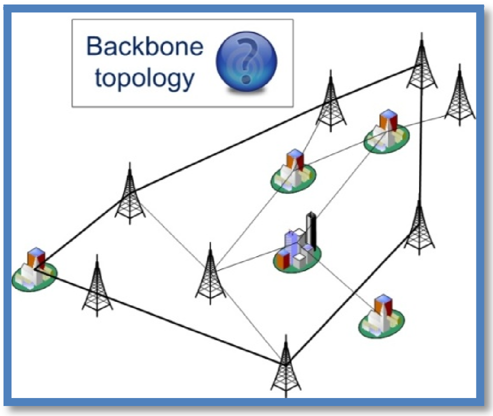


Figure 2: Backbone topology

Next, **Figure 3** shows the process flow diagram:

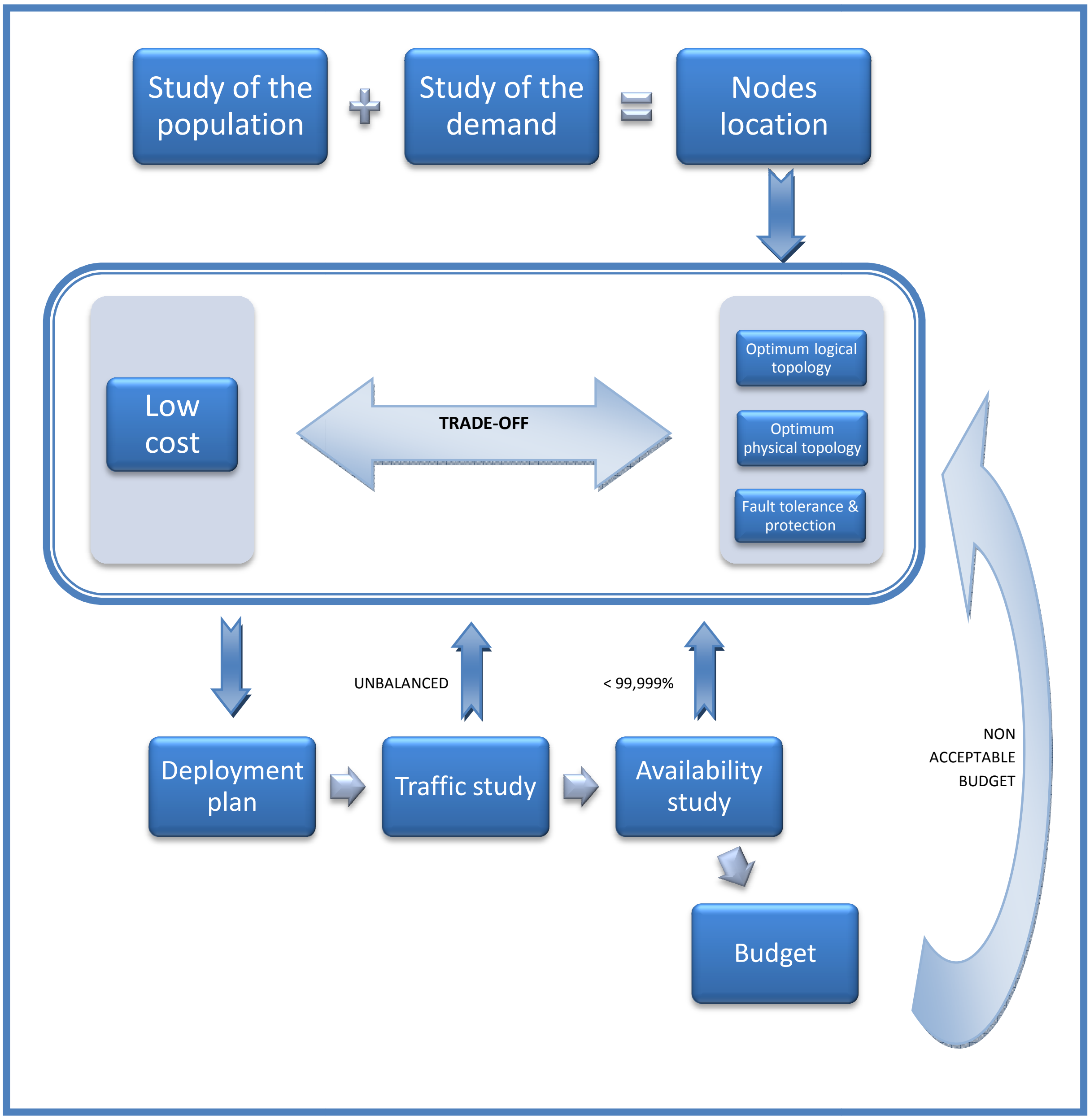


Figure 3: Process diagram

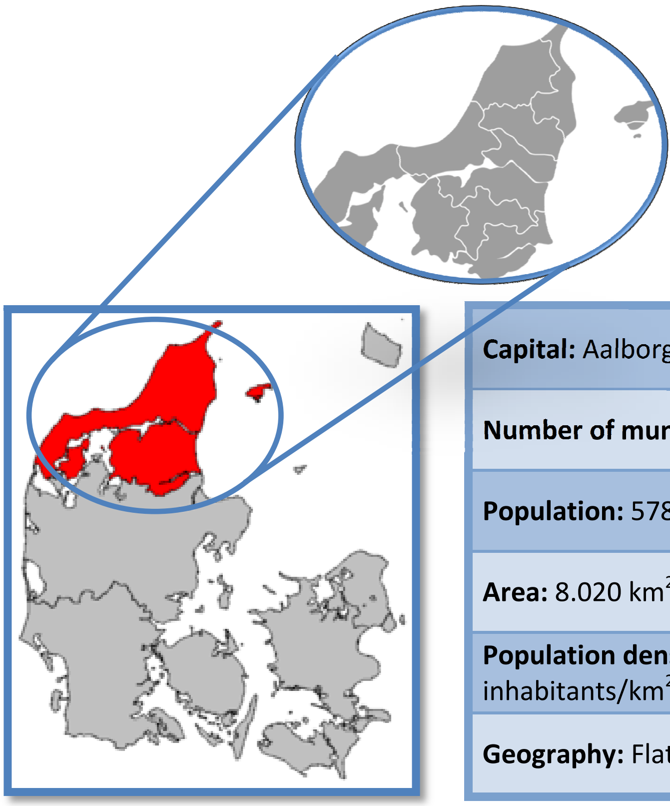
1.4 The Region of Nordjylland

Denmark is divided into five regions and a total of 98 municipalities. The regions were created on 1 January 2007 as part of the 2007 Danish Municipal Reform to replace the country's traditional thirteen counties. At the same time, smaller municipalities (kommuner) were merged into larger units, cutting the number of municipalities from 270 to 98 (National Statistician Department, 2008).

The country consists of a large peninsula, Jutland (Jylland) and a large number of islands. The Faroe Islands and Greenland are autonomous provinces of Denmark with home rules.

Denmark is really flat with little elevation; having an average height above sea level of only 31 metres and the highest natural point is Møllehøj, at 170 metres.

Nordjylland is the northern region of Denmark **(Figure 4)** and it is also the less populated one. Its largest city (and also the capital) is Aalborg, the fourth largest one in Denmark, which population was 100.731 inhabitants (2007). Nordjylland covers an area of 8.020 km^2, which means that its population density is about 72 inhabitants per km^2, the lowest one in the country.



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

Figure 4: The región of Nordjylland

1.5 Description of the current IT Infrastructure

The current situation of the IT Infrastructure in Denmark is quite similar to the situation in other devoloped countries in Europe. Important backbone networks are already deployed but there exist a bottle neck in the access network[5] that covers from the final users till the aggregation nodes (Speta, 2000).

This bottle neck is due the bandwidth limit of the traditional copper lines. The replacement of the old access network based on copper wires from POTS[6] for new generation technologies able to provide higher transfer rates is a really expensive task, especially in areas with low population density as Nordjylland **(1.4The Region of Nordjylland).**

Statistics prove that this replacement has already started in recent years, with FTTH subscriptions increasing more than 100% in 2006 and 2007 **(Figure 5)**.

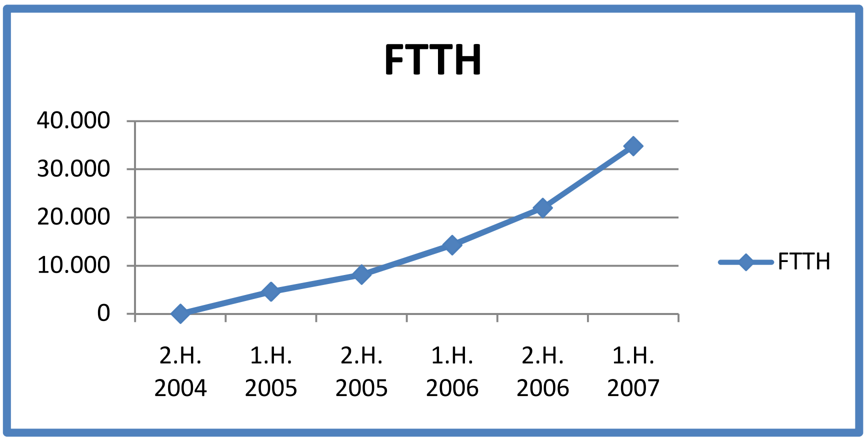


Figure 5: FTTH Subscribers, Denmark, 2004-2007

In this aspect Denmark is one of the most advanced countries in Europe as shown the next graph **(Figure 6)**. (National IT and Telecom Agency, 2007)

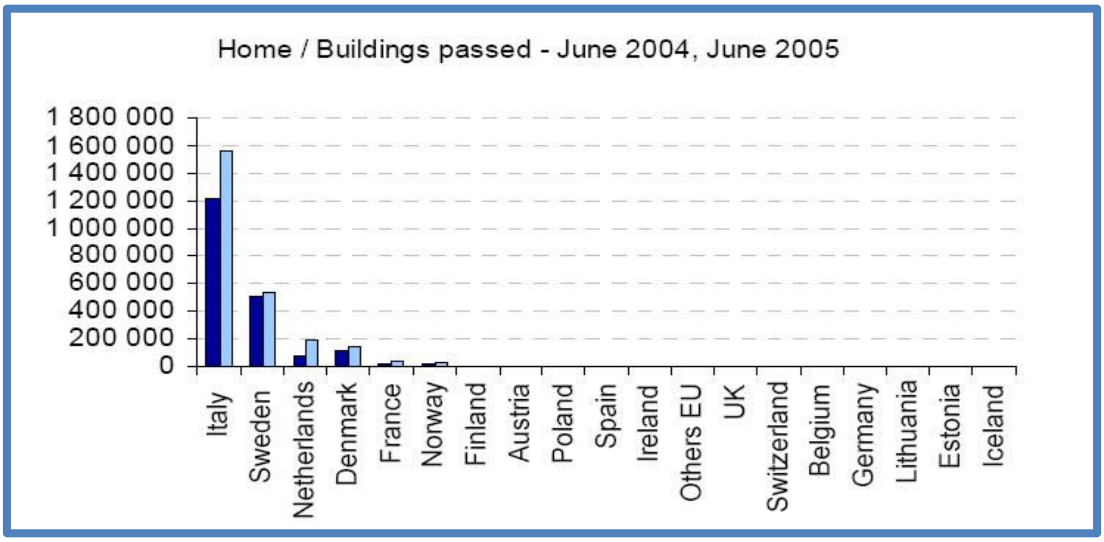


Figure 6: FTTH deployment situation in Europe

[5] Also called Last Mile.
[6] POTS (Plain Old Telephone System)

In despite of this data, the replacement is still in early stages:

Table 1 proves that FTTH technology is only used in less than 2% of the subscribers lines. Techonolgies based on traditional copper wires are the most extended. xDSL and cable modem conections are still increasing and represent more than 90% of the broadband subscriptions in Denmark.

Other technologies as WiFi or WiMAX are growing slowly and do not represent more than 2% of the total.

	2.H. 2004	1.H. 2005	2.H. 2005	1.H. 2006	2.H. 2006	1.H. 2007
xDSL	638.961	714.032	826.439	947.958	1.062.040	1.154.916
Cable modem	296.470	331.521	389.636	490.969	506.734	529.849
FTTH	-	4.575	8.118	14.245	21.961	34.795
FTTx[7]	-	-	-	-	7.611	8.136
Satellite	-	4	111	146	149	7
PLC	-	88	92	95	99	94
WLL[8]	-	4.010	4.785	4.679	3.761	3.820
WiFi	-	8.943	7.806	11.273	5.957	4.951
WiMAX	-	16	2.495	7.248	12.272	13.889
LAN[9]	-	101.752	104.187	108.413	113.624	113.476
Others		250	186	328	672	706
Total	1.017.594	1.165.191	1.343.855	1.585.354	1.734.880	1.854.639

Table 1: Broadband[10] subscriptions, Denmark, 2004-2007.

Concluding the study, it could be stated that even though Denmark is one of the European countries with more advances in IT Infrastructures, there is still a long way ahead. The fixed access network should be replaced in next 12 years by FTTH. The present project pretends to contribute to accelerate this replacement by designing a new reliable and cost effective IT Infrastructure, and proposing strategic deployment plan that allows making profit from the initial investment in short-term (2 years).

[7] Fiber to other than `home`.

[8] Wireless Local Loop. e.g. FWA (Fixed Wireless Access)

[9] Number of households in residential associations, student houses, etc. with broadband subscription via internal network. The network can be based on either PDS cabling or a wireless network (WLAN). The internet connection that the households share via the local network can be fiber optic cable, FWA, xDSL, etc.

[10] Minimum capacity of 144kbit/s.

1.6 Assumptions and notes

This section exposes all the assumptions used in the project. It also clarifies the solutions to the problems occurred while the solution was being performed.

1. Data used in the simulations only include the old region of Nordjylland. Unfortunately, data of the new region was not available when this project was performed. Nevertheless, all the methods, stages and processes would remain identical with the new data.
2. Data processed had an important error: Only businesses around Aalborg municipality were registered in the NTs[11] database. Businesses in other areas were tagged as households. In order to solve this problem, 5% of the households of each municipality have been 're-tagged' as small businesses.
3. Despite of the Access Network (Sevilla, 2008) and this one (the backbone) are related, it is possible to find some differences, especially in the location of the Base Stations. This project has been realized according the BS[12] location results obtained by David Sevilla on April 14, 2008. Changes in his data after that date are not reflected in this project because of the impossibility of finishing it on time.
4. In terms of bandwidth demand, small businesses will have on average similar requirements to the residential users, so identical bandwidth will be provided to them.
5. It has been assumed that important companies and administration will require individual solutions. Due the impossibility of studying in detail every case because of the lack of time and data resources, they have not been tackled. Nevertheless, an extra 20% of the bandwidth in each backbone link will be reserved for them.
6. Reliability of the network: 1 fail per year per 100 km of fiber has been be considered in order to realize this study. (Grover, 2003).
7. Economical cost: The cost of 1 meter of ditch is 28 € (Gustav Helgi Haraldsson; Jens Myrup Pedersen, 2007).
8. Correction of the distances. It is evident that fiber ducts cannot be installed (physically) everywhere. Normally they must follow roads infrastructure. This fact force to correct distances measured in straight line. It has been assumed that, on average, real distances (following roads) are $\sqrt{2}$ times straight line distances. (Phibbs & Luft, 1995).

[11] Network Terminal
[12] Base Station

1.7 Software and tools

Next, **Table 2** shows the programs that have been used in this project:

	Software	Use
	Microsoft Word 2007	The report has been realized using Word 2007 as text processor software.
	Microsoft Visio 2007	Most of the diagrams that illustrate the report have been performed Visio 2007.
	Microsoft Excel 2007	Microsoft Excel 2007 has been useful in the management of data and creation of graphs.
MapInfo	Map Info 7.5 Professional	MapInfo Professional has been used to combine and display, on a single map, data from a variety of sources. The creation of the NTs distribution diagrams and most of the distances calculation have been realized using this application.

Table 2: Software and tools

2. Study of the population

In this chapter the population in Nordjylland is studied. The study includes projections by municipality for the next 20 years. Special attention is paid to the household and small businesses distribution in the entire region.

2.1 Study of the current population by municipality

Region of Nordjylland is composed by 11 municipalities. Next, **(Table 3)** shows the population and the number of households in each municipality (National Statistician Department, 2008).

Municipality	Population	Households
Aalborg	195.145	95.277
Brønderslev	35.525	15.833
Frederikshavn	62.751	29.709
Hjørring	67.121	30.526
Jammerbugt	38.957	16.835
Læsø	2.003	1.050
Mariagerfjord	42.667	18.709
Morsø	22.091	10.188
Rebild	28.753	11.911
Thisted	45.549	20.432
Vesthimmerland	38.277	16.943

Table 3: Municipalities of Nordjylland

*Notice that Aalborg municipality, with a population of 195.145, concentrates around 33% of the inhabitants of the whole region. This fact will be taken into account in the **chapter 4: Nodes Location.***

2.2 Population projections

Due the fact that a new IT Infrastructure should be operating for years, it is also essential to study future population projections. Migrations fluxes and future urban sprawl have to be considered because they affect the Nodes Location procedure **(4 Nodes Location)**.

According (National Statistician Department, 2008), population in Nordjylland will growth arround 2% in the next 20 years **(Figure 7)**. This growth is so slight that, from a global perspective, current data will be perfectly valid for the network planning simulations.

From local perspective this data is not conclusive because it is only focussed on the whole region and it does not consider possible migration fluxes beween municipalities within the region. In order to prevent this event, also population projection by municipality have been consulted **(Figure 8).**

Changes in the population distribution within a city should not affect a backbone network and are out of the objectives of this project **(1.2 Project objective).**

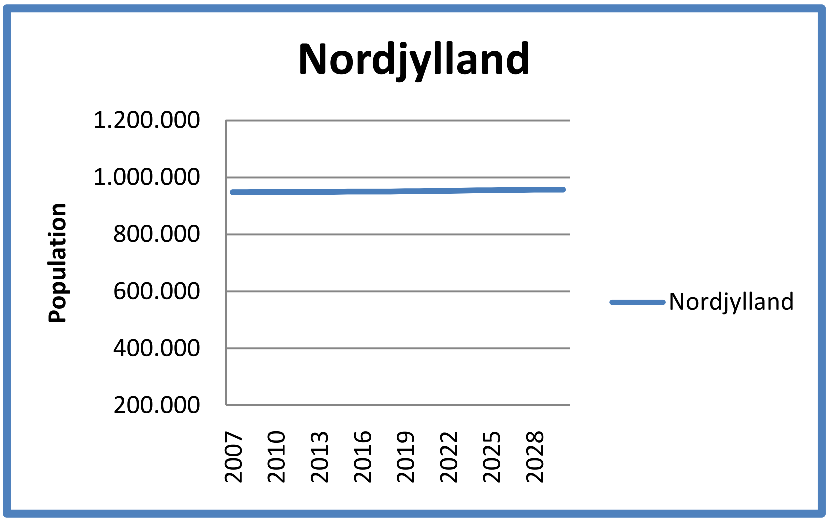


Figure 7: Nordjylland population prediction

Next, **(Figure 8)** shows the estimation of population changes per municipality in the next years (National Statistician Department, 2008):

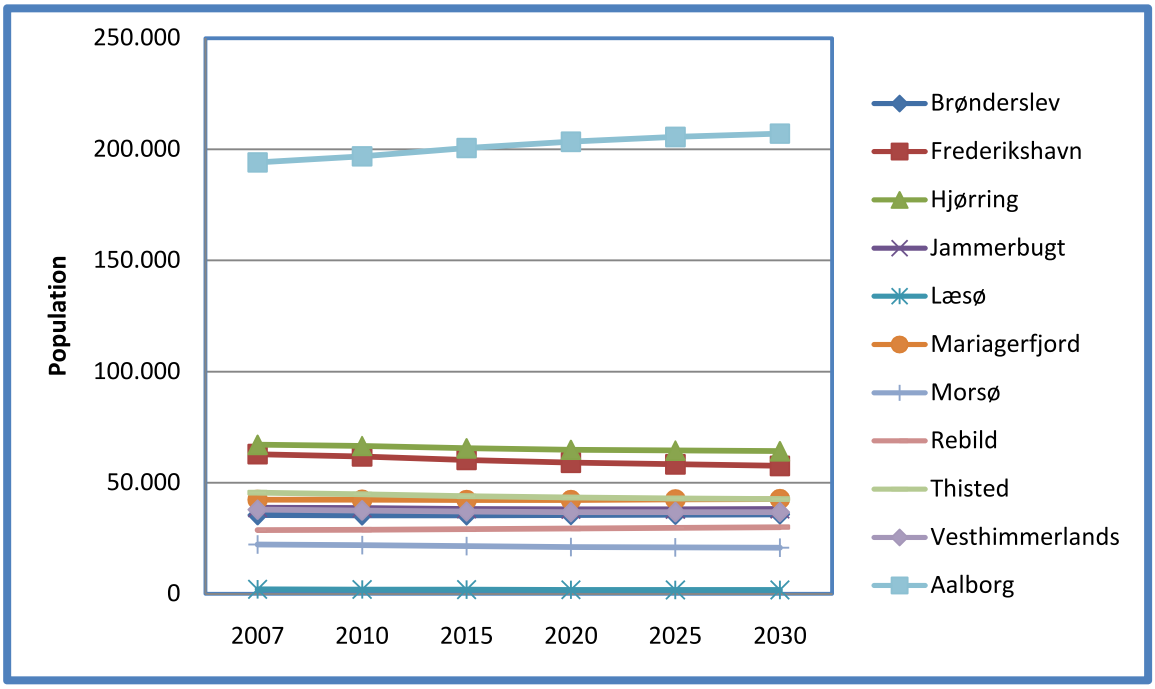


Figure 8: Population growth estimation

Notice that none of the municipalities will register important variations. Only Aalborg municipality, will increase gradually its population achieving 207.005 inhabitants in 2030, which implies a growth of 6,5 %.

The conclusion of the study is favorable because of the fact that demographic stability for the next years simplifies the task of placing the nodes. If important migration fluxes had been predicted, the planning procedure should take into account these changes, which would increase both, the complexity and the total budget.

2.3 Population distribution

Another important point related to the population is their exactly distribution. It is essential to know where the final users are concentrated in order to design a cost-effective network.

MapInfo 7.5 Professional[13] has been used for this process. Two different layers have been displayed:

1) Political map with the municipalities.
2) Networks Terminals[14] (NT).

Once the NTs have been placed on the map, a third layer, composed of a grid with 1564 cells (3x3 km size) has been drawn over them. After it, a thematic map has been created. The results are shown in the next **Figure 9:**

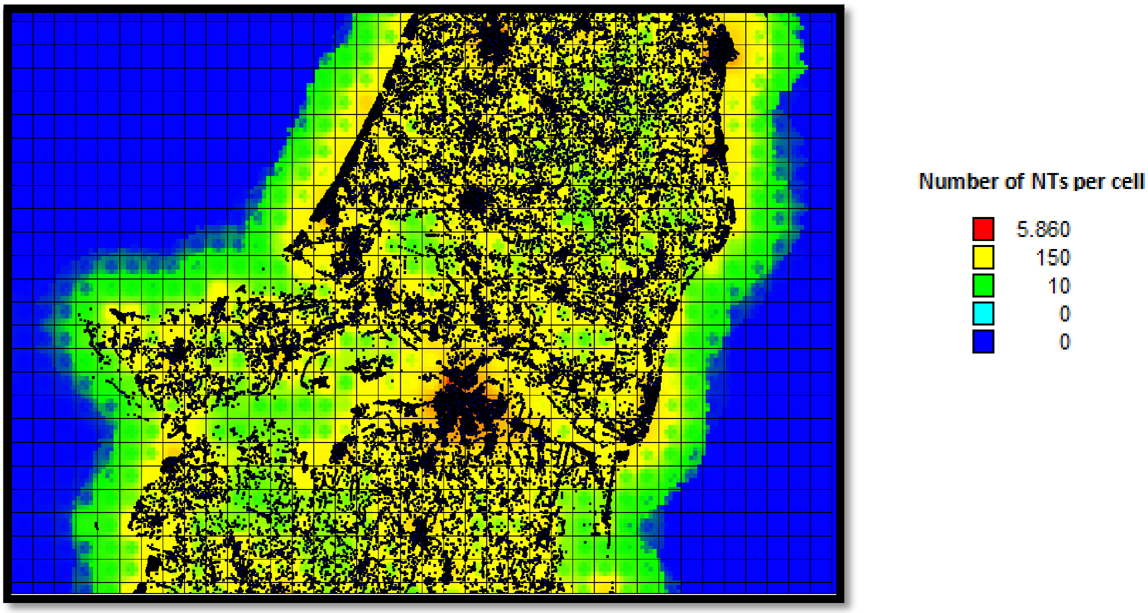


Figure 9: Network Terminal Density Map

Notice that, according to the legend, regions with the most NT density are in yellow or red, whereas low-density areas are in green or blue.

One of the main problems in the creation of the thematic map was the long time that it takes the procedure. Due the huge amount of data, the creation of a thematic map with a cell size of 3km x 3km is more than 7.5 hours[15]. Insofar as the cell size is reduced the time of processing increases dramatically.

[13] MapInfo Professional is a Geographic Information System software product produced by MapInfo Corporation. It has the ability to combine and display, on single map, data from a variety of sources that are in different formats and projections.
[14] NTs include households (234.586) and small businesses (6.848) in the whole region.
[15] Intel Core 2 Duo processor 2 GHz, 800 MHz FSB, 4MB L2 cache, 2G B RAM DDR2.

3. Estimation of the bandwidth demand

This chapter tries to estimate the bandwidth required by each subscriber in the next years. This estimation is essential in order to calculate in next chapters the traffic of the backbone.

In a first approach different sources are consulted in order to estimate this bandwidth. The results from the sources are quite different. They all agree in the difficulty to estimate the data. Then, due the impossibility of obtaining accurate projections, a second approach consisting of establishing scenarios is considered.

3.1 Study of the bandwidth demand

In this section an estimation of the bandwidth demand of the future customers is presented.

Demanded bandwidth by residential costumers increases each year. Among the most common services, voice over IP (VoIP) is the one that consumes less bandwidth: around 0,1 Mbps. Surfing fluently the Internet requires between 5 and 10 Mbps and four HDTV channels using H.264 encoder will require a bandwidth around 30 Mbps[16] **(Figure 10)**. (Coward, 2007)

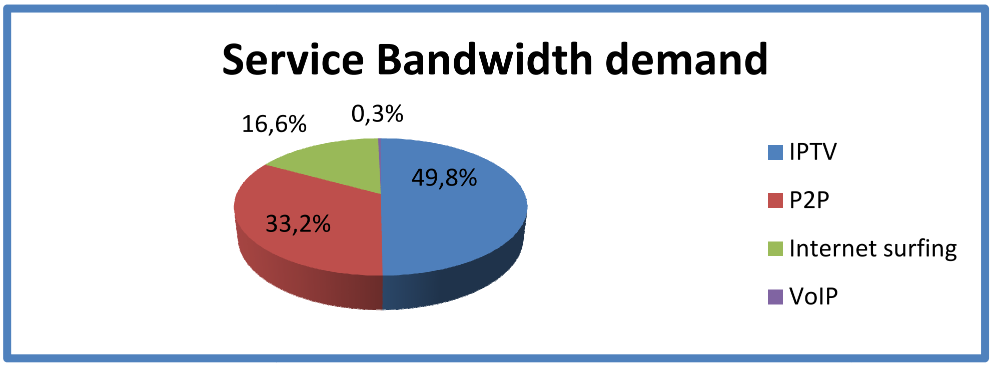


Figure 10: Bandwidth demand by service

Thus, it is essential to provide them a bandwidth between 25 and 100 Mbps (or even more) to use new generation services. (Qwest Corporation, 2005)[17].

As was commented in the chapter's introduction, most of the projections do not conclude with specific results. This is not an exception. A range between 25 and 100 Mbps is not enough accurate in order to simulate with a single value.

[16] Qwest is a leading provider of voice, video and data services across America and the world. www.qwest.com

In terms of bandwidth demand, small businesses will have on average similar requirements to the residential users, so identical bandwidth will be provided to them.

Important businesses and administration should be studied in an individual way depending on their size and activity because they will probably require customized solutions and redundancy in the access network. Due to limited time and data resources these types of clients will not be tackled. The project will be focused on residential subscribers and small businesses. Nevertheless an extra 20% of the total backbone capacity will be reserved to them.

3.2 Definition of the scenarios

Since that task of predicting the bandwidth required by customers in the future is almost impossible, a second approach has been executed. It consists in the creation of three different models or scenarios. Each scenario considers a different bandwidth projection. The network will achieve a trade-off between all of them in such a way that should be cost-effective on one hand, but also scalable and able to provide the most optimistic bandwidth projections on the other one.

Scenario A is the most conservative and estimates an average bandwidth per user of 25 Mbps. The main access technology used by subscribers should be WiMAX.

Scenarios B and C are moderate and optimistic and will predict bandwidths per user of 50 and 100 Mbps respectively. The access technology in scenario B should be FTTH for the urban areas and WiMAX for countryside. Scenario C should use FTTH everywhere plus WiMAX (extra 25 Mbps) for covering mobility[18].

Table 4 shows a summary of the scenarios:

	Projection	Fixed Bandwidth per subscriber	Mobile Bandwidth per subscriber	Fixed Access Technology	Mobile Access Technology
Scenario A	Conservative	25 Mbps	-	WiMAX	-
Scenario B	Moderate	50 Mbps	-	WiMAX or FTTH	-
Scenario C	Optimistic	100 Mbps	25 Mbps	FTTH	WiMAX Mobile

Table 4: Definition of the scenarios

Therefore, these three scenarios will be studied from now on in future stages of the project. This way, independently of the uncertainty about the future, all the predicted range will be covered. Deployment plan, on ***chapter 6****, will give more information about the terms and infrastructure projected to cover each possible scenario.*

[18] Mobile WiMAX deployments allow handoff between Base Stations, therefore the service provider can offer mobility.

4. Nodes Location

This chapter deals with the nodes placement process for the network backbone. It is divided in three sections: The first one introduces the consequences and factors involved and defines some restrictions. The second one explains thoroughly the methods used. Finally, the third one shows the final results.

4.1 Number of nodes: Restrictions and implications

Choosing the number of nodes it is not a simple task because the decision affects the following critical parameters:

1) The topology. Some topologies as N2R cannot be implemented in any number of nodes. So, the decision should take in account this aspect.
2) The traffic distribution. The more the number of nodes the less the traffic they will have to process. Trade-off 1 is focused on this problem.
3) The economical cost. The higher the number of nodes, the higher the cost of the backbone network. But, on the other hand, the less the cost of the access network. Trade-off 2 is focused on this problem.

Next, **Figure 11** gives an overview about these implications:

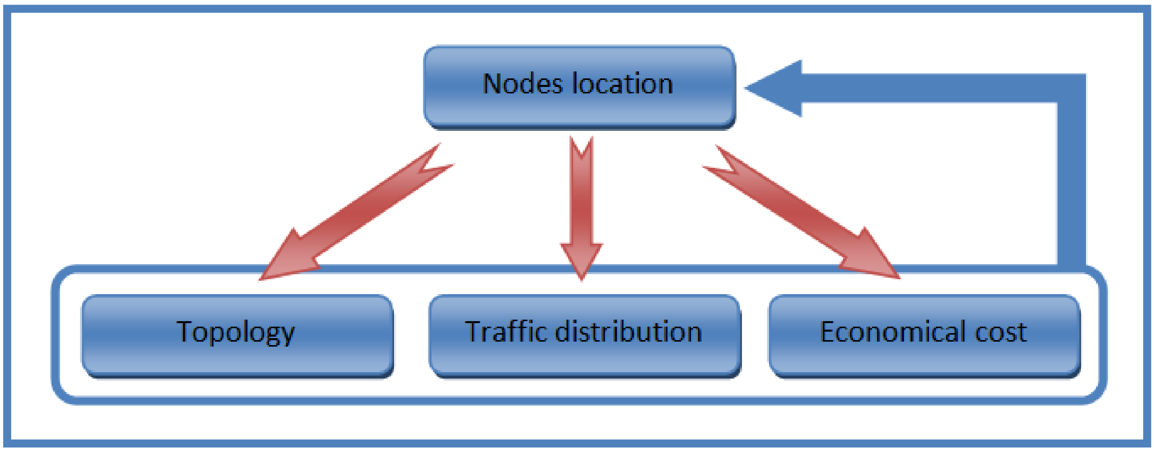


Figure 11: Nodes location iterative process

Following sections describe the most important trade-offs that we have to manage.

4.1.1 Trade-off 1: Minimizing cost vs Reducing the traffic per node

Obviously, a lower number of nodes imply reducing the cost of the backbone. Despite the equipment in each node has to be more powerful and expensive (because more data have to be processed in each node), on the other hand, less equipment is necessary. Also, all the expenses related to premises renting and nodes maintenance decrease.

Supposing that the nodes will give out the traffic equitably (balanced network), the less the number of nodes, the more the traffic that they have to process. This implies worse consequences in the case of a node-failure because the traffic will be concentrated only in a few nodes.

Next, the traffic that should be processed by the nodes in the remote case than all the NTs should use all the bandwidth at the same time is estimated using following methodology:

1) The total gross traffic is obtained by multiplying the total number of NTs for the maximum bandwidth in each scenario.
2) This total traffic is divided by the number of nodes. (It is supposed that all the nodes cover the same number of NTs).

Of course, this case is not realistic, and in **chapter 7 (Traffic Study)** some reduction coefficients will be applied. In spite of the data it is not realistic yet, it should be really useful in order to do some initial calculations.

Next, **Table 5** shows the results:

	Bandwith per NT	Number of NTs	Total[19] (NTs)	TOTAL
Scenario A	25 Mbps	241.434	754.481 Mbytes/s	905.377 Mbytes/s
Scenario B	50 Mbps	241.434	1,508 TeraBytes/s	1,809 TeraBytes/s
Scenario C	125 Mbps[20]	241.434	3,772 TeraBytes/s	4,526 TeraBytes/s

Table 5: Total traffic in the backbone

After calculating the total 'gross' traffic of each scenario, **Figure 12** shows how much of this traffic would be processed per node in function of the backbone's node number.

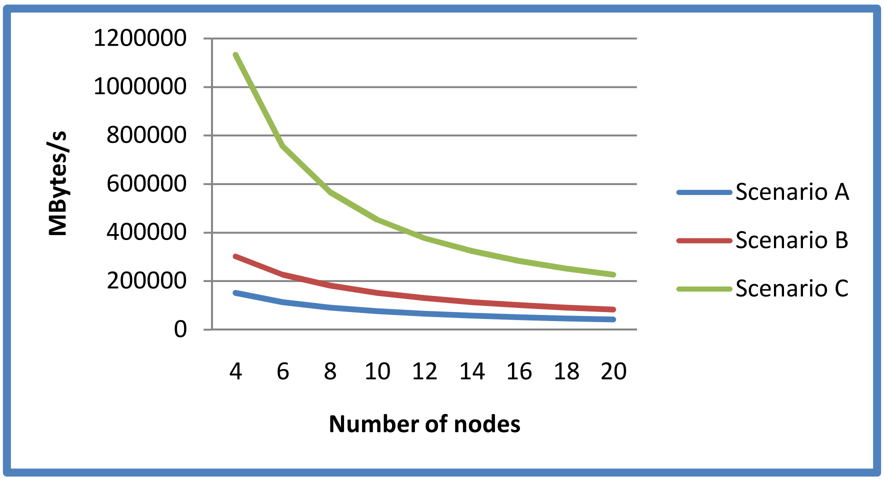


Figure 12: Total traffic per node

Notice that the increment from 4 to 6 nodes would imply that each one of the 'old nodes' should process 33,3% less of traffic. On the other hand, an increment from 20 to 22 nodes only would imply a reduction of 9,10%.

[19] This column contains the total traffic excluding administration and important businesses.
[20] Includes fixed traffic + mobility WiMAX support.

Next graphic **(Figure 13),** illustrates this difference. Insofar as the number of nodes become higher, adding 2 new nodes implies a minor reduction.

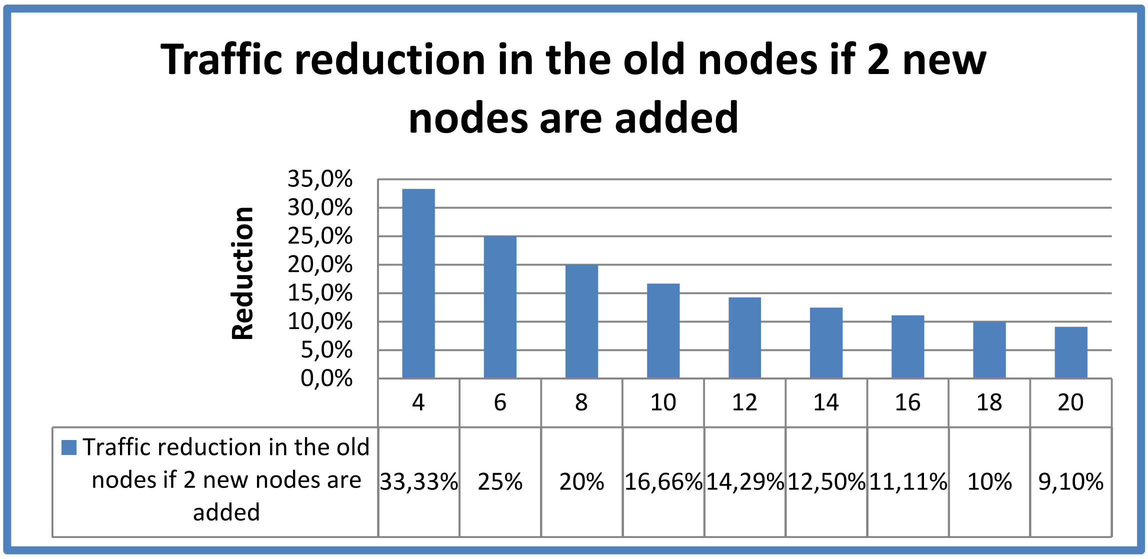


Figure 13: Traffic reduction in the old nodes if 2 new nodes are added

Hence, it is possible to conclude that investing in the increment when the number of nodes is reduced could be interesting (from 6 to 16) but not when the network has more than 20 nodes because the economic investment does not imply an important traffic reduction (less than 9%).

4.1.2 Trade-off 2: Backbone cost vs. Access cost

As was explained in last section, a lower number of nodes reduces the cost of the backbone network but, on the other hand, raises the cost of the access network.

Next, this problem is explained in detail for each scenario:

- Scenario A. In this scenario the access technology used for all the subscribers is WiMAX. This implies that each one of the BS -placed in (Sevilla, 2008)- must be connected to the backbone. Independently of the topology used to connect them, described in detail in (Sevilla, 2008), the less nodes we use the longer average distances between them and the BS.
  Optimal solution for this scenario is not complicated: If each node is placed as close as possible to each BS the cost of the Access Network is minimized.

- Scenario B. This scenario combines FTTH and WiMAX as technologies used in the last mile. This implies linking –apart from the BS- some COs[21] to the backbone.

[21] A central office (CO) is the physical building used to house inside plant equipment including telephone switches.

What it is important to emphasize here is that COs of towns and cities where FTTH is deployed must also be connected to the closest backbone node. Now the location process is not so easy, because the number[22] of COs to connect is much higher than the number of BS. In contrast to the methodology explained for scenario A, it is not possible to place a node next to each COs because this number is too high.

The solution must achieve a compromise between the number of nodes and its location. The less the number of nodes, the less the cost of the backbone, but on the other hand, the more number of nodes, the less average distance between them and the COs (the less the cost of the access network). The ideal number of nodes should be the one that optimizes this trade off and minimizes the global cost of the network.

- Scenario C. This optimistic scenario considers that all the subscribers use FTTH as access technology plus WiMAX for covering mobility. This implies that all the COs –and the BS- must be connected to the backbone.
  Therefore, the criteria for placing the nodes in this scenario should be the same than in scenario B. The only difference is that now, the number of COs to connect to the backbone is much higher.

Next, **Figure 14** illustrates the explained compromise for each scenario:

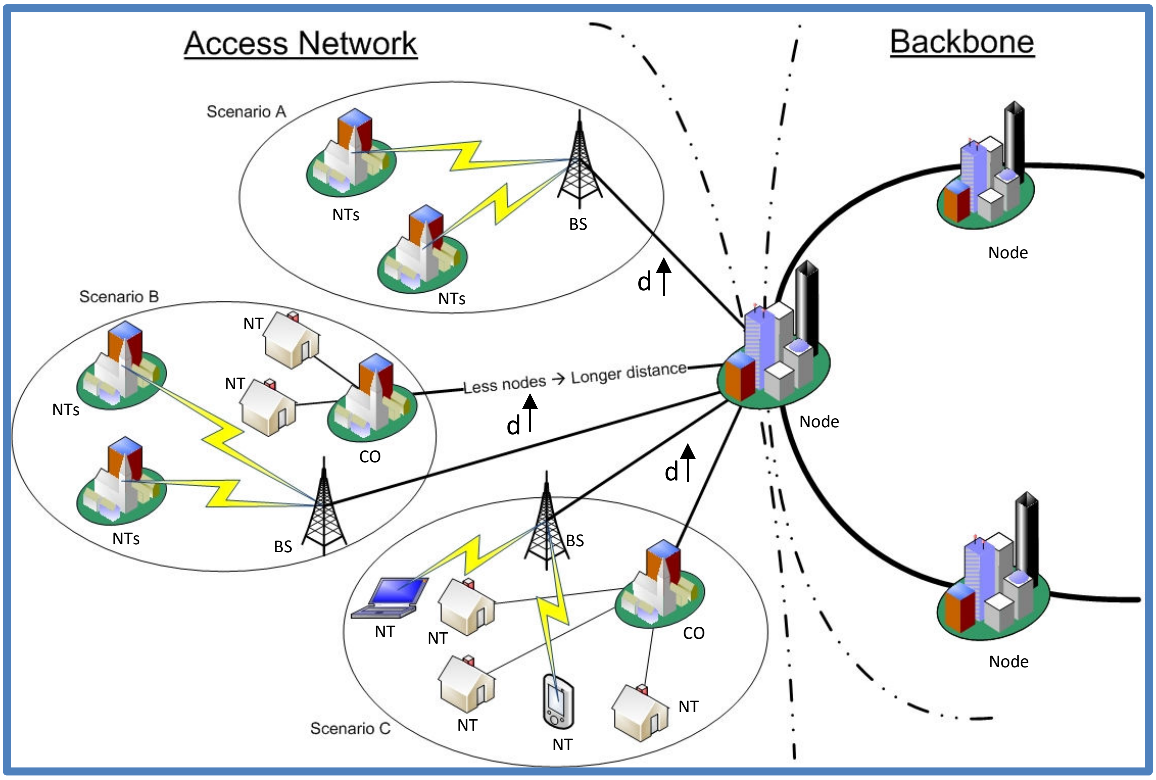


Figure 14: Access network cost increment

[22] Only TDC has more than 355 COs in Nordjylland. (http://tdc.com)

Since the solution must be valid for the next years and it is impossible to predict which of the proposed models will represent the future situation, the network must be designed trying to fulfill the requirements of the three scenarios.

4.2 Methodology

After studying in detail all the consequences of deciding the number of nodes, this section explains the methodology.

The methodology is based on three different approaches:

4.2.1 Approach 1: Locating the nodes in the most densely cells

The first one consisted of placing the nodes in the most densely populated areas of the map. This way we make sure than in B and C scenarios fiber optic costs will be reduced because the distance between the COs and the nodes will be reduced.

This initial approach has been computer-assisted and has been performed from the NT distribution data, already showed in **(2.3 Population distribution).**

After the grid was created, a query was programmed. This query was configured to select the cells with more than a defined quantity of NTs. This way was easy to know the most densely populated regions.

Once we knew the most densely cells, we placed physically the nodes in the COs closest to the selected cells. Using this method lot of money is saved because the creation of a new infrastructure for the nodes would not be cost-effective.

4.2.2 Approach 2: Adapting the nodes to the access network

Secondly, the placement of the WiMAX BSs from the access network (Sevilla, 2008) has been tackled. It has been checked than the distance between the antennas and the nodes is short. In the cases of antennas far away from nodes, new nodes have been projected.

The idea was placing nodes as close as possible to the antennas in order to minimize the distance and obviously the cost:

The criterion is to select as node location the closest CO to the BS. In the cases where the nodes from Approach 1 were not the closest to the BS, new nodes are projected.

4.2.3 Approach 3: Final adjustments. Traffic balancing and backbone adaptation.

Finally, the last approach consisted of realizing some final adjustments to the results obtained in approach 2. The goal was to modify manually the located nodes in such way that they covered similar number of NTs **(Equation 1).**

$$\#\ Nts\ per\ Node = \frac{Total\ number\ of\ NTs}{Number\ of\ nodes} \qquad \text{(Eq. 1)}$$

Thus, the traffic load of each node will be similar (balanced load). This objective must be achieved trying to modify as less as possible the results from lasts approaches in order to avoid affecting too much the rest of compromises.

The total amount of NTs must be evenly distributed among the nodes. In order to perform this approach, circles of 20km radium centered on the nodes have been displayed on a new Map Info Layer. The number of NTs around each coverage area has been counted and compared. Slight changes has been performed till obtaining an evenly distribution.

It is important to take into account than nodes situated in high densely populated areas will have much more NTs than others situated in smaller towns. But notice that in these cases, e. g. Aalborg city and surroundings; approach A already projected multiple nodes for covering a small area. Hence, the total amount of NTs under their coverage is distributed by the total amount of nodes in the area, achieving results really similar to the rest of nodes.

4.3 Final results

This section shows the results obtained for the region of Nordjylland after applying the previous methodology to the NT data. It is divided in four parts. The first three show the results after each one of the approaches. The last one consists on a table that contains the final number of nodes and the name of the city where they will be located.

4.3.1 Results of Approach 1:

Using as criteria placing the nodes in the cells with a number of NTs higher than 3000, next results have been obtained: **(Figure 15)**.

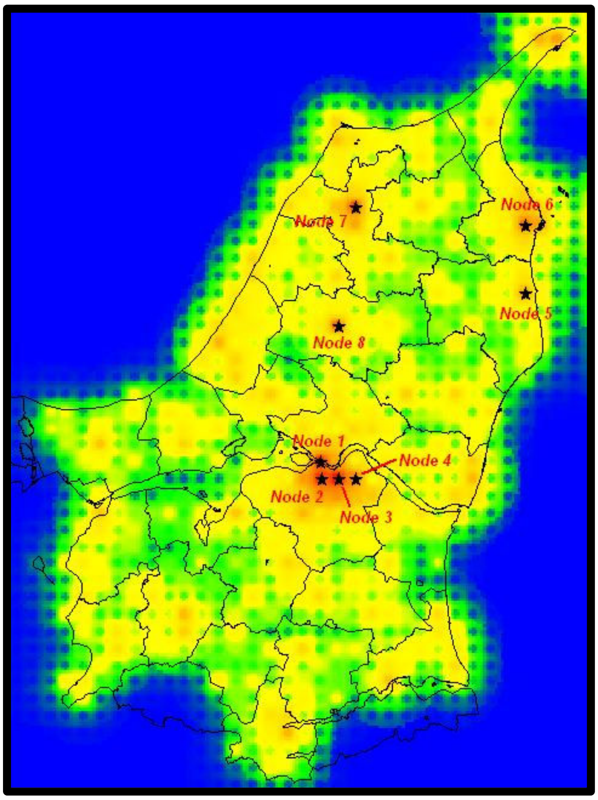


Figure 15: Locating nodes in the most densely cells

Notice that 8 points have been pointed with a star ★: Four in Aalborg and the rest in Frederiskhavn, Saeby, Bronderslev and Hjorring. These points are the ones with higher NT density: more than 333 NT per square km so, following the criteria of minimizing costs, the COs closest to this points will contain the nodes.

The reason because of 3000 NT per cell has been chosen as the limit and not another number is explained next: A higher density only is reached in Aalborg, so this option was ruled out. On the contrary, a lower density was reached in too many cells (around 16 cells have more than 2800 NTs). This number of nodes was too high in order to fulfill the rest of the requirements. Moreover, all the new cells where concentrated in the Aalborg region and the surroundings of other populated cities as Frederikshavn or Hjorring.

4.3.2 Results of Approach 2:

This section shows the results obtained after approach 2.

In order to fulfill this new objective, six new nodes have been projected: three in the south area: Hadsund (9), Hobro (10) and Aars (11). One in the west: Brovst (12), other one in the east in the surroundings of Hals (13) and the last one in the north, in Skagen (14). They have been pointed in **Figure 16** with a triangle ▲ .

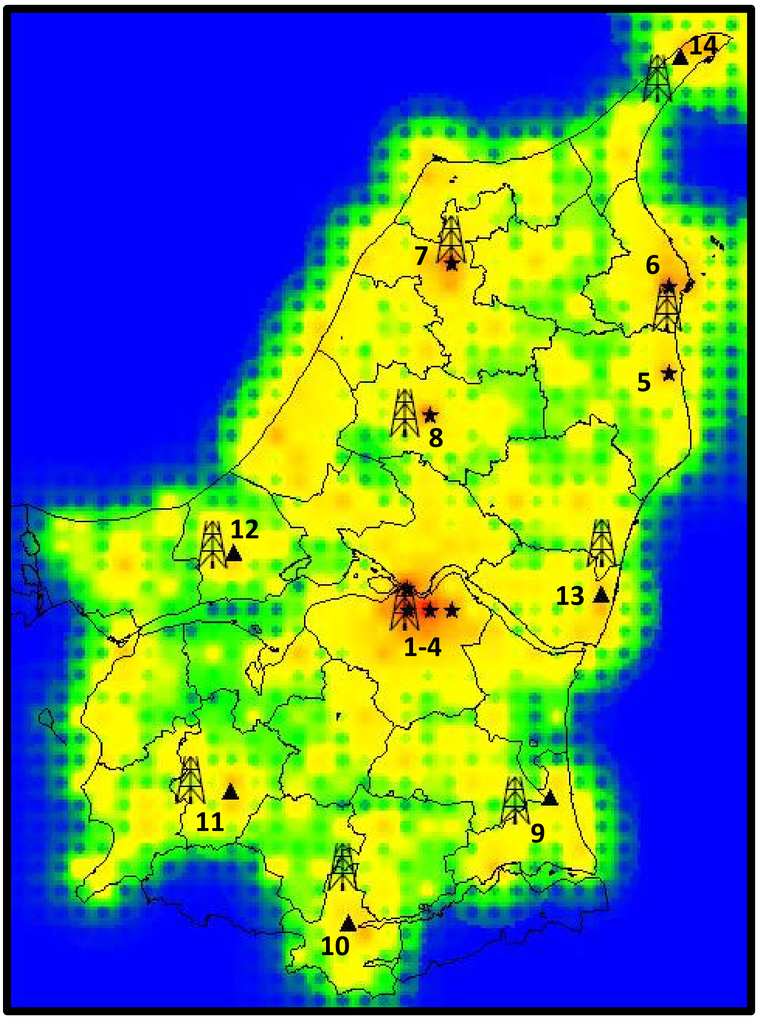


Figure 16: Adjusting nodes to the WiMAX acces network

4.3.3 Results of Approach 3:

This sections shows the results obtained after approach 3.

First of all, next **Figure 17** shows the number of NTs that should cover each node after approach 2.

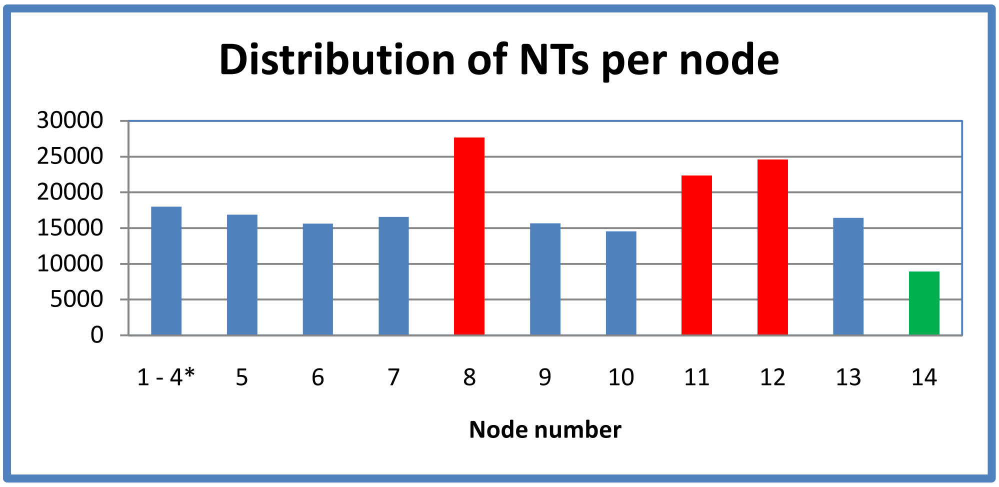


Figure 17: Distribution of NT per Node after approach 2

Notice that three nodes: 8, 11 and 12 have been highlighted in red because they have to cover more NTs than the average. The case of node 14: Skagen is an exception, because due to its atypical geographical situation it covers less NTs than the average. Therefore, some changes are proposed in order achieve a better distribution **(Figure 18)**:

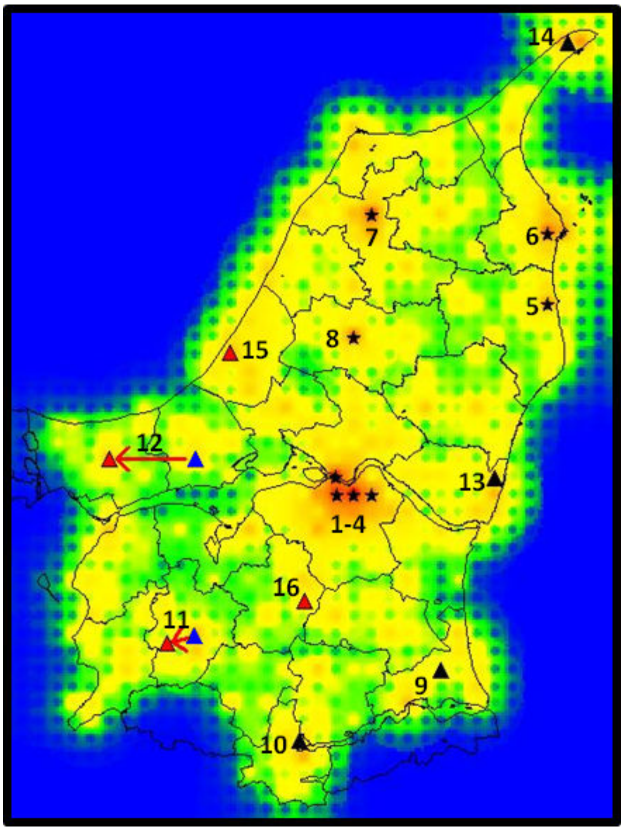


Figure 18: Nodes' final adjustment

Red triangles represent the new nodes or the new location of nodes that have been moved. Blue triangles represent the previous location. The rest of nodes are represented by black stars or triangles, depending on they have been placed there using approach 1 or 2 respectively.

Two nodes have been moved: Brovst → Fjerritslev and East Aars → West Aars. Also, two new nodes have been projected in Blokhus and Stovring. **Figure 18** showed these final adjustments.

After the adjustment, the new distribution of NTs is showed in **Figure 19**:

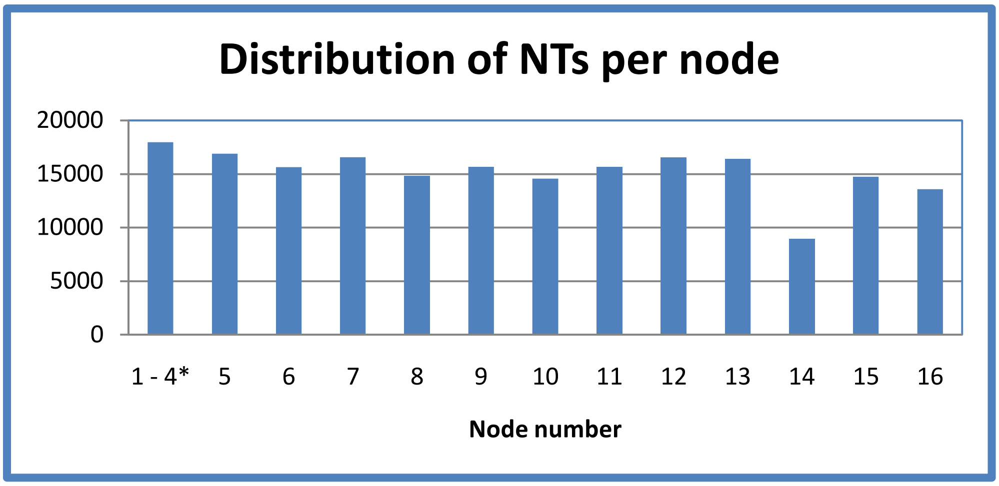


Figure 19: Distribution of NT per Node after approach 3

Notice that, after the adjustments, the distribution of the NTs per node has been improved. NTs concentration in Nodes 8, 11 and 12 has been reduced.

The low NT density of the node 14 cannot be solved because of its particularly geographical situation. If the node is pretended to me moved to the south in order to achieve more balancing then the BS of Skagen and also the FTTH users in B and C scenarios will be too far increasing the cost and .

4.3.4 Nodes location summary

# Node	City	# Node	City
1	Aalborg (Norre Sundby)	9	Hadsund
2	Aalborg (Hasseris)	10	Hobro
3	Aalborg (Center)	11	Aars (West)
4	Aalborg (Vejgard)	12	Fjerritslev
5	Saeby	13	Hals
6	Frederiskhavn	14	Skagen
7	Hjorring	15	Blokhus
8	Bronderslev	16	Stovring

Table 6: Nodes final placement

5. Network topology

Once the nodes have been located, the next stage in the project consists on studying the best way to connect them. This chapter is divided in 3 parts. The first one is an introduction; the topology and topological routing terms are explained in it. The second one deals with the methodology. It explains the parameters that are studied in order to select the best solution. Finally, the third one shows the results. Different topological solutions are compared and the most interesting one is chosen.

5.1 Introduction to topologies and topological routing

Introduction to topologies

In communication networks, a topology is a usually schematic description of the arrangement of a network, including its nodes and connecting lines. There are two ways of defining network geometry: the logical topology and the physical topology. (Groth & Skandier, 2005)

A logical topology is how devices appear connected to the user. A physical topology is how they are actually interconnected with wires and cables.

Recently, optical routing allows us to consider a new case of topology: the optical topology. Optical topology consists of designing a logical topology over a wavelength-routed all-optical network physical topology. The physical topology consists of the nodes and fiber links in the network. On an all-optical network physical topology, we can set up lightpaths between pairs of nodes, where a light path represents a direct optical connection without any intermediate electronics. The set of lightpaths along with the nodes constitutes the logical topology. (Ramaswami & Sivarajan, 1999)

Topological Routing

Efficient routing mechanism is a key attribute in achieving higher QoS and overall performance in networks. In particular, when talking about efficiency, two factors have higher impact: the complexity of the routing algorithm and the memory needed. The traditional routing is memory intensive where routing is decided by the memory or table lookup. For larger networks bigger memory size is needed. (Riaz, 2008)

From the field of multiprocessor systems table-free routing schemes have been known for years. These schemes are not directly applicable to large-scale networks; they rely on the structure having highly regular properties and operating on a limited scale, conditions which are not practicable in large-scale networks. Recent work, however, in the field of large scale networks has proposed the design of networks with global structural properties for the improved support of QoS. Such network design offers the opportunity for applying concepts from multiprocessor systems to large-scale networks, taking advantage of the global properties to introduce table-free routing. This class of routing schemes is called topological routing. (Pedersen, Knudsen, & Madsen, Topological Routing in Large-Scale Networks, 2004).

Topological routing is an alternative to traditional routing methods, based on tables. It allows for very fast restoration and is particularly well suited for large-scale communication where table updates can be time consuming and introduces significant overheads.

In topological routing scheme, packets are routed using the knowledge of the network topology. This means that from any node a packet can be routed only from the knowledge of the address of the current node and also the destination node.

As it will be explained in next section, topological routing can only be implemented in very concrete and organized topologies e.g. N2R or grid.

5.2 Methodology

Focusing on this project, the topological design has been realized following the next methodology:

1) Different topological models have been adapted to the number of nodes defined in chapter **4 Nodes Location** and compared. Next parameters have been used for the comparison:
    a. **Diameter.** The maximum distance (number of hops) between 2 nodes in the network.
    b. **Average distance.** The average number of hops between 2 nodes.
    c. **Connectivity number (Degree).** The number of neighbors of each node.
    d. **Economical cost.** An estimation of the overall fiber deployment cost. This estimation has been realized using Map Info. Distances between nodes has been extracted, corrected and multiplied per the cost of deploying 1 meter of fiber **(1.5 Initial assumptions).**

    Some extra qualitative parameters defined in the SQoS[23] evaluation framework presented at the Information Technology and Telecommunication Conference 2004 (IT&T 04), have been taken into account: (Pedersen, Knudsen, & Madsen, An Evaluation Framework for large-scale network structures, 2004).

    e. **Algorithmic support.** For example, topological routing support.
    f. **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.
    g. **Expandability.** The graph structures have different properties with respect to support SQoS parameters. An expansion of these structures can degrade these

[23] The idea behind SQoS is to establish a next generation communication network infrastructure, which will be providing solid QoS and efficiency. To achieve this, SQoS based network planning concept is promoted which aims at planning physical network infrastructure with good, well-defined and well describable global structural properties. (Pedersen J. M., Structural Quality of Service in Large-Scale Networks, 2005)

properties if not expanded correctly. Some structures, especially planar ones, are easier to expand than the non planar ones

2) The best model according the exposed parameters and the project requirements is chosen.

5.3 Study of the topologies

5.3.1 Single ring

Description of the topology

A ring network is a network topology in which each node connects to exactly two other nodes, forming a circular pathway for signals: a ring. Data travels from node to node, with each node handling every packet **(Figure 20).**

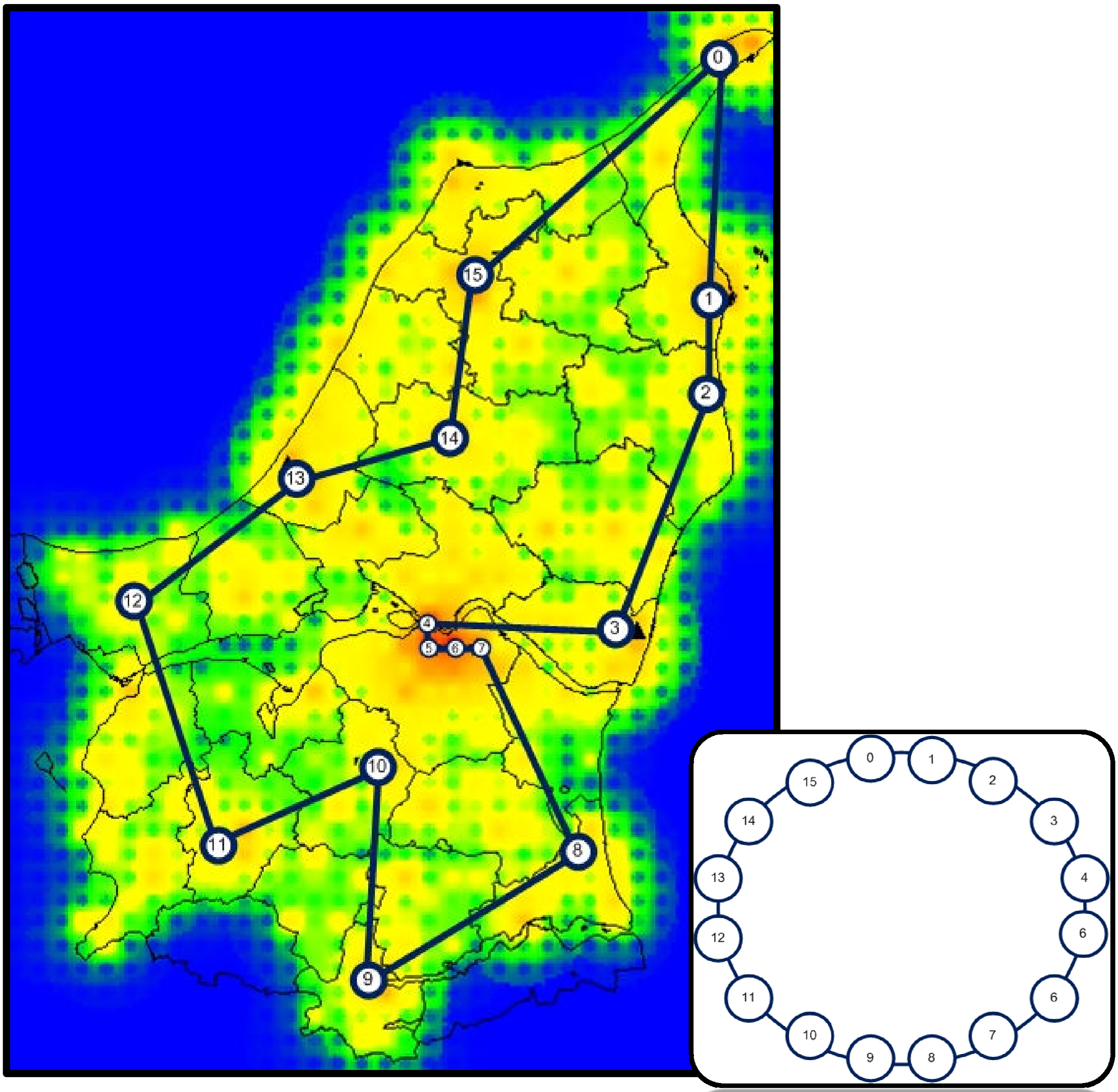


Figure 20: Single Ring Topology

Degree

The degree in single rings is 2 for all the nodes. Each node has 2 peers.

Diameter

The diameter of the network using this topology is 8 **(Figure 21)** for both the primary and the secondary independent path. If the number of nodes would change, the new diameter could be calculated using the following **Equation**[24] **2** or **Equation 3:**

If the number of nodes N is even:

$$Diameter = \frac{N}{2} \qquad \text{(Eq. 2)}$$

If the number of nodes N is odd:

$$Diameter = \frac{N-1}{2} \qquad \text{(Eq. 3)}$$

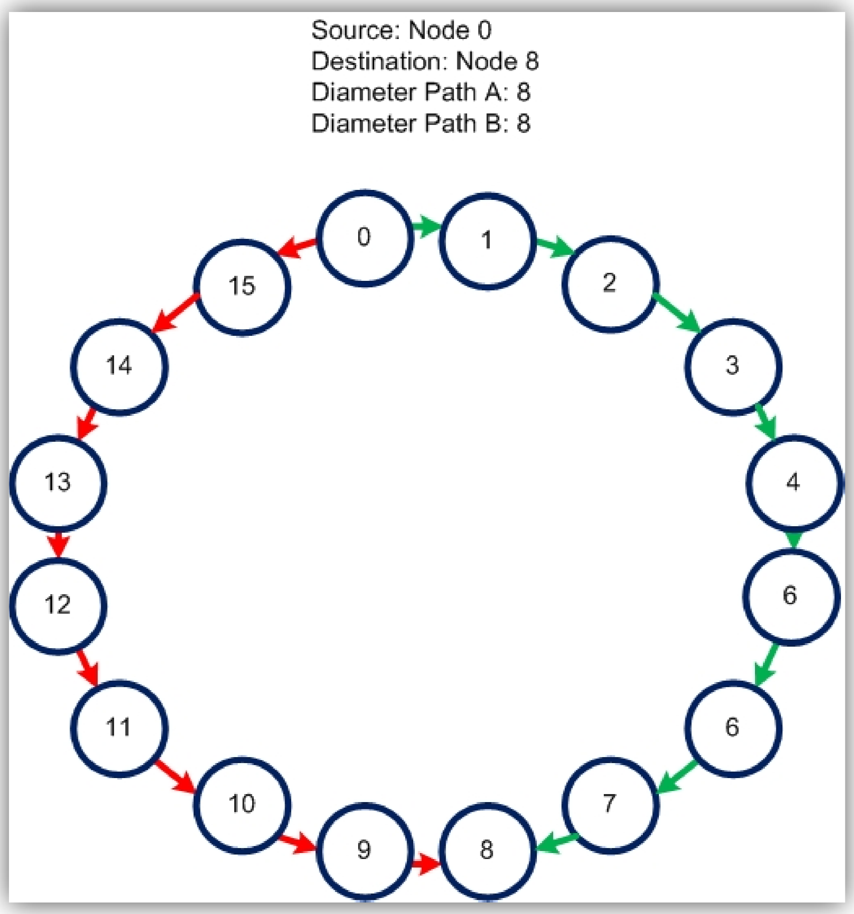


Figure 21: Single Ring Diameter

[24] All the equations in this chapter have been deduced by trial and error method. They are experimentally proved in the Annex 2.

Average distance

The average distance between two nodes for the primary path has been calculated using the **Equation 4 or Equation 5**:

If the number of nodes N is even:

$$AD_{1st\ Path} = \frac{\frac{N}{2} + 2 \cdot \sum_{k=1}^{\frac{N}{2}-1} 1\ neighbour \cdot k\ hops}{N-1} \qquad \text{(Eq. 4)}$$

If the number of nodes N is odd:

$$AD_{1st\ Path} = \frac{2 \cdot \sum_{k=1}^{\frac{N-1}{2}} 1\ neighbour \cdot k\ hops}{N-1} \qquad \text{(Eq. 5)}$$

Our network has 16 nodes, so **Equation 4** is applied, obtaining the next result:

$$\boxed{AD_{1st\ Path} = \frac{8 + 2 \cdot (1 + 2 + 3 + 5 + 6 + 7)}{15} = 4{,}27}$$

The average distance for the secondary path has been calculated using the **Equation 6**:

$$AD_{2nd\ Path} = \frac{\frac{N}{2} + 2 \cdot \sum_{k=1}^{\frac{N}{2}-1} (N-k)\ hops \cdot 1neighbour}{N-1} \qquad \text{(Eq. 6)}$$

If N was not even next **Equation 7** should be used:

$$AD_{2nd\ Path} = \frac{2 \cdot \sum_{k=1}^{\frac{N-1}{2}} (N-k) hops \cdot 1\ neighbour}{N-1} \qquad \text{(Eq. 7)}$$

Our network has 16 nodes, so **Equation 6** is applied, obtaining the next result:

$$\boxed{AD_{2nd\ Path} = \frac{8 + 2 \cdot (1 + 2 + 3 + 5 + 6 + 7) +}{15} = 11{,}73}$$

Economical cost

	Distance[25] (Km)	Cost[26] (Euros)
TOTAL	**511,266**	**14.315.448 €**

[25] Distances have been measured with MapInfo 'ruler tool' and multiplied by 1,41 according **(1.6 Assumptions and notes).**

[26] The cost of 1 meter of ditch is 28 €. **(9.1Assumptions)**

5.3.2 Double ring

Description of the topology

In this project, the double ring term is used to describe the following topology **(Figure 22):**

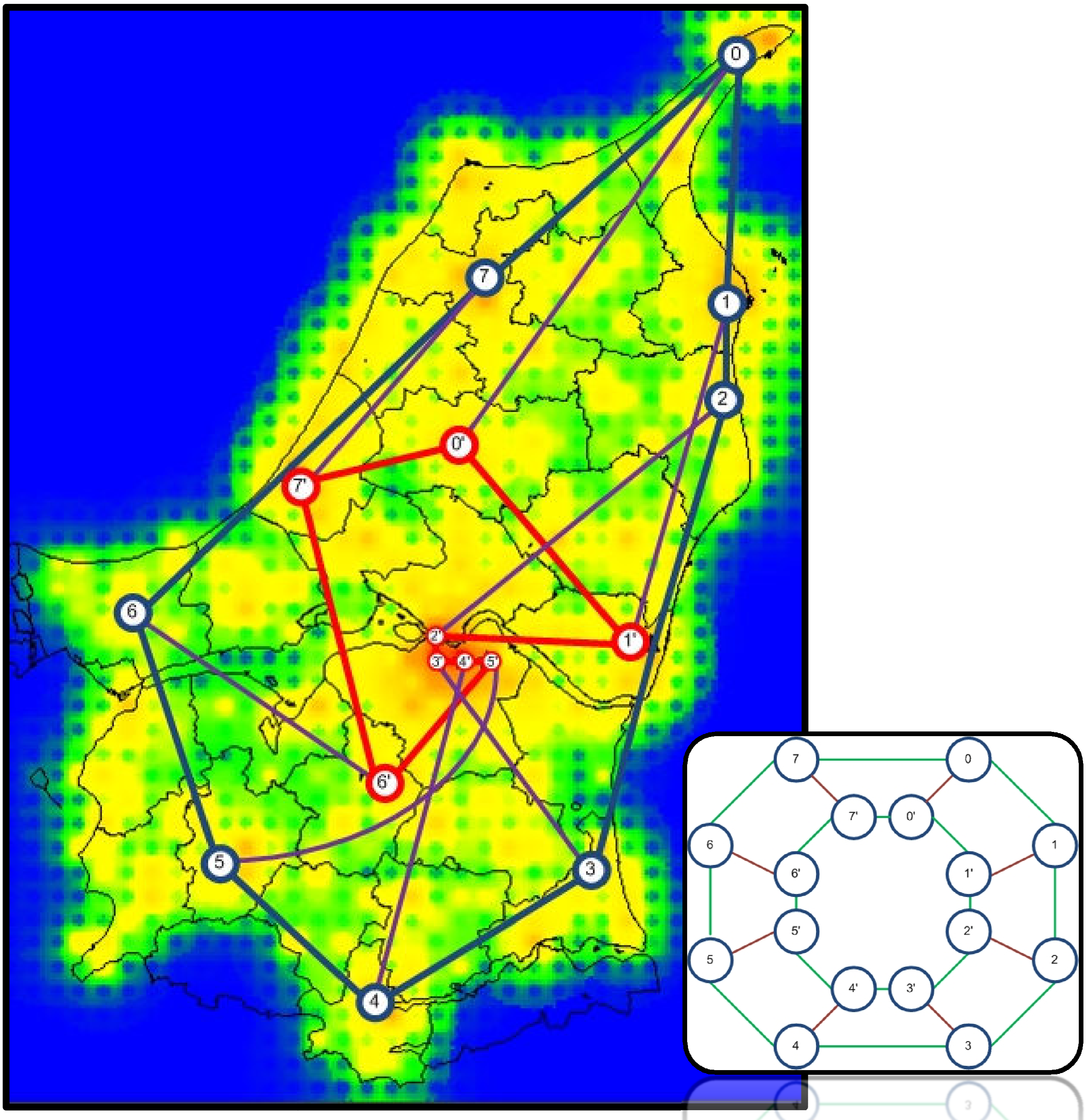


Figure 22: Double Ring Topology

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 3 connected topologies, which offer easy routing, restoration and protections schemes, but suffer from large distances. (Pedersen, Riaz, & Madsen, 2005).

Degree

In this aspect the structure is completely regular. Each node has always 3 peers.

Diameter

The diameter of the network using this topology is 5 for both the primary and the secondary independent path **(Figure 23)**. If the number of nodes would change, the new diameter could be calculated using the following **Equation 8 or 9**:

If N is multiple of 4:

$$Diameter = \frac{N}{4} + 1 \qquad \text{(Eq. 8)}$$

If N is not multiple of 4:

$$Diameter = \frac{\frac{N}{2}+1}{2} \qquad \text{(Eq. 9)}$$

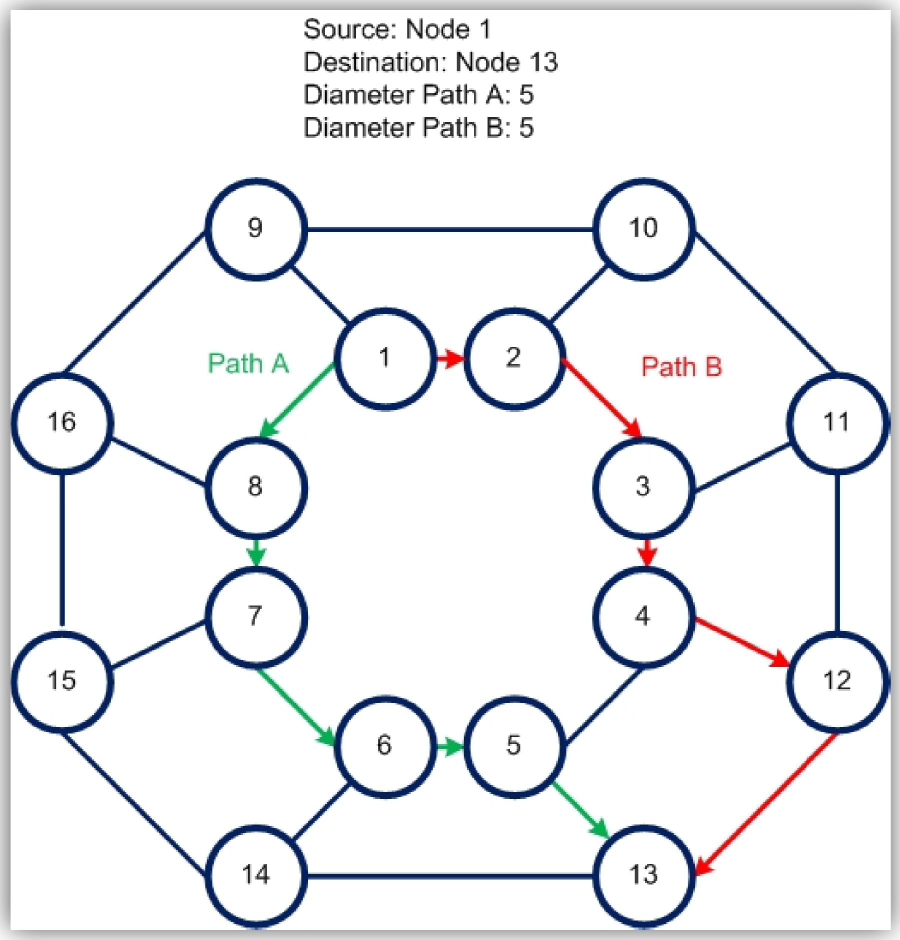


Figure 23: Double Ring Diameter

Average distance

The average distance between two nodes for the primary path can be calculated using the following equations:

If N is multiple of 4 **Equation 10** must be used:

$$AD_{1st\ Path} = \frac{3\ neighbours \cdot 1\ hop + \sum_{k=1}^{\frac{N}{4}-1} 4\ nbs \cdot k\ hops\ + 3\ nbs\ \frac{N}{4}+1\ nb \cdot (\frac{N}{4}+1)}{N-1} \quad \text{(Eq.10)}$$

If N is not multiple of 4 **Equation 11** must be used:

$$AD_{1st\ Path} = \frac{3\ neighbours \cdot 1\ hop + \sum_{k=1}^{\frac{N}{4}+\frac{1}{2}} 4\ nbs \cdot k\ hops\ + 2\ nb \cdot (\frac{\frac{N}{2}+1}{2})}{N-1} \quad \text{(Eq.11)}$$

Our network has 16 nodes, so **Equation 4** is applied, obtaining the next result:

$$\boxed{AD_{1st\ Path} = \frac{3 \cdot 1 + 4 \cdot 2 + 4 \cdot 3 + 3 \cdot 4 + 1 \cdot 5}{15} = 2{,}667}$$

The average distance for the secondary path has been calculated using the **Equation 12**:

$$AD_{2nd\ Path} = \frac{(\sum_{k=1}^{\frac{N}{4}-1} 2(k+2)) + \frac{N}{4} + (\sum_{k=2}^{\frac{N}{4}} 2k) + (\frac{N}{4}+1)}{N-1} \quad \text{(Eq. 12)}$$

If N was not multiple of 4 **Equation 13** must be used:

$$AD_{2nd\ Path} = \frac{3 + (\sum_{k=2}^{\frac{N}{4}+\frac{1}{2}} 2k) + (\sum_{k=1}^{\frac{N}{4}-\frac{1}{2}} 2(k+2))}{N-1} \quad \text{(Eq. 13)}$$

Our network has 16 nodes, so **Equation 12** is applied, obtaining the next result:

$$\boxed{AD_{2nd\ Path} = \frac{1 \cdot 3 + 4 \cdot 3 + 2 \cdot 2 + 4 \cdot 4 + 1 \cdot 5 + 2 \cdot 5 + 1 \cdot 4}{15} = 3{,}6}$$

Economical cost

	Distance[27] (Km)	Cost[28] (Euros)
Outer Ring	425,4	11.911.299
Inner Ring	211,6	5.924.800
Connections	484,2	13.557.600
TOTAL	**1121,2**	**31.393.699 €**

[27] Distances have been measured with MapInfo 'ruler tool' and multiplied by 1,41 according **(1.6 Assumptions and notes).**
[28] The cost of 1 meter of ditch is 28 €. **(9.1Assumptions)**

5.3.3 N2R (8,3)

Description of the topology

The N2R topology **(Figure 24)** 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 neighbor nodes. 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 I_i 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. (Jorgensen, Pedersen, & Pedersen, 2005).

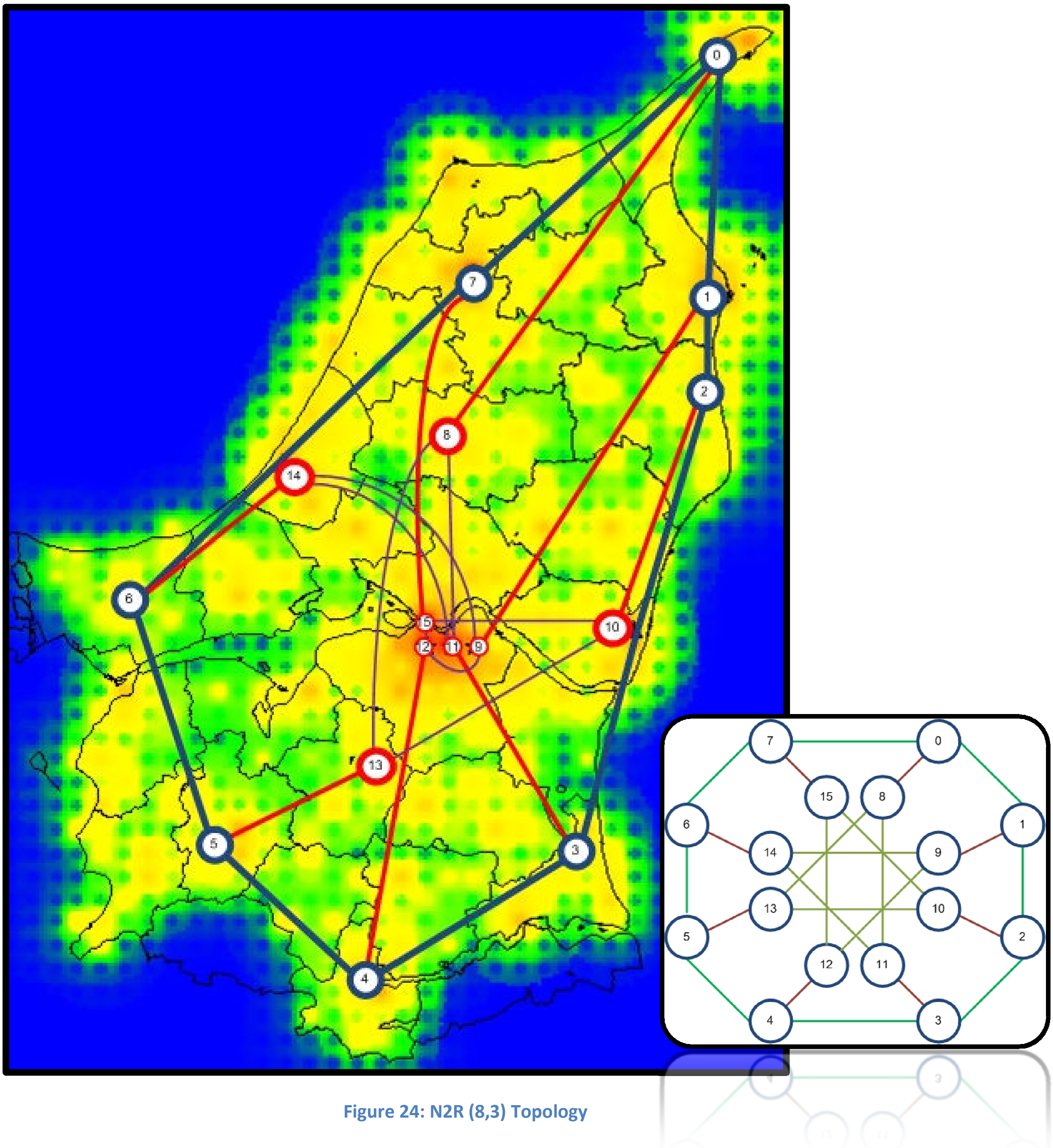


Figure 24: N2R (8,3) Topology

Degree

In this aspect the structure is identical to the previous case: Each node has always 3 peers.

Diameter

The diameter of the network using this topology is 4 for the primary **(Figure 25)** and 5 for the secondary independent path **(Figure 26).** General equations have not been deduced because variable q has direct influence in all the parameters, including the final budget. Modifying q parameter implies dramatically changes in the connections of the inner ring. Moreover, as was introduced in the first part of this section, only few combinations of number of nodes are accepted. Therefore, applying this topology for other numbers and distribution of nodes is not so trivial. The case should be studied particularly.

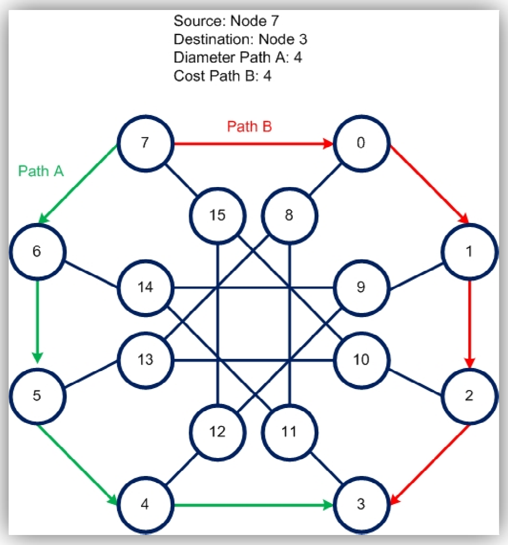


Figure 25: N2R (8,3) Diameter Path A

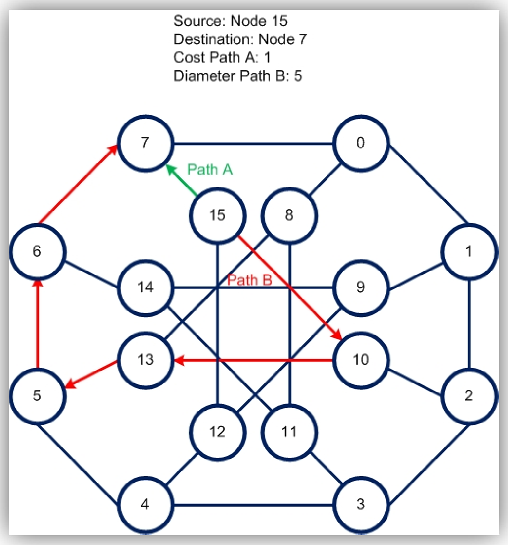


Figure 26: N2R (8,3) Diameter Path B

Average distance

Due the difficulty to deduce the formulas for this topology, in this case, the average distances between two nodes for both the primary and the secondary independent path have been calculated checking all the possible combinations **(Table 7a-d)**:

	#	Source	Destination	Hops 1^{st} Indep. Path	Hops 2^{nd} Indep. Path
From outer to inner ring	1	7	15	1	5
	2	7	8	2	4
	3	7	9	3	3
	4	7	10	2	4
	5	7	11	4	4
	6	7	12	2	4
	7	7	13	3	3
	8	7	14	2	4

Table 7a: N2R (8,3) Table of distances

	#	Source	Destination	Hops 1^{st} Indep. Path	Hops 2^{nd} Indep. Path
From outer to outer ring	9	7	0	1	5
	10	7	1	2	4
	11	7	2	3	3
	12	7	3	4	4
	13	7	4	3	3
	14	7	5	2	4
	15	7	6	1	5

Table 7b: N2R (8,3) Table of distances

	#	Source	Destination	Hops 1^{st} Indep. Path	Hops 2^{nd} Indep. Path
From inner to inner ring	1	15	8	3	3
	2	15	9	2	4
	3	15	10	1	5
	4	15	11	4	4
	5	15	12	1	5
	6	15	13	2	4
	7	15	14	3	3

Table 7c: N2R (8,3) Table of distances

	#	Source	Destination	Hops 1^{st} Indep. Path	Hops 2^{nd} Indep. Path
From inner to outer ring	8	15	7	1	5
	9	15	0	2	4
	10	15	1	3	3
	11	15	2	2	4
	12	15	3	3	3
	13	15	4	2	4
	14	15	5	3	3
	15	15	6	2	4

Table 7d: N2R (8,3) Table of distances

Next, the average is calculated:

$$AD_{1st\ Path} = \frac{19 + 16 + 16 + 18}{15 + 15} = 2{,}3$$

$$AD_{2nd\ Path} = \frac{31 + 28 + 28 + 30}{15 + 15} = 3{,}9$$

Further information about the detailed paths can be found in **Appendix A.**

Economical cost

	Distance[29] (Km)	Cost[30] (Euros)
Outer Ring	425,4	11.911.299
Inner Ring	291,8	8.170.400
Connections	390,4	10.931.200
TOTAL	**1.107,6**	**31.012.800 €**

5.3.4 4-Regular Grid Topology[31]

Description of the topology

A 4-regular Grid topology **(Figure 27)** 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 dim_x and dim_y be prohibitive integers. Every node in N is associated with a pair of coordinates (x,y) such that 0 ≤ dim_x and 0≤ydim_y, 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 (dim_x+1)(dim_y+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. (Riaz, 2008)

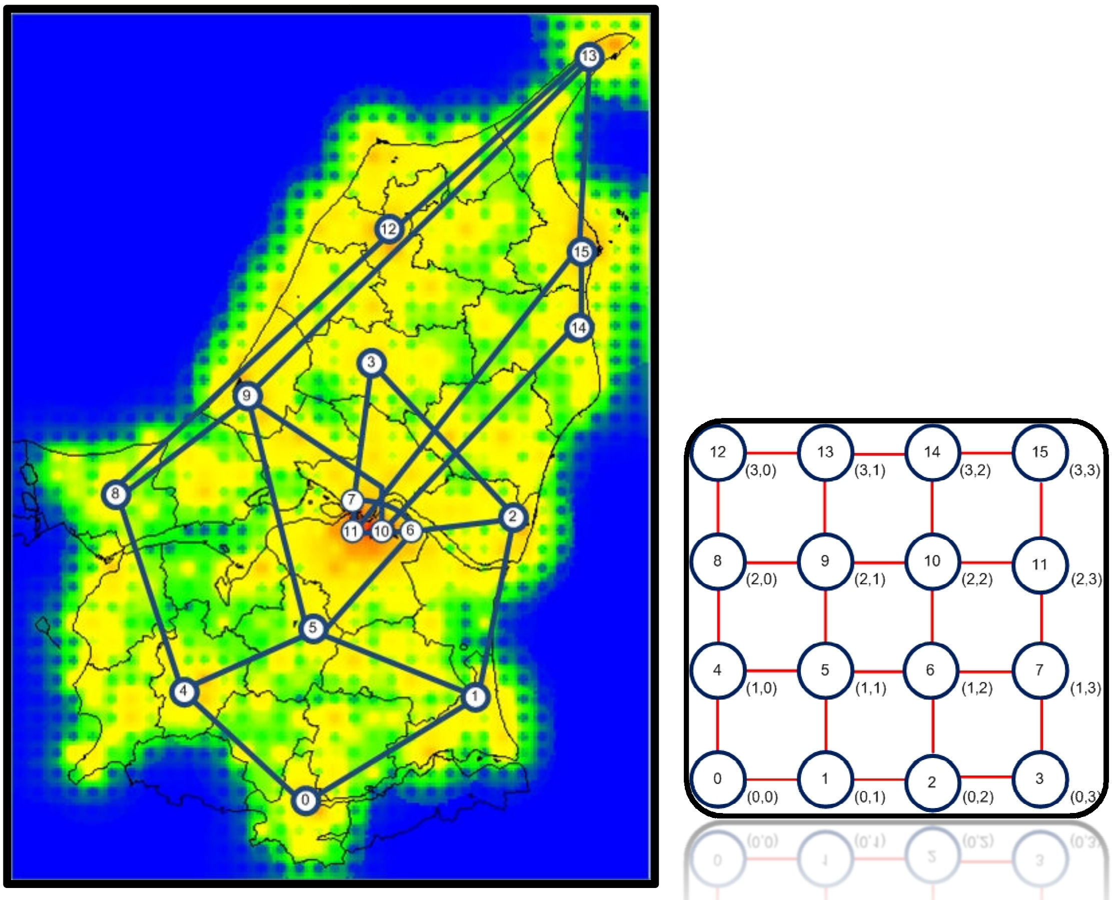


Figure 27: 4-regular Grid Topology

[29] Distances have been measured with MapInfo 'ruler tool' and multiplied by 1,41 according **(1.6 Assumptions and notes).**

[30] The cost of 1 meter of ditch is 28 €. **(9.1Assumptions)**

[31] Also known as 2D mesh.

As was commented in the introduction of this chapter, one of the main advantages of some topologies is their ability to support topological routing algorithms. 4-regular grid scheme will route packets from source to destination in a number of hops corresponding to the sum of the differences of the coordinates in the two directions. This routing principle is generalized on the following **(Figure 28)**:

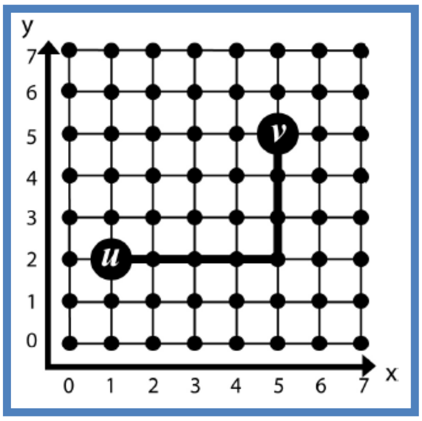


Figure 28: Topological routing in 4-square Grid Topology

The nodes are addressed according to the coordinate system. Routing a packet from *u* to *v* is done hop by hop: in every node, the address of *v* is compared with to the current address. Base on the differences in *x* and *y* coordinates a next hop is chosen, which reduces the difference in one of the directions. The scheme is not deterministic since in some nodes two next hops can be chosen between. (Pedersen, Knudsen, & Madsen, Topological Routing in Large-Scale Networks, 2004)

Degree

In this aspect the structure is different from the previous topologies Depending on the situation of the nodes the connectivity number is 4 for the central nodes, 3 for the nodes placed on the sides, and the worst case, 2 for the nodes at the corners.

In order to obtain perfect geometry and a connectivity number constant, torus topologies **(Figure 29)** could be applied. They were ruled out because of the enormous difficulty to apply them to planar geography. The economical cost of the network would increase dramatically[32].

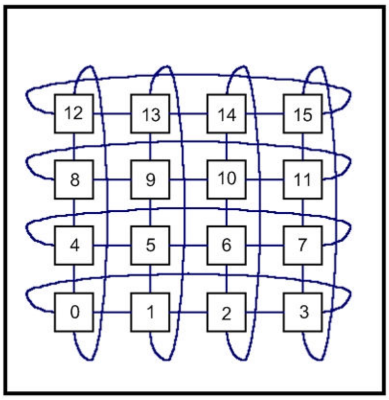


Figure 29: Discarded Torus Topology

[32] The economical cost of deploying this topology is estimated in **Appendix B: Future topologies.**

Diameter

The diameter of the network using 4-regular grid topology is 6 for both the primary and the secondary independent path **(Figure 30)**. If the number of nodes changes the new diameter can be calculated using the following **Equation 14**:

$$Diameter = 2\sqrt{N} - 2 \qquad \text{(Eq. 14)}$$

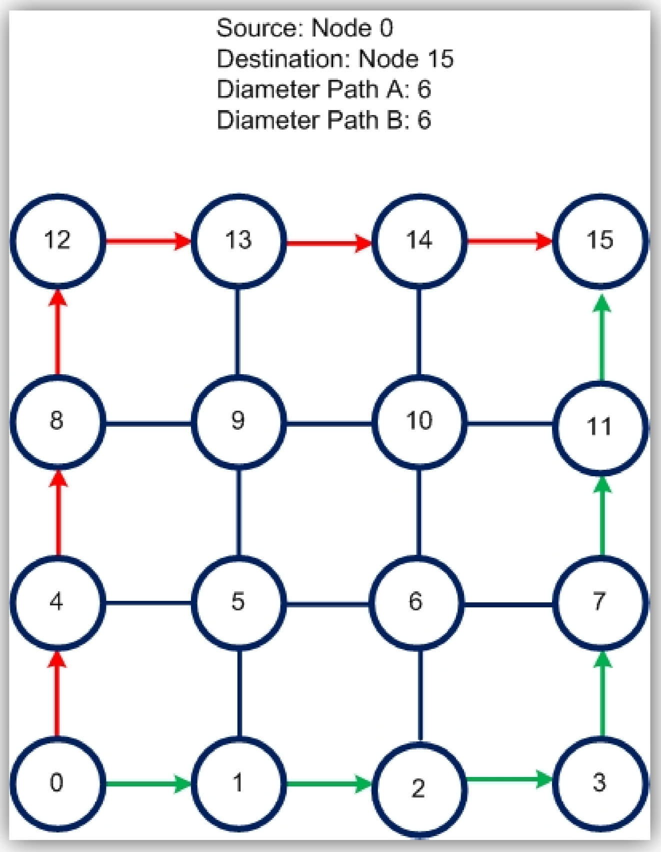


Figure 30: 4-regular Grid Topology Diameter

Average distance

The average distances between two nodes for both the primary and the secondary independent path have been calculated checking all the possible combinations **(Table 8a-c)**.

	#	Source	Destination	Hops 1st Indep. Path	Hops 2nd Indep. Path
From central node to all	1	5	0	2	2
	2	5	1	1	3
	3	5	2	2	2
	4	5	3	3	3
	5	5	4	1	3
	6	5	6	1	3
	7	5	7	2	4
	8	5	8	2	2
	9	5	9	1	3

	#	Source	Destination	Hops 1st Indep. Path	Hops 2nd Indep. Path
From central node to all	10	5	10	2	2
	11	5	11	3	3
	12	5	12	3	3
	13	5	13	2	4
	14	5	14	3	3
	15	5	15	4	4

Table 8a: 4-regular Grid Topology. Table of Distances.

	#	Source	Destination	Hops 1st Indep. Path	Hops 2nd Indep. Path
From corner to al	1	0	1	1	3
	2	0	2	2	4
	3	0	3	3	5
	4	0	4	1	3
	5	0	5	2	2
	6	0	6	3	3
	7	0	7	4	4
	8	0	8	2	4
	9	0	9	3	3
	10	0	10	4	4
	11	0	11	5	5
	12	0	12	3	5
	13	0	13	4	4
	14	0	14	5	5
	15	0	15	6	6

Table 8b: 4-regular Grid Topology. Table of Distances.

	#	Source	Destination	Hops 1st Indep. Path	Hops 2nd Indep. Path
From side node to al	1	1	0	1	3
	2	1	2	1	3
	3	1	3	2	4
	4	1	4	2	2
	5	1	5	1	3
	6	1	6	2	2
	7	1	7	3	3
	8	1	8	3	3
	9	1	9	2	4
	10	1	10	3	3
	11	1	11	4	4
	12	1	12	4	4
	13	1	13	3	5
	14	1	14	4	4
	15	1	15	5	5

Table 8c: 4-regular Grid Topology. Table of Distances.

Next, the average distance is calculated:

$$AD_{1st\ Path} = \frac{48 + 32 + 40}{15 + 15 + 15} = 2{,}33$$

$$AD_{2nd\ Path} = \frac{60 + 44 + 52}{15 + 15 + 15} = 3{,}46$$

Further information about the detailed paths can be found in **Appendix A.**

Economical cost

	Distance[33] (Km)	Cost[34] (Euros)
Physical Independency	**1110,234**	31.145.552 €

5.4 Comparison and conclusion

After studying different kinds of topologies, next table summarizes the results and helps us in the final decision:

	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**

Table 9: Comparison of topologies

After the study realized in last section, next conclusions are deduced:

1) *Ring topology is a really economical solution, but it is also the most limited one in all the studied features. Its large diameter and its longer average distance force it to be non-recommendable for next generation networks.*
2) *Focusing on degree 3 topologies, it has been proved that N2R is clearly much more powerful (in terms of average distances and diameter) than standard double ring. Also in this particular case N2R has a lower economical cost. Hence, it is strongly recommendable in front of standard double ring.*

---

[33] Distances have been measured with MapInfo 'ruler tool' and multiplied by 1,41 according **(1.6 Assumptions and notes).**

[34] The cost of 1 meter of ditch is 28 €. **(9.1Assumptions)**

3) 4-Regular Grid offers a similar prize to N2R. Its diameter is longer than in N2R, but on the other hand, the average distance for the second independent path is favorable to it. Also the scalability (it is easy to change the 4-Regular mesh into a triangular one – **Appendix B: Future topologies***-) and the possibility of using topological routing are valued but also difficult to quantify.*

In spite of the comparison realized there are not enough arguments to decide between N2R topology or 4-Regular Grid: The study is not conclusive. Both should be evaluated in detail and compared in next stages: traffic analysis, deployment plans, etc. in order to know which one satisfy better the necessities.

Due to time limitations 4-Regular Grid has been chosen as the topology to be studied in next sections. One of the future lines of action should be realizing the same studies for the N2R topology and compare the results. ***(10.2*** **Future lines*****)***

6. Deployment plan

This chapter proposes a strategic deployment plan for the new IT Infrastructure. The goal of it is converting the network as soon as possible in an operable one and, since then, improving it till achieving the final chosen 4-Regular grid topology. The chapter is divided in three sections: first one introduces briefly the importance of the deployment one. Then the second one explains in detail the deployment stages. Finally, the third one introduces some future policies.

6.1 The importance of the deployment plan

In networking, usually a good strategic deployment plan can be the key factor that finally decides if a network is or not constructed. Due this critical importance, deployment policies must be studied deeply.

From a commercial point of view, what new telecommunication providers require is minimizing the initial investment and starting making profits as soon as possible. These benefits will be essential for recovering the initial investment and also for keeping improving the network till achieving the projected topology. (Werbach, 1997).

In order to make this possible next section details the proposed deployment plan.

6.2 Deployment stages

The deployment plan has been divided in 3 different stages:

- 1st stage. The first stage consists on converting the network in operable as soon as possible. In order to achieve this goal the critical links has been identified and they will be prioritized. Once critical links are operative the network is 100% operable for the scenario A.
- 2nd stage. In the second stage the network is improved till achieving the topological objectives projected in last section. The network is 100% operable for all the scenarios. However, not all physical independent paths are yet implemented.
- 3rd stage. After the third stage the network is completely finished and fulfils all the initial requirements. The links are physically independents.

6.2.1 1st stage

The main goal of the first stage is achieving an operative and functional backbone in a short term and giving priority to the cost in front of other parameters as diameter or average distances. This way the initial investment will start soon generating profits that could be vital for the development of the future stages.

The suggested term for this initial stage is 2 years. In these 2 years, the backbone should be operative for covering class A scenario. In order to do it, next tasks must be completed:

1) Performing all the nodes that are closer to the BS: 0, 1, 2, 3, 4, 6, 7, 8, 10, 11, 12, 14 and 15 **(Figure 31)**.

2) Connecting the nodes with the BS.
3) Connecting the nodes between them. In order to do that task the links from the topology must be studied. Only prioritized links must be constructed in this stage.

Which links shall we consider as prioritized?

After the topological study, realized in **chapter 5**, it is known that one of the most inexpensive and fastest ways of achieving an operative backbone is using a ring topology. However, not any ring can be valid: Due the fact that this solution is only transitory and that next stages will continue improving the network, all the links planned must be used in future stages. Otherwise the solution will not be optimum because money invested in some links for the initial stage will not be used nevermore in future.

The proposed solution consists on a single ring that guarantees basic reliability and two independent paths since the first moment at a really low cost **(9 Budget)**. Moreover, future stages will take advantage of this projection by recycling 100% of the presented infrastructure **(Figure 31)**.

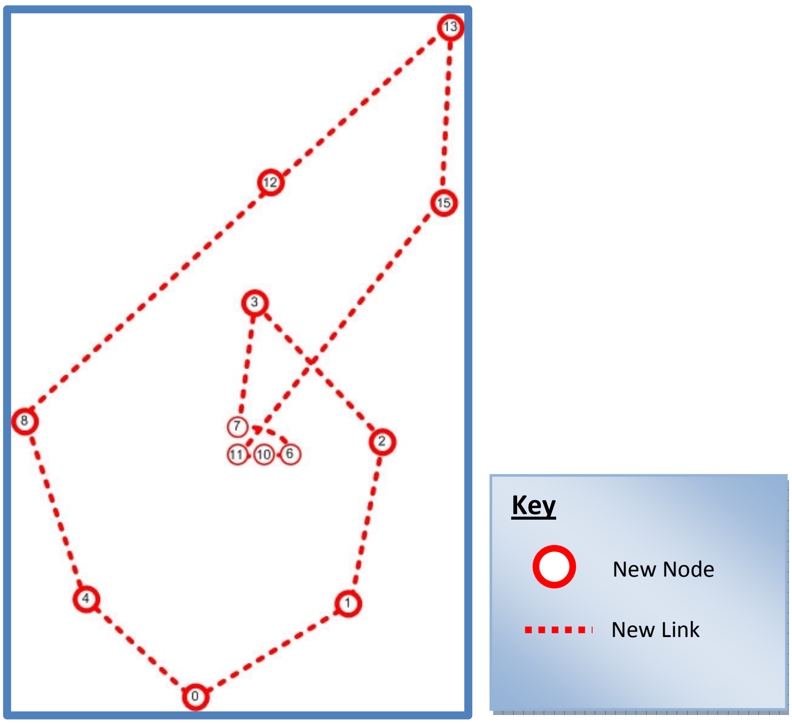


Figure 31: Deployment plan. Stage 1.

6.2.2 2nd stage.

The main goal of the second stage is achieving the proposed topological solution **(5 Network topology)** in a term of 8 years. In order to achieve it next tasks must be realized:

1) Deploying the rest of nodes: Nodes 5, 9 and 14.
2) Connecting the necessary nodes for achieving the 4-regular grid topology **(Figure 32)**.

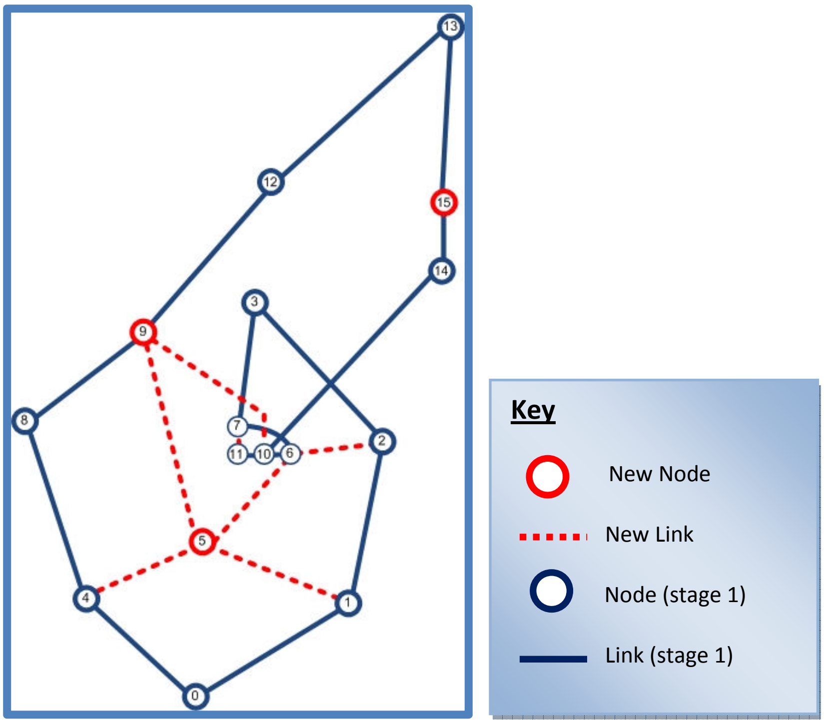


Figure 32: Deployment plan. Stage 2.

It is important to emphasize that although in the end of this stage the network is completed from a topological point of view, with the purpose of minimizing the economical cost, some links are sharing physical paths. Due the fact that more than one link is sharing a physical path, the independency of the paths is not real what causes a decrease in the global availability **(8 Availability Study)**. The links that share physical paths are detailed in next **Figure 33**:

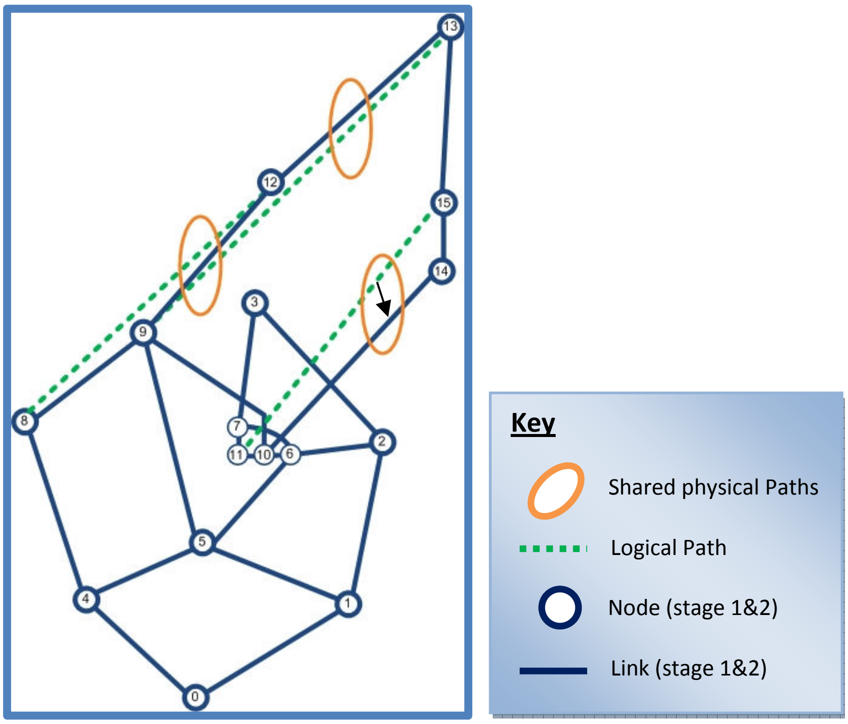


Figure 33: Stage 2. Shared physical paths.

6.2.3 3rd stage.

The third stage consists of achieving the physical independency projected in chapter **5 Network topology**. The term for achieving this stage is 12 years.

In order to do it, logical links that shared physical paths **(Figure 33)** must be separated. To perform this task, next, **Figure 34** show the new necessary links:

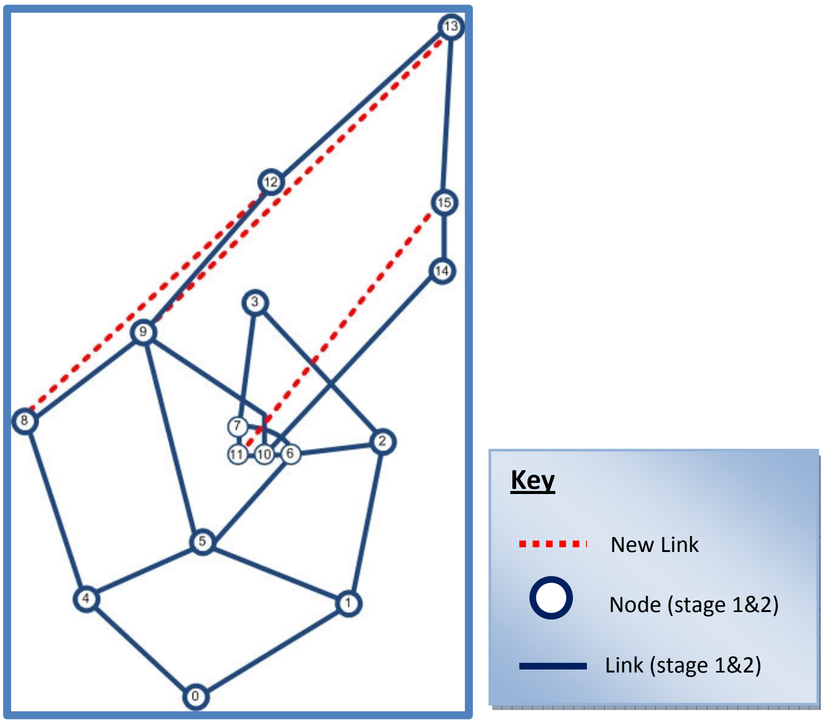


Figure 34: Deployment plan. Stage 3.

After the 3rd stage the network will perfectly fit in the projected topology, fulfilling by this way all the initial requirements **(1.2 Project objectives)**.

6.3 Future policies

The future of the network is impossible to predict. And it is just by this reason that it has been designed as dynamic and possible. Many improvements could be applied in future to the designed topology recycling the entire previous infrastructure:

- The grid could grow up in extension: adding more nodes.
- The performance (diameter, average distances, reliability, etc) could be improved:
  - Converting them in a Torus topology. (8 more links will be deployed).
  - Other possibility is adding only 9 more links, and transforming the network in a triangular mesh instead of a squared mesh.

Some illustrations of these new possible extensions can be found in **Appendix B: Future topologies**.

7. Traffic Study

This chapter estimates the overall traffic that will have each link of the network. This is an important stage in network planning because allows identifying future bottlenecks and act in consequence, and, it also gives a result about how balanced the network is. The chapter is divided in three sections: The first one details the initial assumptions; the second one explains thoroughly the methodology; finally, the third one shows the results and comments them.

7.1 Initial assumptions

As has been commented throughout the project, to estimate traffic in future is not an easy task and, by this reason, three different future scenarios were created **(Chapter 3 Estimation of the bandwidth demand)**.

Different assumptions and requirements have been applied to them:

1) From the total traffic, 50% will be IPTV traffic and 50% other data **(Figure 10)**. From this second 50%, 10% will have as destination another NT connected to the same node (local traffic), other 10% will have as destination an NT connected to another node (regional traffic), and the rest (80%) will go to external networks/Internet. (Medina, Taft, Salamatian, & S. Bhattacharyya, 2002)
2) 40% of the bandwidth will be guaranteed for all the subscribers.
3) 20% of penetration. Statistics shows that, apart from TDC, the rest of ISP do not have more than 10% of penetration in the market. Therefore, an optimistic maximum penetration margin of 20% has been projected for the designed network for the next 12 years. **(Appendix C: Traffic statistics).**
4) A maximum of 40% of the users connected at same time. 10% of the users were connected at same time in USA in 1999. In short term view this data is almost the double and it would be increasing gradually during the next years. So, it is estimated that a 40% of the users will be connected at same time in long term. (Strom, 1999).
5) It has been assumed that 2 Internet gateways are necessary in order to achieve high reliability. Also for the IPTV services 2 IPTV servers have been estimated.
6) In order to calculate the traffic is basic to define where the IPTV servers and the Internet Gateways will be located. Two different approaches have been compared:
    a. In the first one, it has been assumed that the IPTV servers are located at nodes 6 and 9 and that Internet Exchange Points are placed in nodes 5 and 10 **(Figure 35).** This configuration is symmetric and the most reliable because the servers&gateways are placed at the central nodes, which are the ones with higher degree (4).
    b. In the second one, it has been assumed that the IPTV servers are located at nodes 1 and 14 and that the Internet Exchange Points are placed in nodes 7 and 8 **(Figure 36)**. This configuration is also reliable because the selected nodes are degree 3. It is symmetric and more distributed that the first one **(7.2 Methodology)**.

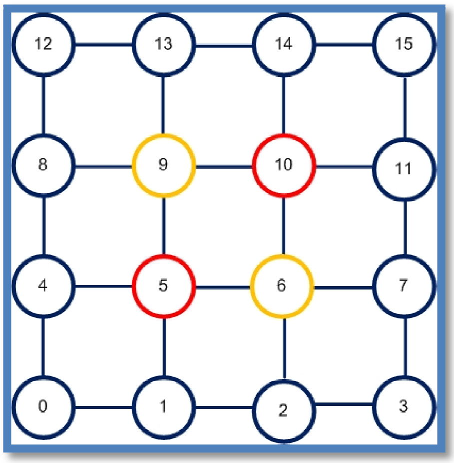


Figure 35: IPTV servers and Internet Gateways Situation. Approach 1

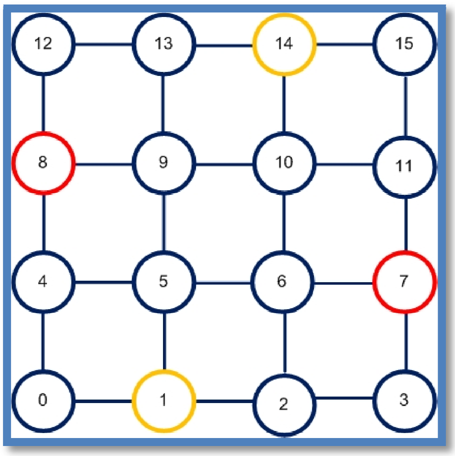


Figure 36: IPTV servers and Internet Gateways Situation. Approach 2

7.2 Methodology

Next stages have been performed in order to estimate the traffic per link:

1) For each one of the possible scenarios, the traffic that each node is going to process is calculated. In order to do that, the number of NTs that is covering each node is extracted from the NTs data layer using MapInfo software. Next, this number of NT is multiplied by a different bandwidth (25, 50 or 125 Mbps) depending on the scenario that is being calculated.
2) After that, some reduction coefficients are applied because of two different facts:
    a. Penetration coefficient of 20%. (Assumption 3)
    b. 40% of users connected at same time. (Assumption 4)

    Therefore, the total traffic per node has been multiplied per 0,08.

3) *Then, the paths for the different traffic flows have been defined and compared for both approaches (Assumption 6). In order to do that, two different traffics have been considered:*
    a. IPTV Traffic. Paths for the IPTV traffic have been manually defined. The criteria used for the assignment was double: 1^{st} minimizing the average distance (number of hops) between the IPTV server and the destination node and 2^{nd} trying to distribute and balancing the traffic between the links.
    b. External Data traffic. The criteria used for this assignment are the same than used before for IPTV traffic: 1^{st} minimizing the average distance (number of hops) between the nodes and the Internet Gateway and 2^{nd} trying to achieve this objective balancing as much as possible the network.

    Studying the regional traffic accurately is not an easy task due the huge amount of possibilities. There are 16 projected nodes, each one of these nodes can send/receive data to/from the rest. So, there are 16x15 different communications paths. On the other hand we realize that the regional traffic is only 5% of the total amount of traffic, which is not significant compared to Internet traffic or IPTV. Hence, regional traffic has not taken into account for deciding the approach.

Details of the defined paths can be found in **Appendix D: Definition of the paths**. Next, **Figure 37** and **Figure 38** show the number of fluxes that each link must support:

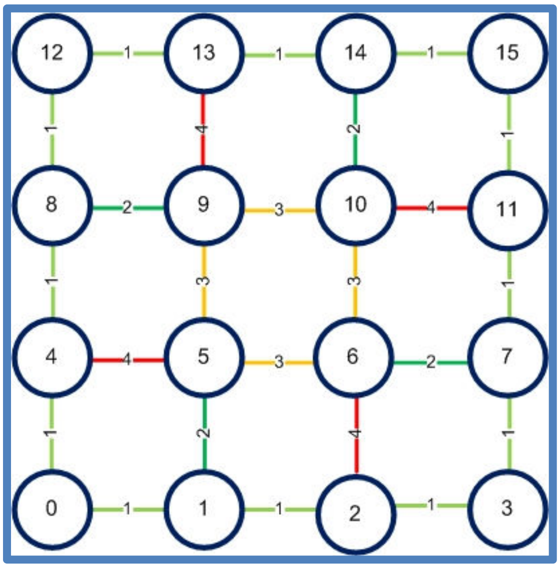


Figure 37: Fluxes per link. Approach 1

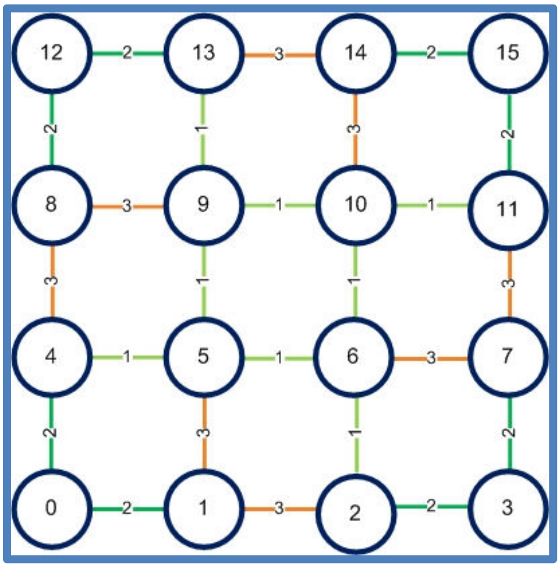


Figure 38: Fluxes per link. Approach 2

Notice that the second approach is more balanced that the first one. There are not links with 4 fluxes, and the traffic is better distributed. Therefore, ITPV servers will be definitely placed at nodes 9 and 14 and Internet Gateways at 7 and 8 ***(Figure 36)****.*

4) Finally, once the best approach has been chosen, the summations of the different traffics that flow per each link are calculated. IPTV and external traffic are easy to calculate because there are only 16 different flows and due the regularity of the topology, optimal paths can be easily manually defined **(Appendix D: Definition of the paths).** On the other hand, regional traffic has 140 different possibilities. As was commented before, regional traffic is only 5% of the total traffic, which is not significant compared to Internet traffic or IPTV. This way, it could be assumed that in the worst case, a link will transport 3 times the average of the traffic sent between 2 nodes in the network **(Figure 39)**:

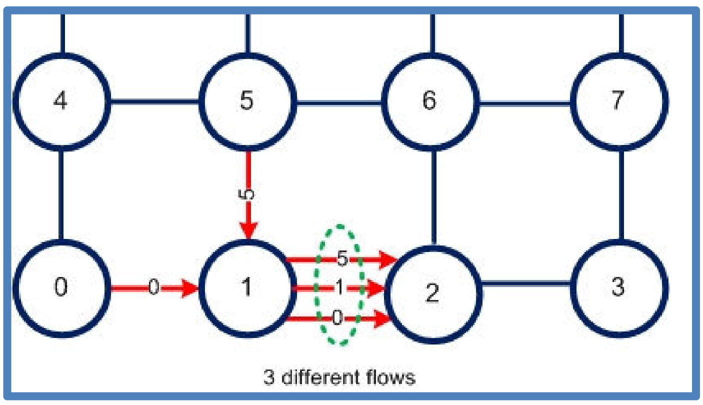


Figure 39: Regional traffic worst case.

7.3 Results

Next, **Table 10** summarizes the calculation of the maximum traffic generated per node (Stages 1&2) in scenario A:

Then, **Table 11** and **Table 12** summarize the maximum rate in Mbps per flux for the IPTV Service and external traffic.

Finally, using the previous results plus the paths defined in **Appendix D: Definition of the paths,** the summation of the maximum traffic per link is realized. Final results are showed in **Table 13a-c**. Notice that after the summation of the IPTV traffic, external traffic, and the regional average Traffic x 3, an extra 40% of bandwidth has been reserved in each link: 20% for OAM[35] and 20% for big companies' traffic **(1.5 Initial assumptions).** After that the final bandwidth projection in each link has been multiplied per 2 in order to guarantee enough bandwidth in the links in case of failure.

[35] Operations, Administration and Maintenance.

# Node	Number of NTs	Gross Traffic [Mbps]	Clear Traffic [Mbps]				
			Total	50% IPTV	5% Local Traffic	5% Regional Traffic	40% External Traffic
0	13.909	347.725	27.818	13.909	1.390,9	1.390,9	11.127,2
1	15.020	375.500	30.040	15.020	1.502	1.502	12.016
2	15.774	394.350	31.548	15.774	1.577,4	1.577,4	12.619,2
3	14.131	353.275	28.262	14.131	1.413,1	1.413,1	11.304,8
4	15.019	375.475	30.038	15.019	1.501,9	1.501,9	12.015,2
5	12.910	322.750	25.820	12.910	1.291	1.291	10.328
6	17.326	433.150	34.652	17.326	1.732,6	1.732,6	13.860,8
7	17.326	433.150	34.652	17.326	1.732,6	1.732,6	13.860,8
8	15.878	396.950	31.756	15.878	1.587,8	1.587,8	12.702,4
9	14.100	352.500	28.200	14.100	1.410	1.410	1.1280
10	17.326	433.150	34.652	17.326	1.732,6	1.732,6	13.860,8
11	17.326	433.150	34.652	17.326	1.732,6	1.732,6	13.860,8
12	15.895	397.375	31.790	15.895	1.589,5	1.589,5	12.716
13	8.288	207.200	16.576	8.288	828,8	828,8	6.630,4
14	16.232	405.800	32.464	16.232	1.623,2	1.623,2	12.985,6
15	14.974	374.350	29.948	14.974	1.497,4	1.497,4	1.1979,2
Total	241.434	6.035.850	482.868	241.434	24.143,4	24.143,4	193.147,2

Table 10: Traffic per Node. Scenario A. Worst Case

		IPTV Flux rate															
		Destination															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Origin	1	13.909		15.774	14.131	15.019	12.910	17.326	17.326	-	-	-	-	-	-	-	-
	14	-	-	-	-	-	-	-	-	15.878	14.100	17.326	17.326	15.895	8.288		14.974

Table 11: IPTV Fluxes [Mbps]. Scenario A

		External Flux rate															
		Origin															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Dest.	7	-	-	12.619	11.305	-	-	13.861		-	-	13.861	13.861	-	-	12.986	11.979
	8	11.127	12.016	-	-	12.015	10.328	-	-		11.280	-	-	12.716	6.630	-	-

Table 12: External traffic fluxes. [Mbps]. Scenario A

Table 13a			IPTV Traffic per Link. Scenario A													
			Fluxes:													
Links	Origin	Destination	1→0	1→2	1→3	1→4	1→5	1→6	1→7	14→8	14→9	14→10	14→11	14→12	14→13	14→15
	0	1	13.909			15.019										
	1	2		15.774	14.131											
	2	3			14.131											
	4	5														
	5	6						17.326	17.326							
	6	7							17.326							
	8	9								15.878						
	9	10								15.878						
	10	11														
	12	13												15.895		
	13	14									14.100			15.895	8.288	
	14	15											17.326			14.974
	0	4				15.019										
	1	5					12.910	17.326	17.326							
	2	6														
	3	7														
	4	8														
	5	9														
	6	10														
	7	11														
	8	12														
	9	13									14.100					
	10	14								15.878		17.326				
	11	15											17.326			

Table 13b

Links			External Traffic per Link. . Scenario A													
			Fluxes:													
	Origin	Destination	0→8	1→8	2→7	3→7	4→8	5→8	6→7	9→8	10→7	11→7	12→8	13→8	14→7	15→7
	0	1														
	1	2														
	2	3														
	4	5						10.328								
	5	6														
	6	7			12.619				13.861						12.986	
	8	9		12.016						11.280						
	9	10														
	10	11									13.861					
	12	13												6.630		
	13	14														
	14	15														
	0	4	11.127													
	1	5		12.016												
	2	6			12.619											
	3	7				11.305										
	4	8	11.127				12.015	10.328								
	5	9		12.016												
	6	10													12.986	
	7	11									13.861	13.861				11.979
	8	12											12.716	6.630		
	9	13														
	10	14													12.986	
	11	15														11.979

Links	Origin	Destination	Reg. avg. Traffic x 3	Semi Total	+40%	Total	Total with BW reservation
	0	1	4.467	33.395	13357,8871	46.753	**93.506**
	1	2	4.467	34.372	13748,6871	48.120	**96.240**
	2	3	4.467	18.598	7439,08711	26.037	**52.074**
	4	5	4.467	14.795	5917,88711	20.713	**41.426**
	5	6	4.467	39.119	15647,4871	54.766	**109.532**
	6	7	4.467	61.258	24503,3271	85.762	**171.524**
	8	9	4.467	43.641	17456,2871	61.097	**122.194**
	9	10	4.467	20.345	8137,88711	28.483	**56.966**
	10	11	4.467	18.328	7331,00711	25.659	**51.318**
	12	13	4.467	26.992	10796,8471	37.789	**75.578**
	13	14	4.467	42.750	17099,8871	59.850	**119.700**
	14	15	4.467	36.767	14706,6871	51.473	**102.946**
	0	4	4.467	30.613	12245,1671	42.858	**85.716**
	1	5	4.467	64.045	25617,8871	89.663	**179.326**
	2	6	4.467	17.086	6834,36711	23.920	**47.840**
	3	7	4.467	15.772	6308,60711	22.080	**44.160**
	4	8	4.467	37.937	15174,8471	53.112	**106.224**
	5	9	4.467	16.483	6593,08711	23.076	**46.152**
	6	10	4.467	17.452	6980,92711	24.433	**48.866**
	7	11	4.467	44.168	17667,0071	61.835	**123.670**
	8	12	4.467	23.813	9525,24711	33.338	**66.676**
	9	13	4.467	18.567	7426,68711	25.993	**51.986**
	10	14	4.467	50.656	20262,5271	70.919	**141.838**
	11	15	4.467	33.772	13508,7671	47.281	**94.562**

Table 13c: Scenario A. Traffic per Link. Worst Case

Even though the IT Infrastructure has been carefully planned, trying to distribute evenly the users and using regular grid topology to connect the nodes, if centralized services as IPTV or Internet traffic of higher levels are run over it, then most part of the effort is lost: Links around these nodes will be extremely loaded and, on the other hand, links far from these 'hot points' will not have almost traffic.

The solution to this problem is not easy. The global tendency of the networks is integrating services, so nowadays a network cannot be planned for a single service, as was the case of the Plain Old Telephony Service years ago. So, if all the power of the projected IT Infrastructure three different solutions are proposed:

1. *Planning the services taking into account the characteristics and topology of the IT Infrastructure: For example, distributing IPTV servers and Internet Gateways with the purpose of achieving a balanced traffic apart from reliability or the cost of providing protection. This solution is difficult to apply in real networks because it is not cost-effective for the service providers (e.g. IPTV providers).*

2. *Applying DiffServ (e.g. DSCP[36]): This method consists of labeling the fluxes according the service in such a way that the ones corresponding to vital services as telemedicine would be prioritized in front other services as P2P that would use the excess of bandwidth.* (IETF, 2003)
3. *Using optical routing: One of the main advantages of optical routing is the low latency. Taking advantage of this issue, the requirement of using the shortest path between a pair of nodes could be eliminated which opens up the possibility of making algorithms to define new paths with traffic distribution as the main requirement to satisfy.*

Same procedure has been applied to scenarios B and C. Details of the results can be found in. Next, **Figure 40** summarizes the results:

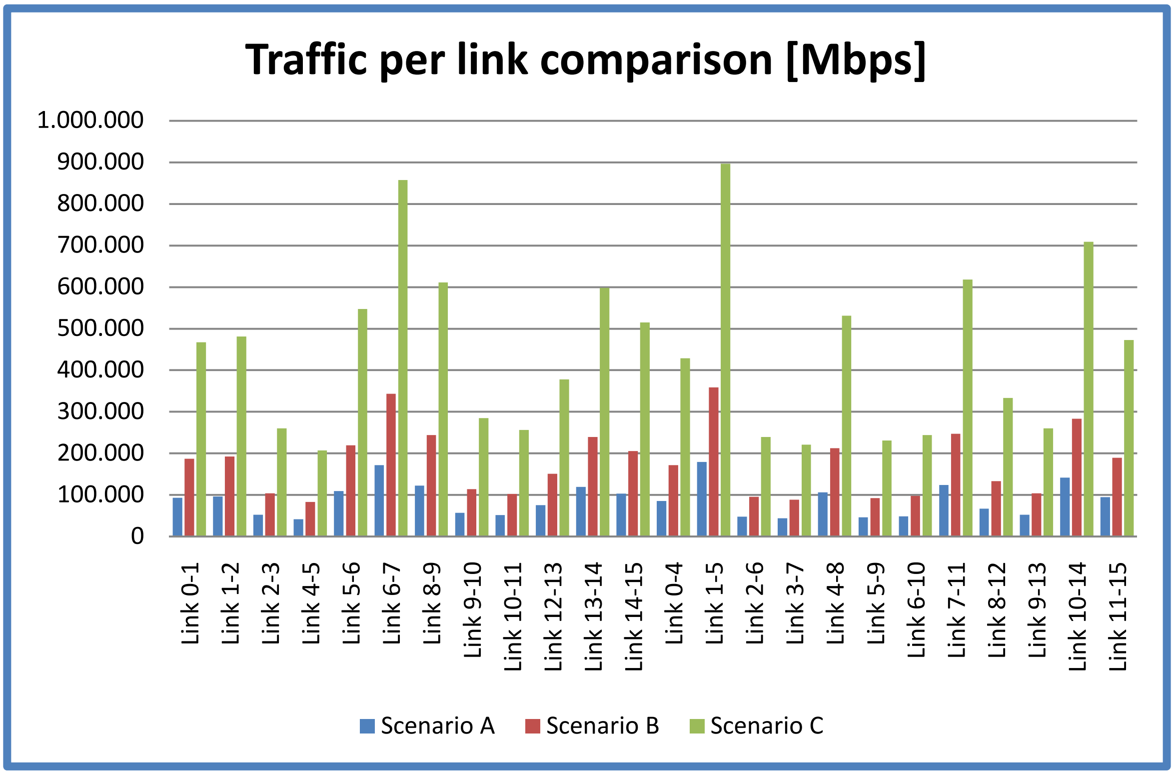


Figure 40: Traffic per link. [Mbps]. Worst Case.

As was expected, results of scenario B and C correspond exactly with the A scenario results but multiplied per 2 and 5 respectively, so previous conclusions and proposals are valid for these cases too.

[36] Differentiated Services Code Point (DSCP) is a field in the header of IP packets for packet classification purposes.

8. Availability Study

This chapter calculates the availability of the network. It is divided in three sections. The first one introduces the term availability and explains some parameters. The second explains the methodology used for the calculation. Finally, the third one exposes the final results.

8.1 Introduction

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 the interval. (EventHelix, 2007)

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

MTBF

Mean Time Between Failures (MTBF), as the name suggests, is the average time between failure of hardware modules. It is the average time a manufacturer estimates before a failure occurs in a hardware module.

FITS

FITS is a more intuitive way of representing MTBF. FITS is nothing but the total number of failures of the module in a billion hours (i.e. 1000,000,000 hours).

MTTR

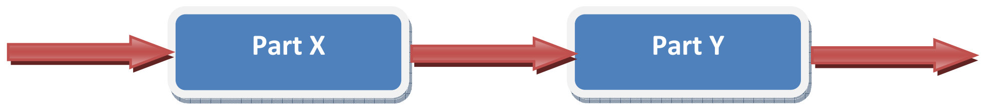
Mean Time To Repair (MTTR), is the time taken to repair a failed hardware module. In an operational system, repair generally means replacing the hardware module. Thus hardware MTTR could be viewed as mean time to replace a failed hardware module. It should be a goal of system designers to allow for a high MTTR value and still achieve the system reliability goals.

8.2 Methodology

Network Availability is calculated by modeling the system as an interconnection of parts in series and parallel (EventHelix, 2007). 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 inoperable, 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.

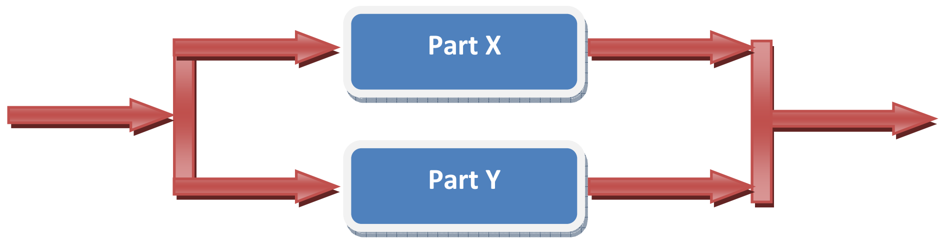
Availability in Series



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 equation below:

$$A = A_x \cdot A_y \qquad \text{(Eq. 15)}$$

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 equation below:

$$A = 1 - [(1 - A_x)(1 - A_y)] \qquad \text{(Eq. 16)}$$

Calculating Availability of Individual Components

This paragraph explains the how to calculate 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:

$$A = \frac{MTBF}{MTBF+MTTR} \qquad \text{(Eq. 17)}$$

Assumptions and data

1) 1 error per year per 100km of ditch.
2) Fails in the nodes have not been considered.
3) 1.110 km of ditch in total.
4) 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.
5) 24 hours to fix a failure.
6) 24 links.

Focusing on our project next procedure has been followed in order to calculate the availability:

i. Estimating the MTBF for each link. This data has been extracted from assumption 1.
ii. Estimating the MTTR. This data has been extracted from assumption 5.
iii. Looking for the worst combination: Pair of links covering the corner node with longest links.
iv. Calculating the availability in parallel of both cases.

8.3 Results

First of all MTBF is calculated for each link. **Table 14** shows the results:

Link		Distance [km]	Prob. Failure per year	Prob. Failure per day	MTBF (days)
Origin	Termination				
0	1	38,2	0,38211	0,001046877	**955**
1	2	47,7	0,47799	0,001309562	**763**
2	3	47	0,47094	0,001290247	**775**
4	5	35,1	0,35109	0,00096189	**1.039**
5	6	29,1	0,29187	0,000799644	**1250**
6	7	5,6	0,0564	0,000154521	**6471**
8	9	38,6	0,38634	0,001058466	**944**
9	10	45,1	0,4512	0,001236164	**808**
10	11	0,7	0,00705	1,93151E-05	**51.773**
12	13	62,4	0,62463	0,001711315	**584**
13	14	62,7	0,62745	0,001719041	**581**
14	15	17,1	0,17061	0,000467425	**2.139**
0	4	39,7	0,39762	0,00108937	**917**
1	5	36,8	0,36801	0,001008247	**991**
2	6	35,2	0,3525	0,000965753	**1.035**
3	7	34,12	0,34122	0,000934849	**1.069**
4	8	46,	0,4653	0,001274795	**784**
5	9	62,8	0,62886	0,001722904	**580**
6	10	0,7	0,00705	1,93151E-05	**51.773**
11	15	80,7	0,80793	0,002213507	**451**
8	12	86,5	0,86574	0,00237189	**421**
9	13	110,2	1,10262	0,003020877	**331**
10	14	65,9	0,65988	0,00180789	**553**
11	15	80,7	0,80793	0,002213507	**451**

Table 14: MTBF Calculation

Then, MTTR is extracted from assumption 5:

MTTR = 24 hours = 1 day

After that, the worst case has been considered:

The node with higher probability of failure is Node 12, because it is at the corner (degree 2) and its links are the longest pair: Link 8-12 (61,4 km) and link 12-13 (44,3 km). Therefore the availability of both links is calculated applying **Equation 17**:

$$A_{8\rightarrow 12} = \frac{421}{1+421} = 0{,}99763$$

$$A_{12\rightarrow 13} = \frac{584}{1+584} = 0{,}99829$$

Finally, applying **Equation 16**, the availability in parallel of both cases is:

$$\boxed{A = 1 - [(1-0{,}99763)\cdot(1-0{,}99829)] = 0{,}999995948}$$

The result is satisfactory because the requirement of achieving availability higher than 99,999% (five 9's) have been achieved.

9. Budget

This chapter estimates the economical cost of the network. This way the proposed solution could be compared with other possible solutions in terms of cost. The budget has been split up according the terms of the deployment plan. This means that the cost of every stage has been calculated individually.

9.1 Assumptions

Only the cost of the physical layer has been calculated. It includes basically the cost of the ditch, the fibers, the blowing and the renting of the Central Offices as locals for placing the nodes' equipment.

Other costs related to other layers as equipment, operation and management, etc. have not been considered by two reasons: First the necessity of delimiting the project, focusing it on the physical layer. And second, the difficulty of getting prizes from hardware providers.

Next, the prizes per unit used in the calculation of the budget are listed:

- 28 € per meter of ditch. Including ditch, duct, fiber and labour cost. (Gustav Helgi Haraldsson; Jens Myrup Pedersen, 2007)
- 8.000 € per restoration of the room's node. Costs relative to electricity maintenance and other costs have not been considered. (TDC, 2007)

9.2 Investment projection

Next**, Table 15, Table 16** and **Table 17** show a projection of the necessary investment in each one of the stages.

Stage 1			
Variable	**Amount**	**Cost per unit [€]**	**Total cost [€]**
Links[37]	525.507 [m]	28 €/m	14.714.196
Nodes	13	8.000	104.000
		Total:	14.818.196

Table 15: Economical cost summary. Stage 1

Stage 2			
Variable	**Amount**	**Cost per unit [€]**	**Total cost [€]**
Links	227.151 [m]	28 €/m	6.360.228
Nodes	3	8.000	24.000
		Total:	6.384.228

Table 16: Economical cost summary. Stage 2

[37] Including ditch, duct, fiber and labour cost.

Stage 3			
Variable	Amount	Cost per unit [€]	Total cost [€]
Links	134.373 [m]	28 €/m	3.762.444
Nodes	-	-	-
		Total:	3.762.444

Table 17: Economical cost summary. Stage 3

Table 18 shows the total backbone cost:

Stage	Cost
1	14.818.196
2	6.384.228
3	3.762.444
Total	24.964.868

Table 18: Total cost

Finally, **Figure 41** shows the investment thorough next 12 years:

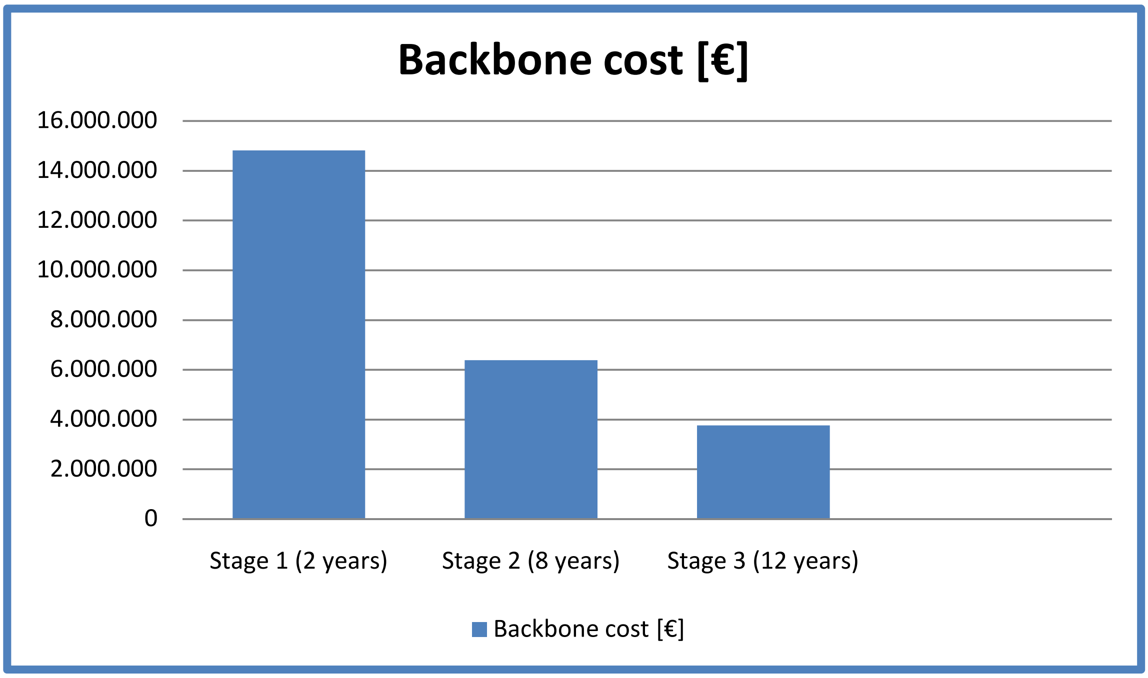


Figure 41: Backbone cost

The backbone investment plan contrasts with the access network investment plan where the most important economical effort must be done in stages 2 and 3 where FTTH is deployed. Thus the global investment will be reduced in first years and increasing gradually in the next 12. (Sevilla, 2008)

Guidelines about how to calculate in detail the budget are introduced in **10.2 Future lines.**

10.Conclusion & Future lines

This chapter is divided in two sections: The first one contains the conclusion of the thesis and the second one gives an overview of the future lines of action in relation with the network planned.

10.1 Conclusion

After the realized studies it could be concluded that the network planning process is not trivial. There are many parameters involved in the methodology, and it is impossible to find the perfect solution. Achieving trade-offs between all these parameters (cost, reliability, scalability, etc) has been the key for achieving an interesting solution that fulfils all the initial requirements:

1) **Cover more than 95% of the NTs.** The proposed solution covers more than 95% of the NTs since the first stage. This is possible thanks to the WiMAX technology.
2) **Scalability.** Between the studied topologies, 4-regular grid is one of the most scalable and dynamic solution. The network can achieve initially a ring shape, reducing the necessary investment. Then it can be gradually improved till achieving a grid topology, or even in the future, a torus or triangular one.
3) **Reduced cost.** Maintaining a reduced cost has been one of the goals along all the decisions taken during the project. Moreover, the proposed deployment plan tries to minimize the economical cost in the first stages of the construction. Allowing by this way making profits in low-term.
4) **Availability.** Chapter 8 proved that the proposed solution also fulfilled the availability five 9s requirement. In the worst of the case, the availability is higher that the necessary.
5) **Balanced network.** This requirement has been one of the most difficult to fulfill during the project. The nodes were located in such a way that the subscribers were evenly distributed. But if all of them are using centralized services as IPTV, or are trying to connect external networks using a unique exchange point, then the traffic distribution becomes extremely unbalanced. This problem does not seem to have a clear solution. A partial used solution is trying to define the shortest paths in such a way that if there two or three different possibilities the links with less traffic are used. Trying to distribute as much as possible the services along the nodes and using optical routing in order to reduce the distance problem are other solutions. This last solution would allow using not only the shortest paths between two nodes, offering by this way much more possibilities of balancing the traffic.

Other of the main difficulties dealt during the project was the impossibility of predicting the future necessary bandwidth. In telecommunication it is really complicated to predict what will happen in next 15 years. New services may appear and modify the traffic projections or the traffic model. It is just by this reason that the network could not be designed based on a single projected bandwidth value. Thus, the network has been created in order to satisfy the initial requirements for 3 different scenarios: From the most conservative one, where WiMAX was supposed to be the technology for the access network till the most optimistic ones, where all the NT on the region are supposed to use FTTH as access technology and up to 125 Mbps of bandwidth.

Regarding to the methods applied in the project, Map Info has been a key factor in order to achieve the results. This software has been used to manage the network terminals data, essential to locate the nodes in the areas with higher NT density **(Chapter 4).**

Last conclusion, and probably the most general and important one is the necessity of paying more attention to the physical layer of the networks, more precisely the infrastructure level. Until recent years the large part of the telecommunication infrastructure was primarily planned and deployed to provide connectivity rather than QoS. This can be noticed in the current backbones topologies based on point to point, single rings or interconnected rings. The idea behind SQoS (Structural QoS) is to establish a next generation communication network infrastructure, which will be providing solid QoS and efficiency. To achieve this, SQoS based network planning concept is promoted which aims at planning physical network infrastructure with good and well defined structural properties.

10.2 Future lines

Network planning process involves many fields. Often it has been necessary to delimit these fields or cases of study. Some work proposals are showed in this section. Most of them consist of omitted parts of the current project:

- Expanding the work done to the whole country. Paying special attention to the connection with external and international networks.
- Expanding the study of the topologies. New topologies as triangular or hexagonal mesh could be included in the comparison.
- Expanding the deployment plan and budget including N2R topology in order to compare the final results with the 4-regular grid topology.
- Automation of the methodology for optimizing the physical paths. Algorithms should be created in order to decide which roads are the most suitable for the deployment of the physical topology. This would allow to realize the calculation without any approximation (1,41 factor).
- Automation of the methodology for optimizing the fluxes with the purpose of balancing the traffic, cost of the protections, reliability, etc..
- Environmental studies. Studying the environmental impact of the new network.
- More precise budget could be calculated following next recommendations:
    a. Defining the physical paths and calculating exactly the real distance.
    b. Studying the prizes per meter of ditch in function of the area and type of terrain.
    c. Studying the different kinds of fiber optics cable, and comparing its capacity with the traffic study in order to select the most appropriated one.
- Making a business plan, including market study, improved budget, break-even point, etc.

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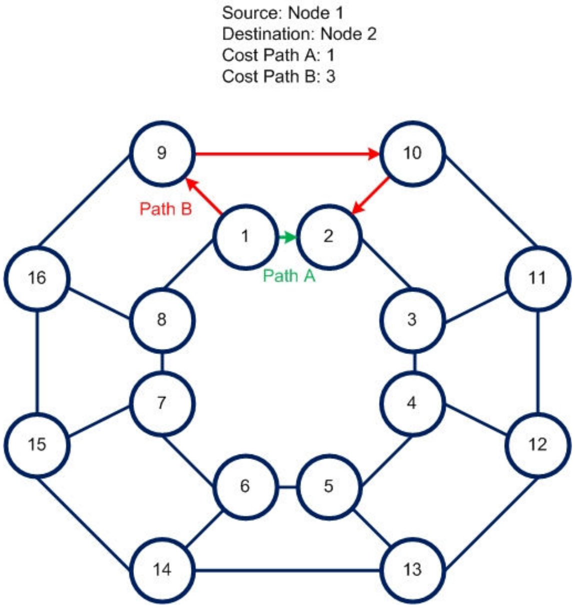
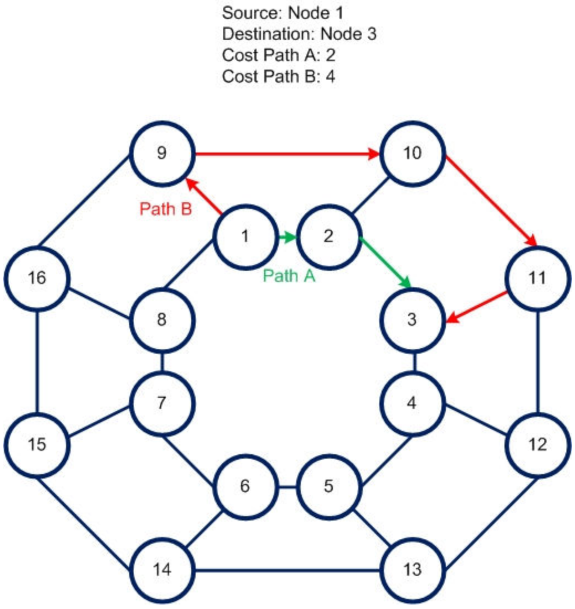
Appendix A: Primary and secondary proposed paths

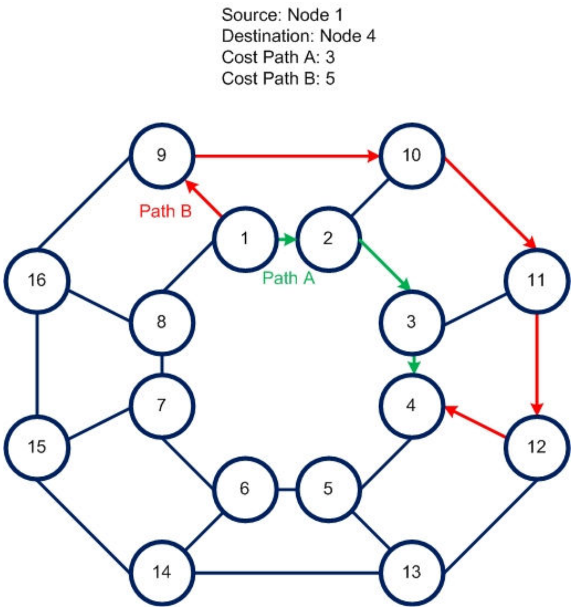
This appendix details the proposed paths for Double Ring and N2R topologies. The results have been compared in **chapter 5** in order to decide which has lower average distances.

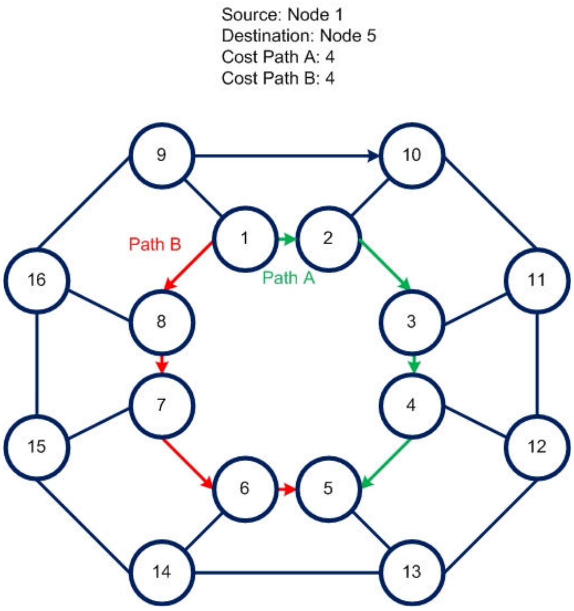
Double Ring Topology: Definition of the shortest paths.

Next figure show the proposed paths from the node 1 to the rest nodes. The criterion has been minimizing the number of hops. The solution is not unique. The solution could be extended to the rest of possibilities.

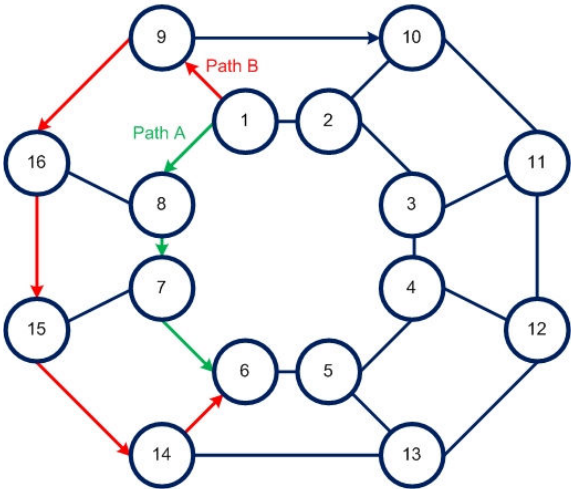




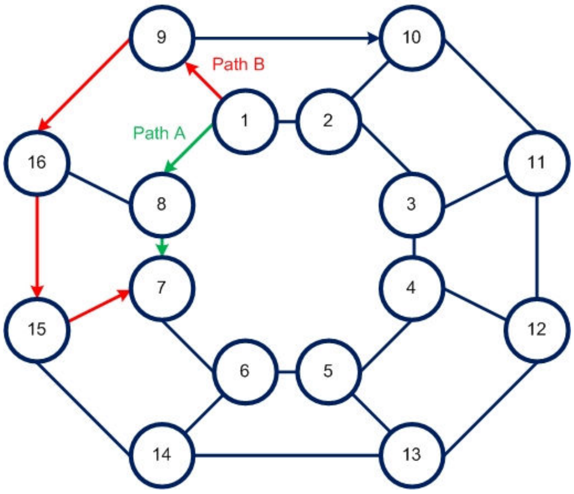




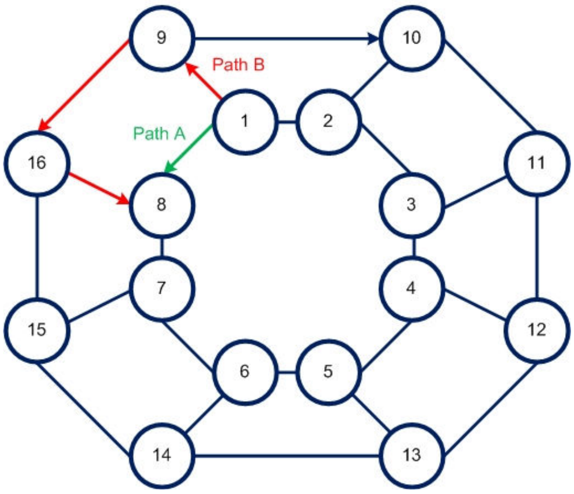
Source: Node 1
Destination: Node 6
Cost Path A: 3
Cost Path B: 5



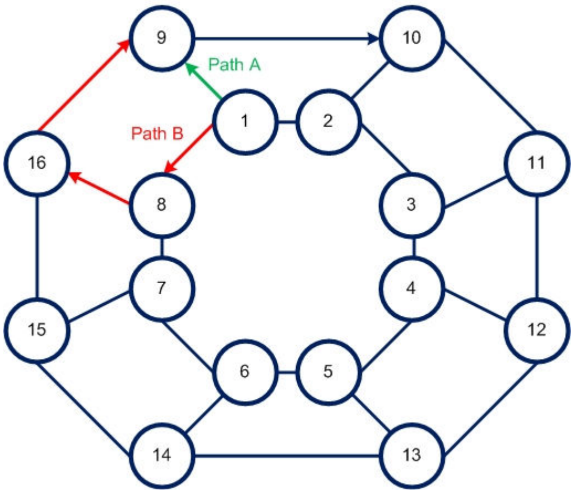
Source: Node 1
Destination: Node 7
Cost Path A: 2
Cost Path B: 4



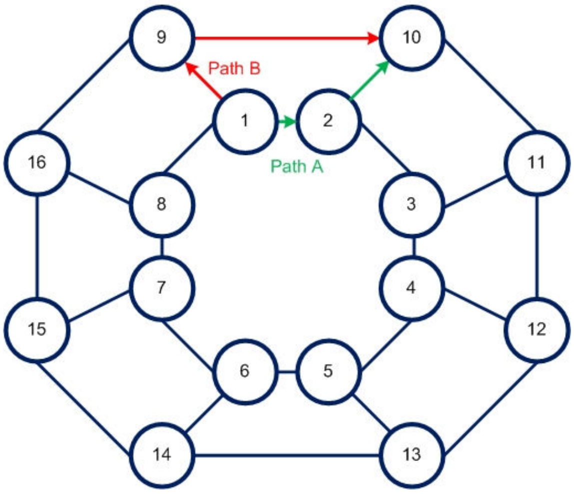
Source: Node 1
Destination: Node 8
Cost Path A: 1
Cost Path B: 3



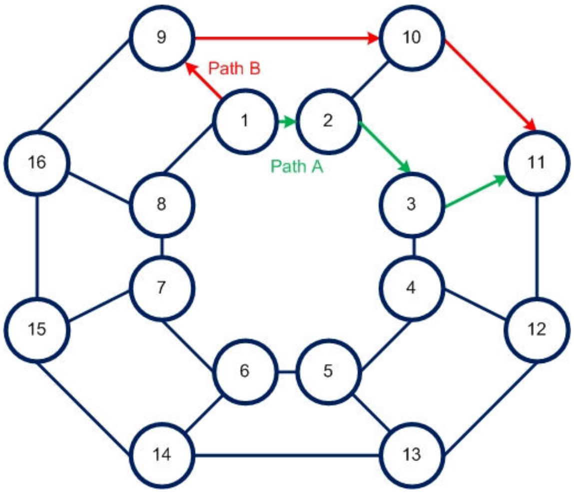
Source: Node 1
Destination: Node 9
Cost Path A: 1
Cost Path B: 3



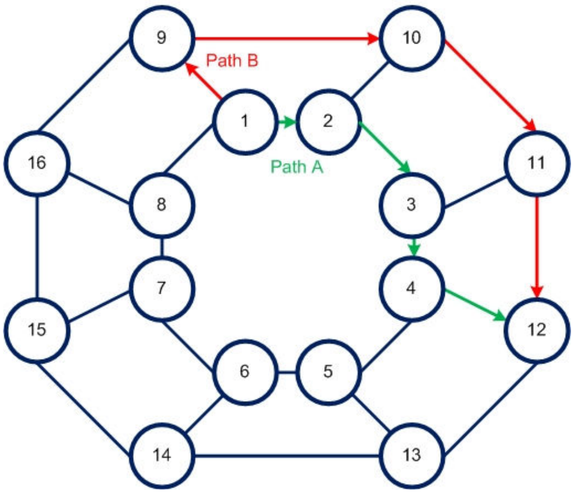
Source: Node 1
Destination: Node 10
Cost Path A: 2
Cost Path B: 2



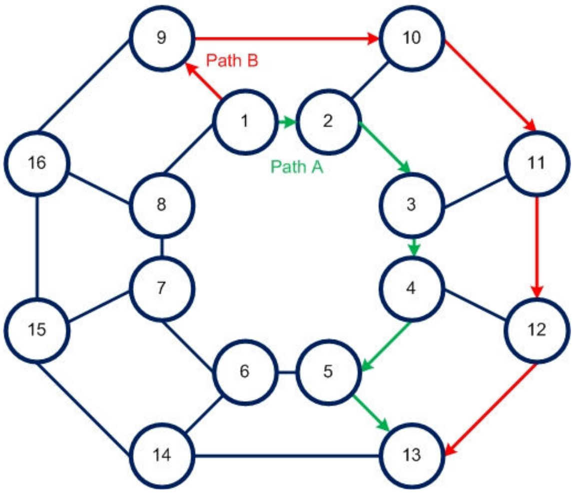
Source: Node 1
Destination: Node 11
Cost Path A: 3
Cost Path B: 3



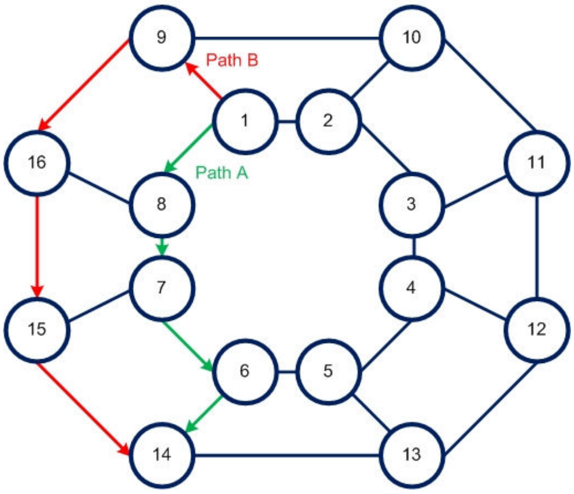
Source: Node 1
Destination: Node 12
Cost Path A: 4
Cost Path B: 4



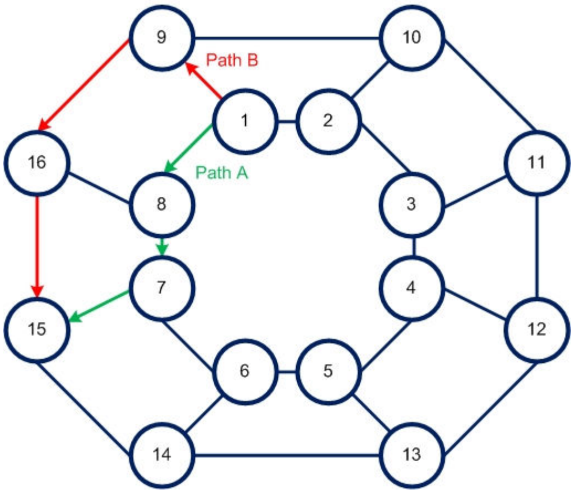
Source: Node 1
Destination: Node 13
Cost Path A: 5
Cost Path B: 5



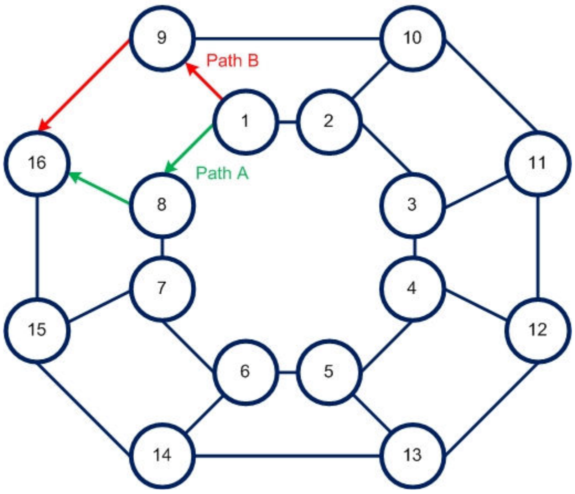
Source: Node 1
Destination: Node 14
Cost Path A: 4
Cost Path B: 4



Source: Node 1
Destination: Node 15
Cost Path A: 3
Cost Path B: 3

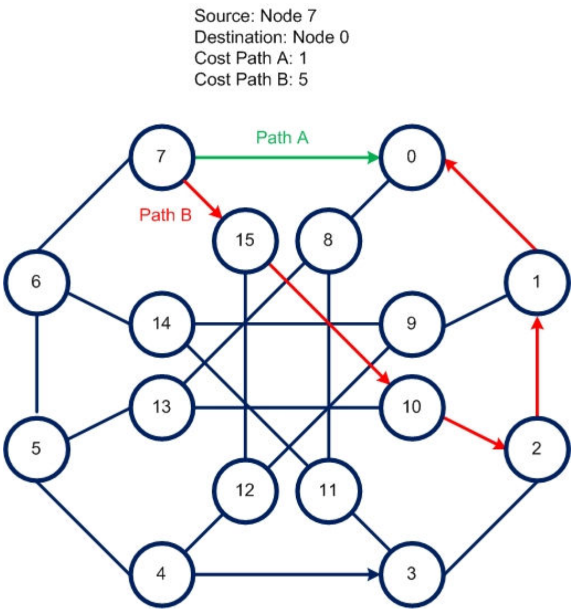


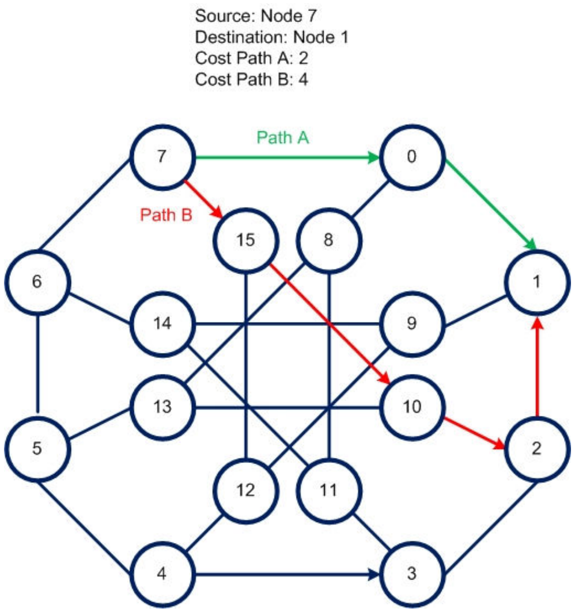
Source: Node 1
Destination: Node 16
Cost Path A: 2
Cost Path B: 2

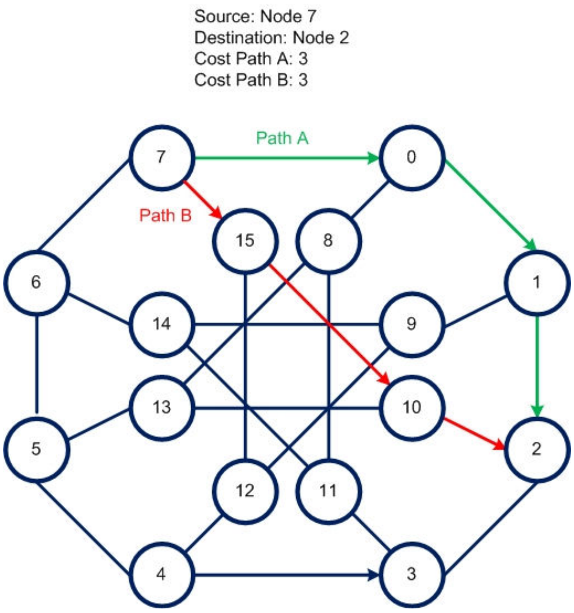


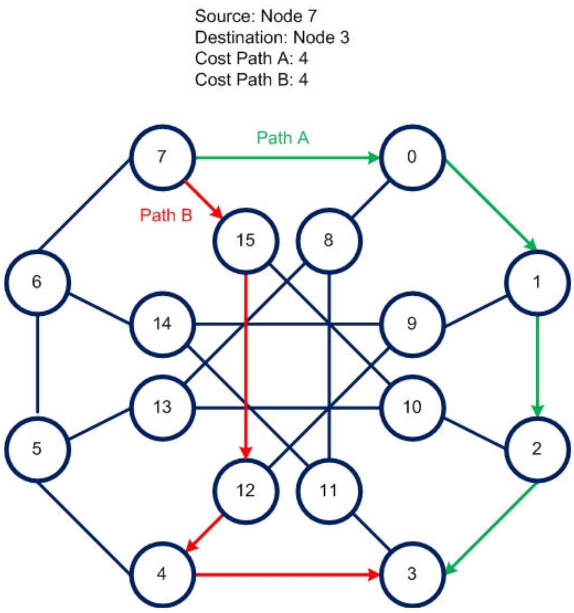
N2R (8,3) Topology: Definition of the shortest paths.

Next group of figures show the proposed paths from the node 7 to the rest nodes. The criterion has been minimizing the number of hops. The solution is not unique. The solution could be extended to the rest of possibilities.

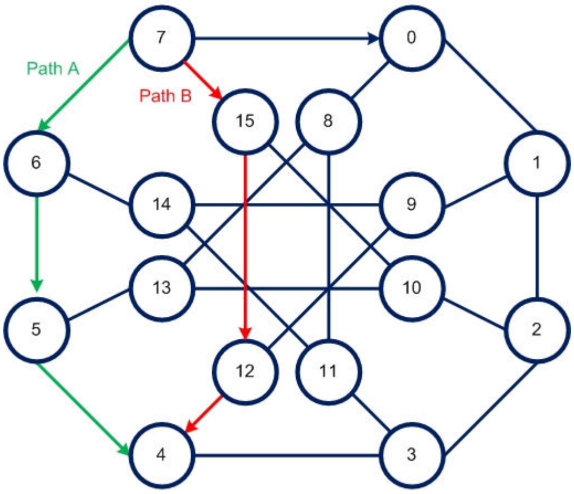




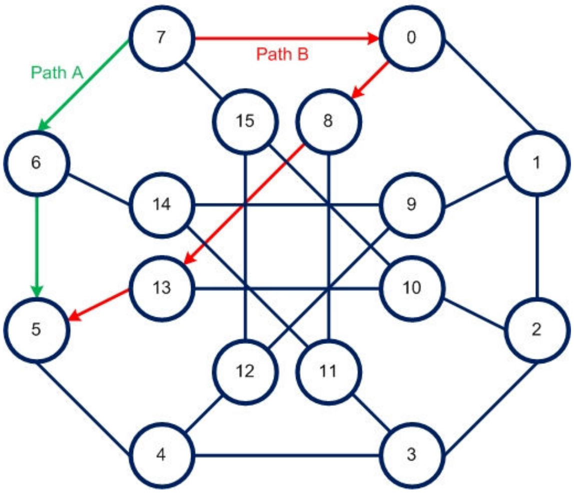




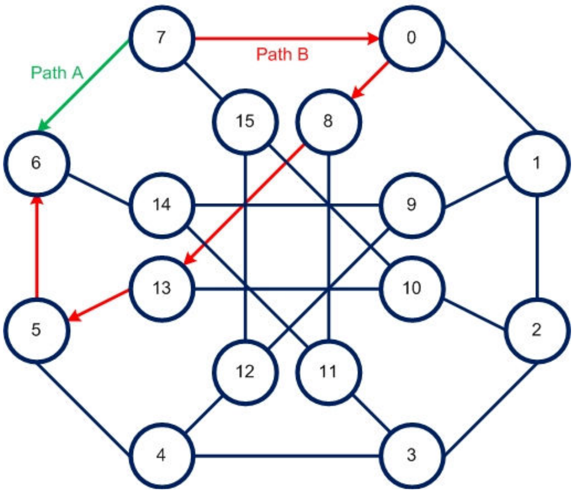
Source: Node 7
Destination: Node 4
Cost Path A: 3
Cost Path B: 3



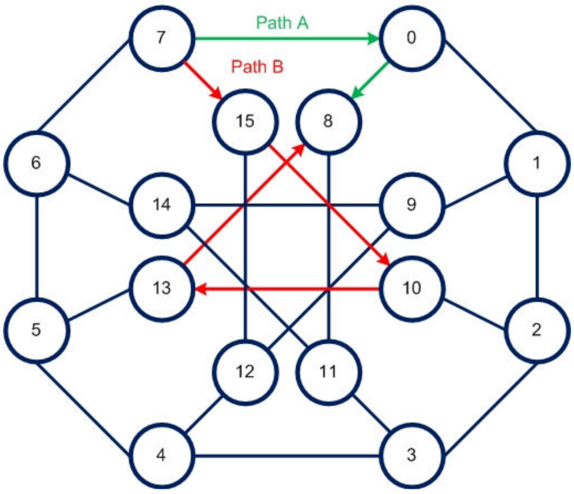
Source: Node 7
Destination: Node 5
Cost Path A: 2
Cost Path B: 4



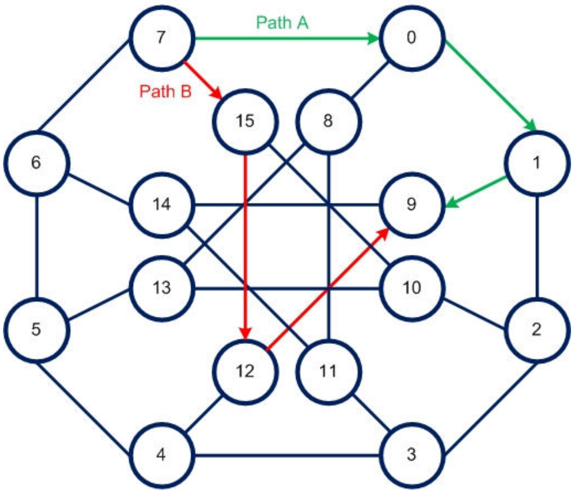
Source: Node 7
Destination: Node 6
Cost Path A: 1
Cost Path B: 5



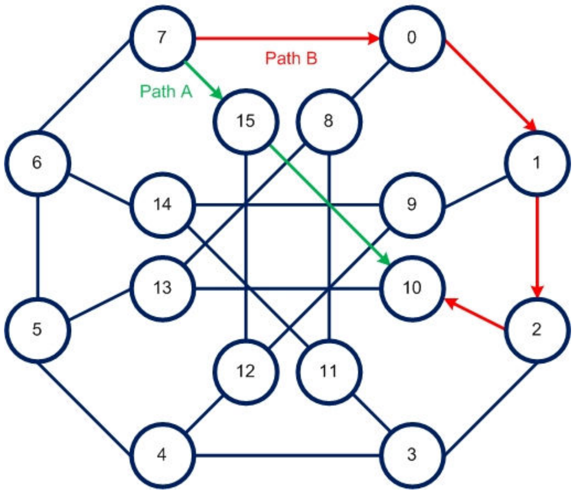
Source: Node 7
Destination: Node 8
Cost Path A: 2
Cost Path B: 4



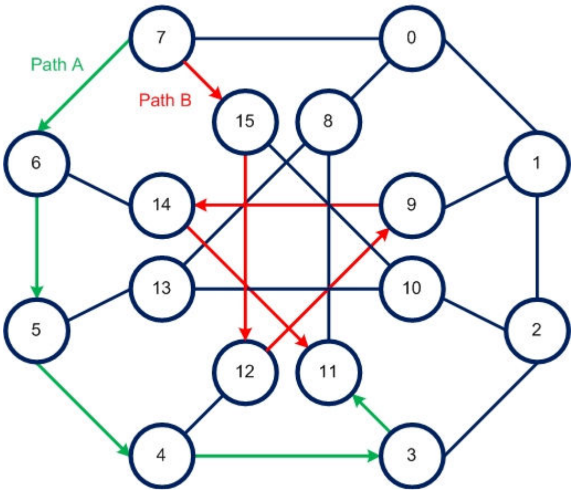
Source: Node 7
Destination: Node 9
Cost Path A: 3
Cost Path B: 3



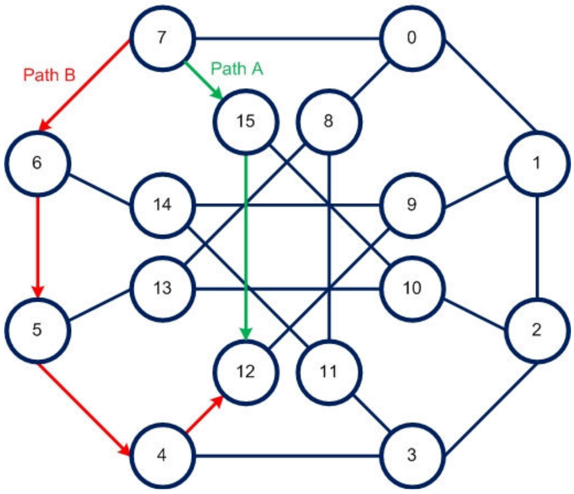
Source: Node 7
Destination: Node 10
Cost Path A: 2
Cost Path B: 4



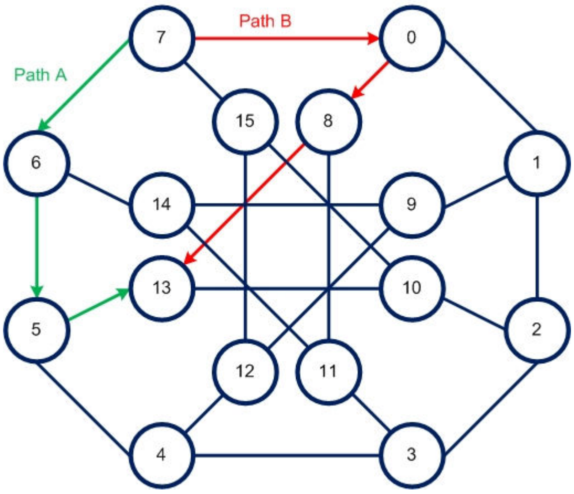
Source: Node 7
Destination: Node 11
Cost Path A: 5
Cost Path B: 4



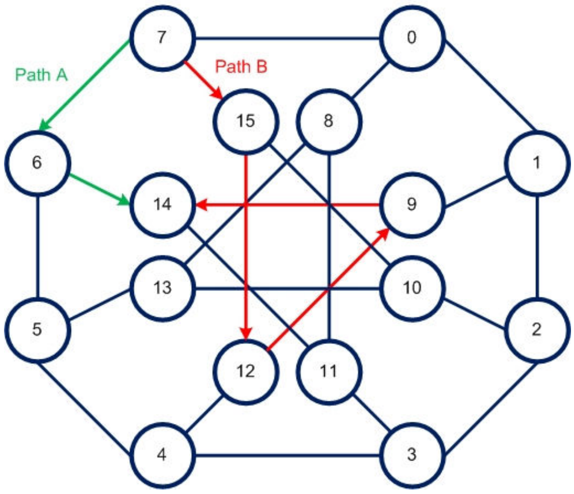
Source: Node 7
Destination: Node 12
Cost Path A: 2
Cost Path B: 4



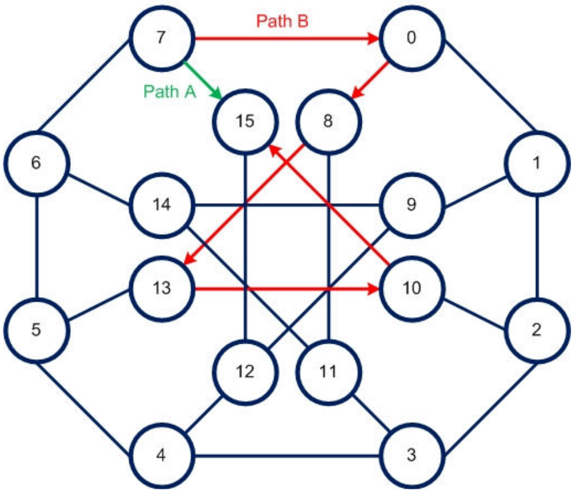
Source: Node 7
Destination: Node 13
Cost Path A: 3
Cost Path B: 3



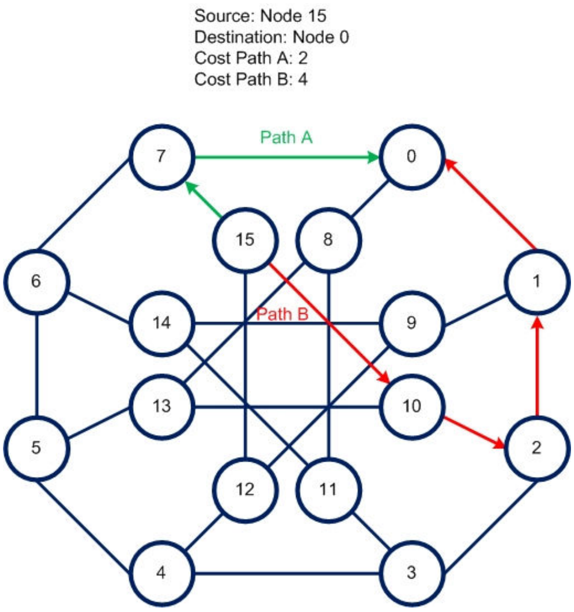
Source: Node 7
Destination: Node 14
Cost Path A: 2
Cost Path B: 4

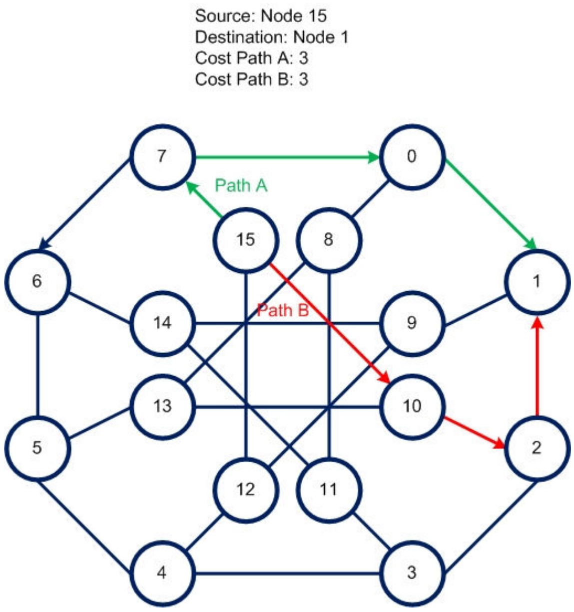


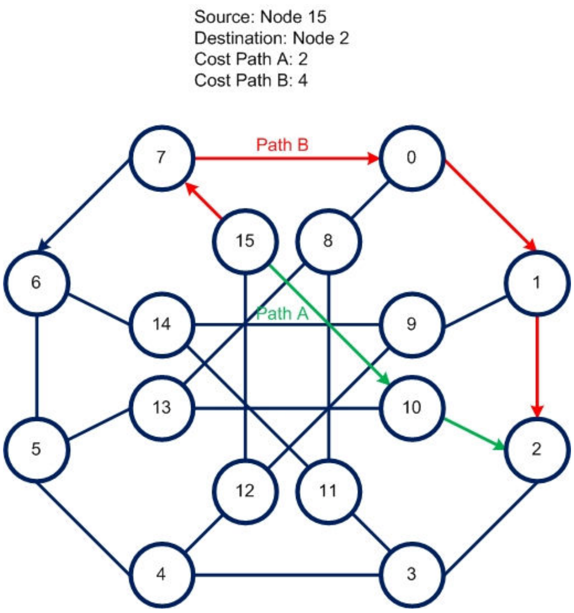
Source: Node 7
Destination: Node 15
Cost Path A: 1
Cost Path B: 5

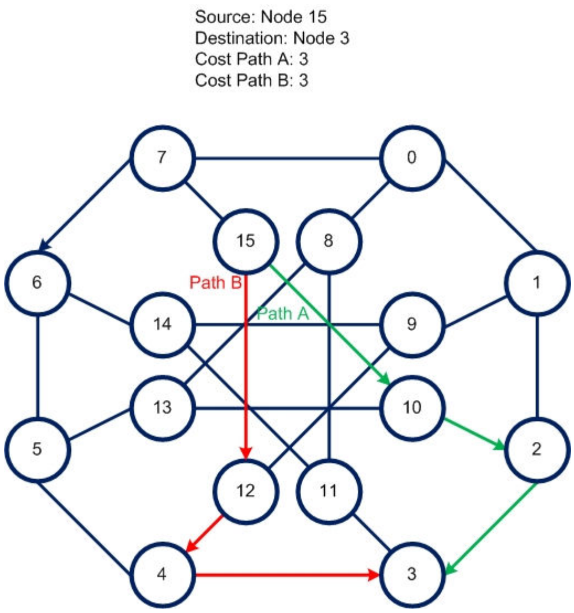


Next figures show the proposed paths from the node 7 to the rest nodes. The criterion has been minimizing the number of hops. The solution is not unique. The solution could be extended to the rest of possibilities.

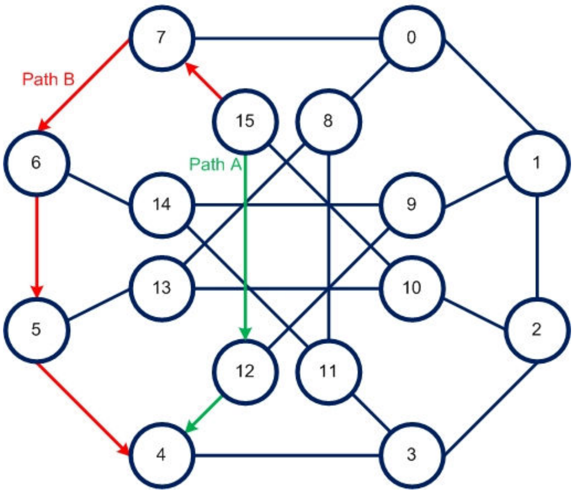




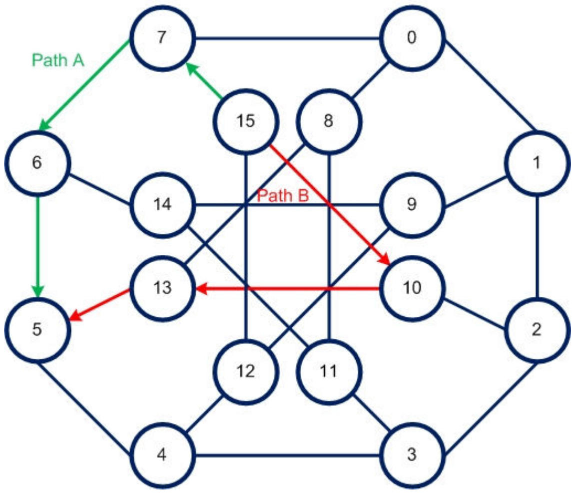




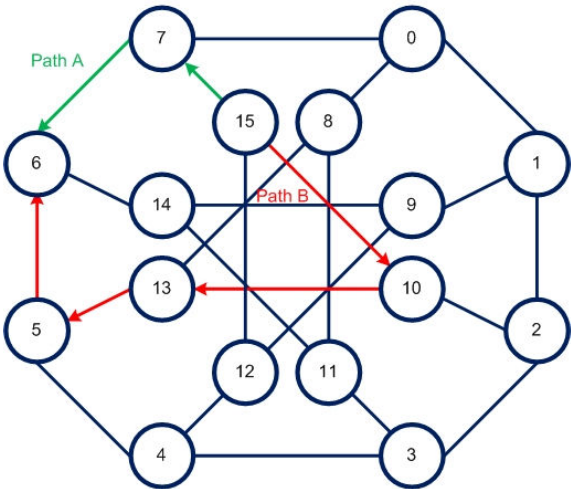
Source: Node 15
Destination: Node 4
Cost Path A: 2
Cost Path B: 4



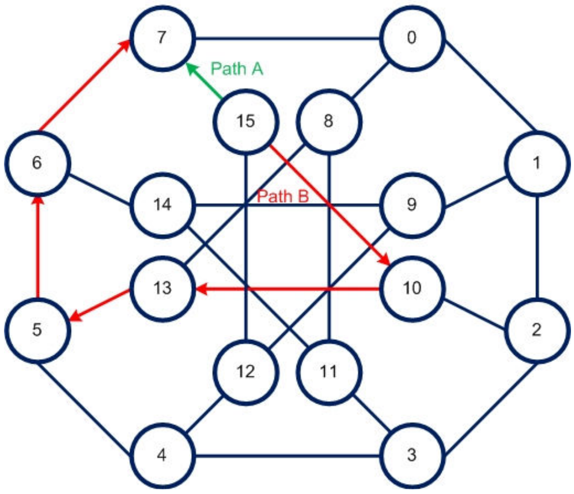
Source: Node 15
Destination: Node 5
Cost Path A: 3
Cost Path B: 3

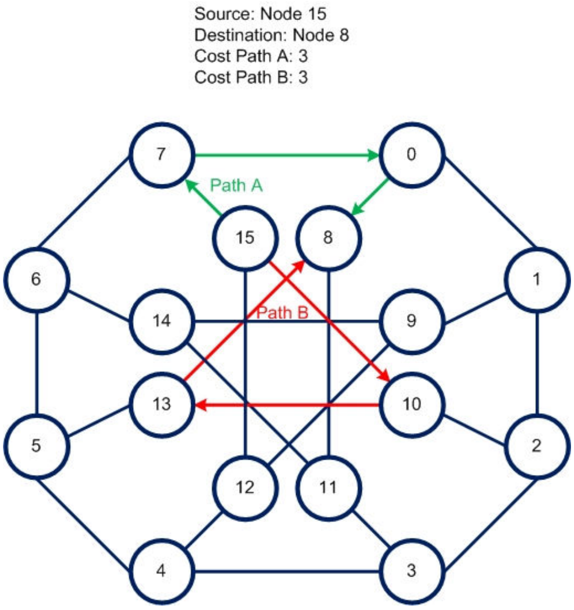


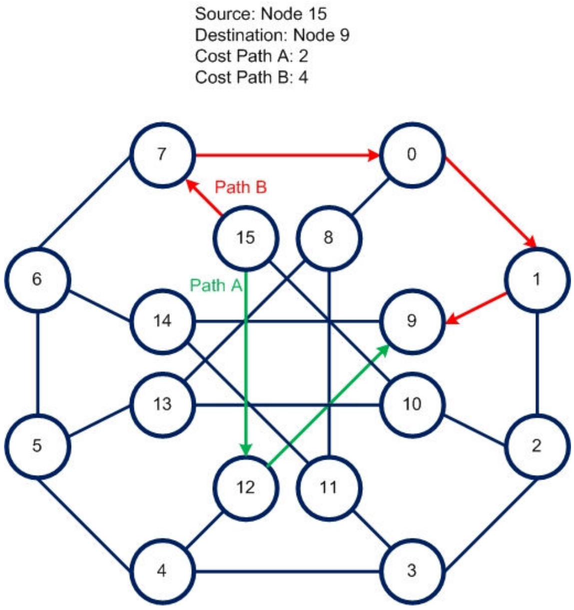
Source: Node 15
Destination: Node 6
Cost Path A: 2
Cost Path B: 4

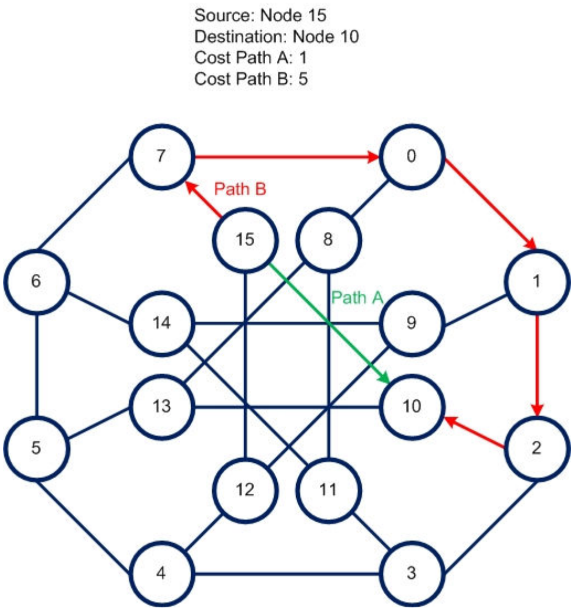


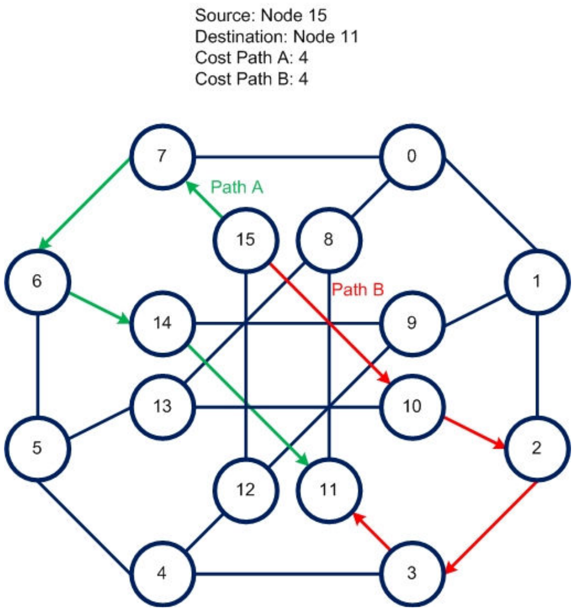
Source: Node 15
Destination: Node 7
Cost Path A: 1
Cost Path B: 5



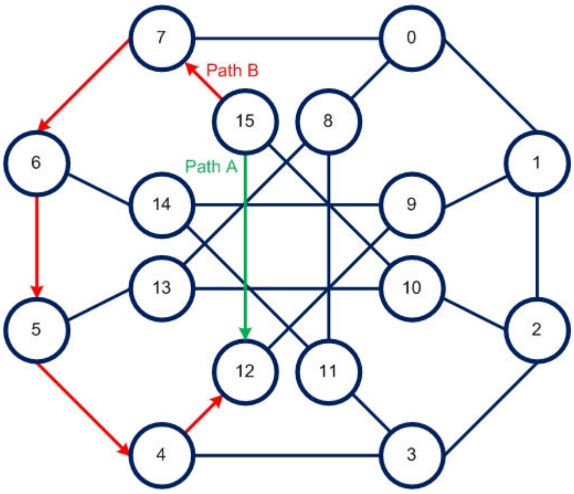

Source: Node 15
Destination: Node 8
Cost Path A: 3
Cost Path B: 3
Path A
Path B


Source: Node 15
Destination: Node 9
Cost Path A: 2
Cost Path B: 4
Path B
Path A

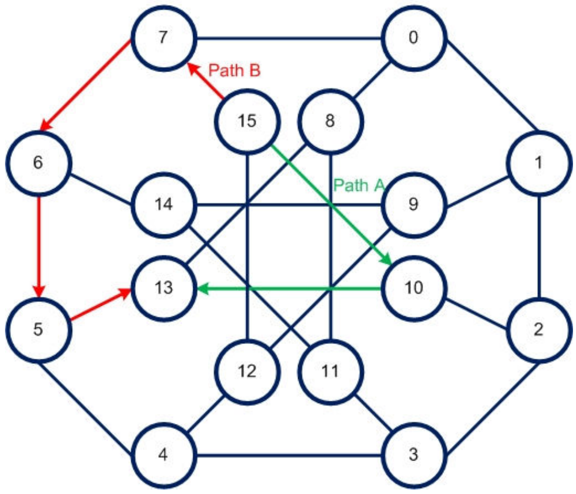

Source: Node 15
Destination: Node 10
Cost Path A: 1
Cost Path B: 5
Path B
Path A


Source: Node 15
Destination: Node 11
Cost Path A: 4
Cost Path B: 4
Path A
Path B

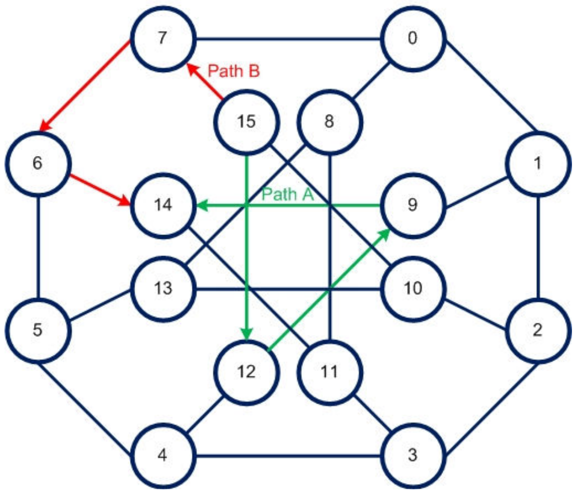
Source: Node 15
Destination: Node 12
Cost Path A: 1
Cost Path B: 5



Source: Node 15
Destination: Node 13
Cost Path A: 2
Cost Path B: 4



Source: Node 15
Destination: Node 14
Cost Path A: 3
Cost Path B: 3



Appendix B: Future topologies

This appendix shows the diagrams of two possible future topologies. As can be checked on the figures, the whole infrastructure of the 4-Regular Grid topology is recycled which demonstrate that the networks fulfils the cost-effective and scalability requirements. Only some new links are projected in order to achieve an improved network with higher performance.

Figure 42 shows the triangular mesh topology. Its main advantage is the higher degree: 6.

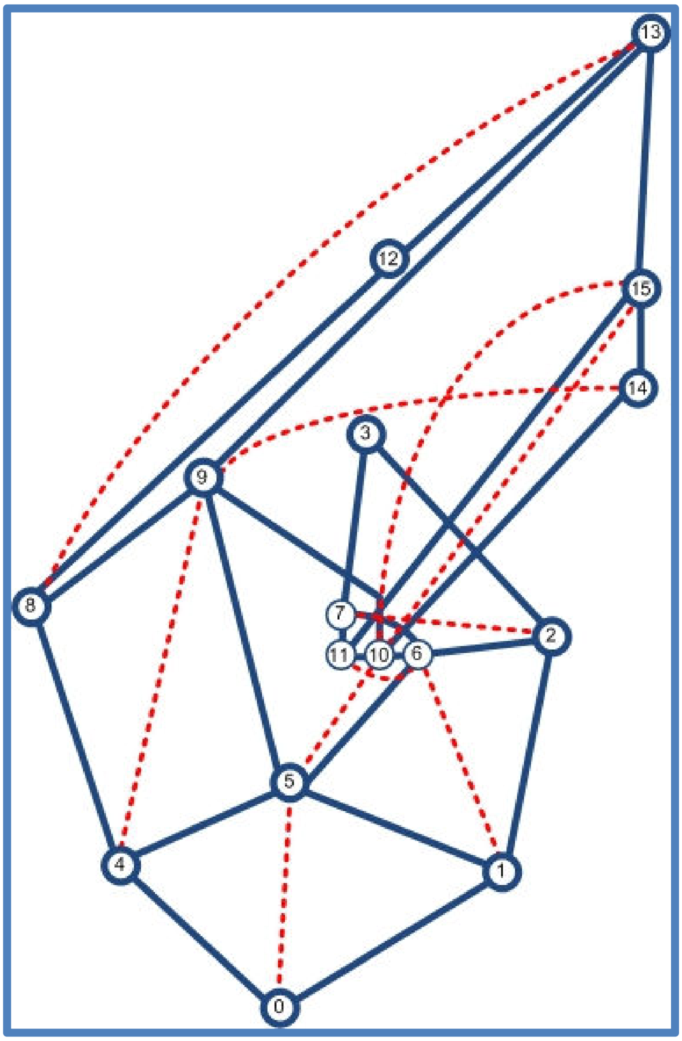


Figure 42: Triangular topology

Next, Figure 43 shows an alternative option. It consists on converting the 4-Regular Gris topology in a torus one. Torus topologies are completely regular. Its lower diameter and lower average distances between nodes are the main advantages.

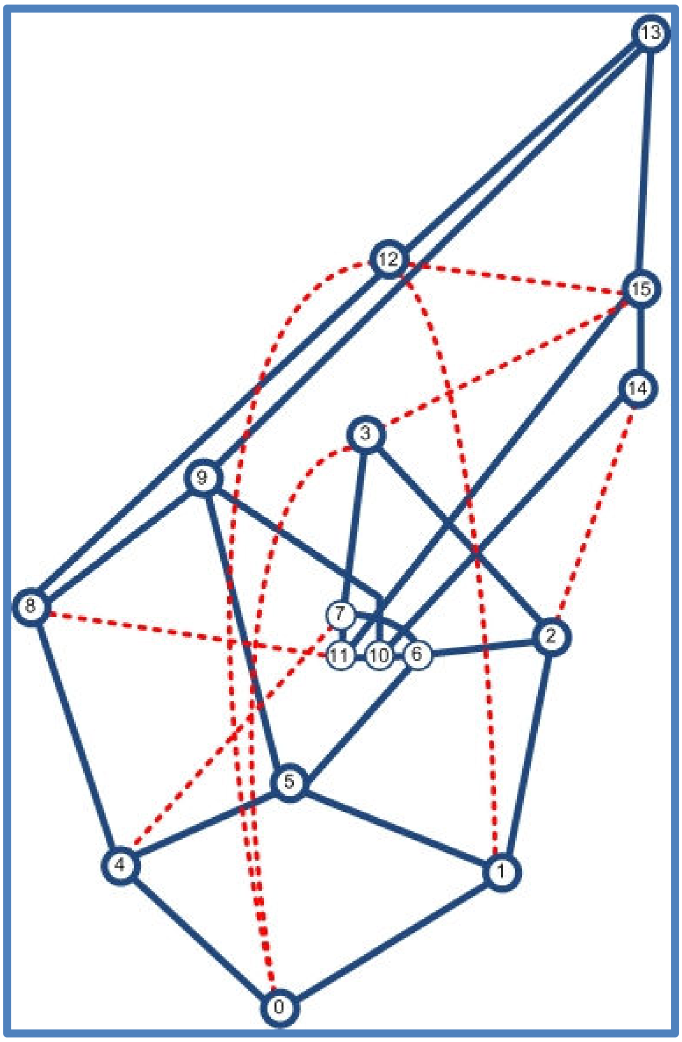


Figure 43: Torus topology

Next the economical cost of improving the 4-regular grid topology to previous ones is estimated:

Topology	Distance[38] (Km)	Cost[39] (Euros)
Torus	611	1.7108.000
Triangular mesh	760	2.128.0000

[38] It is only calculated the distance of the links in red color (new ones). Distances have been measured with MapInfo 'ruler tool' and multiplied by 1,41 according **(1.6 Assumptions and notes).**

[39] The cost of 1 meter of ditch is 28 €. **(9.1Assumptions)**

Appendix C: Traffic statistics

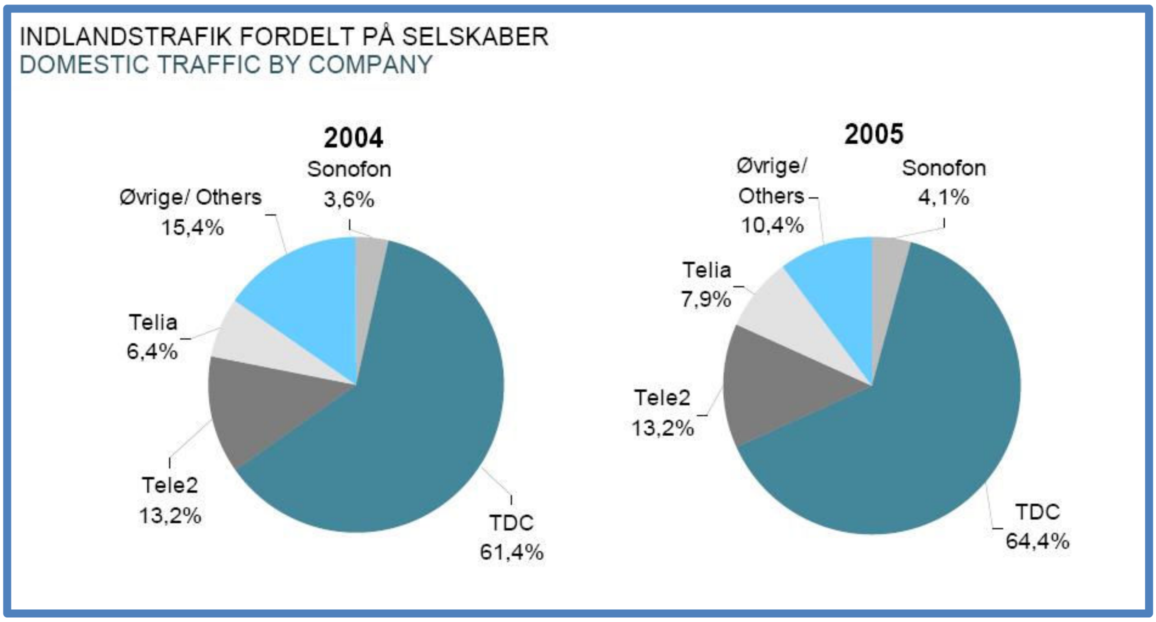


Figure 44: Domestic traffic by company. Denmark (National IT and Telecom Agency, 2007)

Ultimo perioden End of period					Markedsandele Market shares			
	2002	2003	2004	2005	2002	2003	2004	2005
Cybercity	95.107	92.335	115.671	144.698	6,2%	5,5%	6,9%	8,1%
Dansk Kabel-TV	•	•	•	50.371	•	•	•	2,8%
Orange	56.385	39.695	21.914	•	3,7%	2,4%	1,3%	•
TDC	881.255	1.014.207	1.074.892	1.102.283	57,5%	60,4%	63,9%	61,5%
Tele 2	178.701	164.290	132.755	158.637	11,7%	9,8%	7,9%	8,9%
Telia	129.018	141.729	151.888	34.487	8,4%	8,4%	9,0%	1,9%
TeliaStofa	…	…	…	146.727	…	…	…	8,2%
Tiscali	146.400	150.068	88.279	•	9,5%	8,9%	5,2%	•
Øvrige[2] Others[2]	46.183	75.987	97.236**	264.509	3,0%	4,5%	5,8%**	8,6%
Abonnementer i alt **Subscriptions in total**	1.533.049	1.678.311	1.682.635**	1.791.341	100%	100%	100%	100%
- heraf erhverv - of which businesses	139.236	235.438	295.963**	360.893	•	•	•	20,2%
- heraf privat - of which private	1.393.786	1.442.873	1.400.169**	1.430.448	•	•	•	79,8%
Tilslutningsmetode[3] **Type of connection[3]**								
- dial-up - dial-up	1.825.973	1.987.093	696.655	467.863	•	•	•	26,2%
- direkte opkobling - direct connection	468.730	733.858	1.027.993	1.313.186	•	•	•	73,2%
Abonnementer pr. 100 indbyggere Subscriptions per 100 inhabitants	28,5	31,1	31,3	32,9	•	•	•	•

Table 19: ISP Market shares. Denmark. (National IT and Telecom Agency, 2007)

Appendix D: Definition of the paths

This appendix shows the results of the assignment of the paths for the most representative traffic flows: the IPTV traffic and the external one. They both are 90% of the total traffic of the network. **(Figure 45 & Figure 46).**

Methodology

Due the regular topology of the network, this process has been performed manually. Other complex topologies or networks with a higher number of nodes would require individual algorithms in order to calculate optimum paths.

Two criteria have been followed in order to get the desired results:

1) Minimizing the average distance. This implies that the path between 2 points must be always minimal.
2) In the cases where more than 1 path between 2 points is possible, it has be chosen the one with less load.

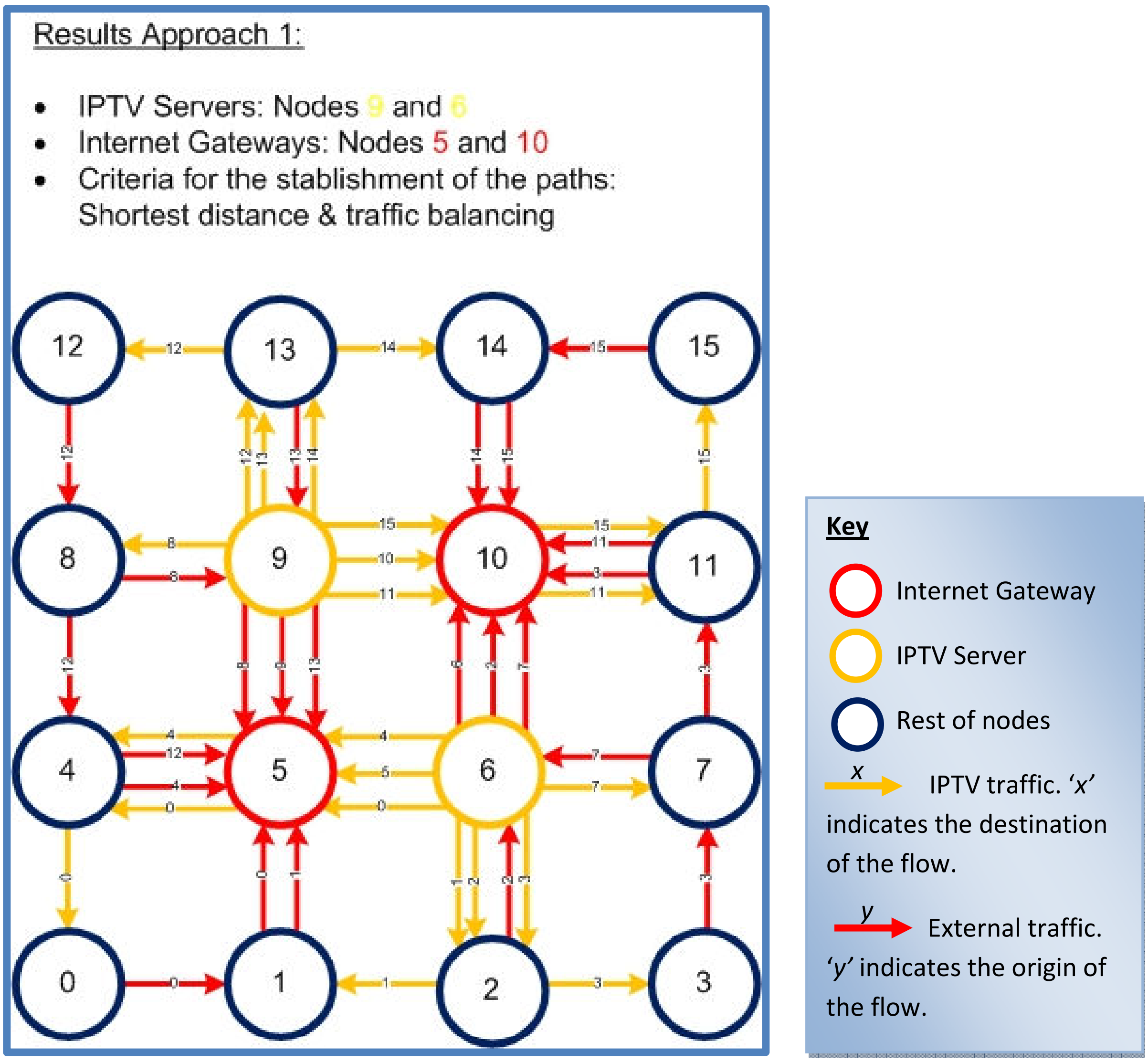


Figure 45: Detailed paths for IPTV and external traffic. Approach 1.

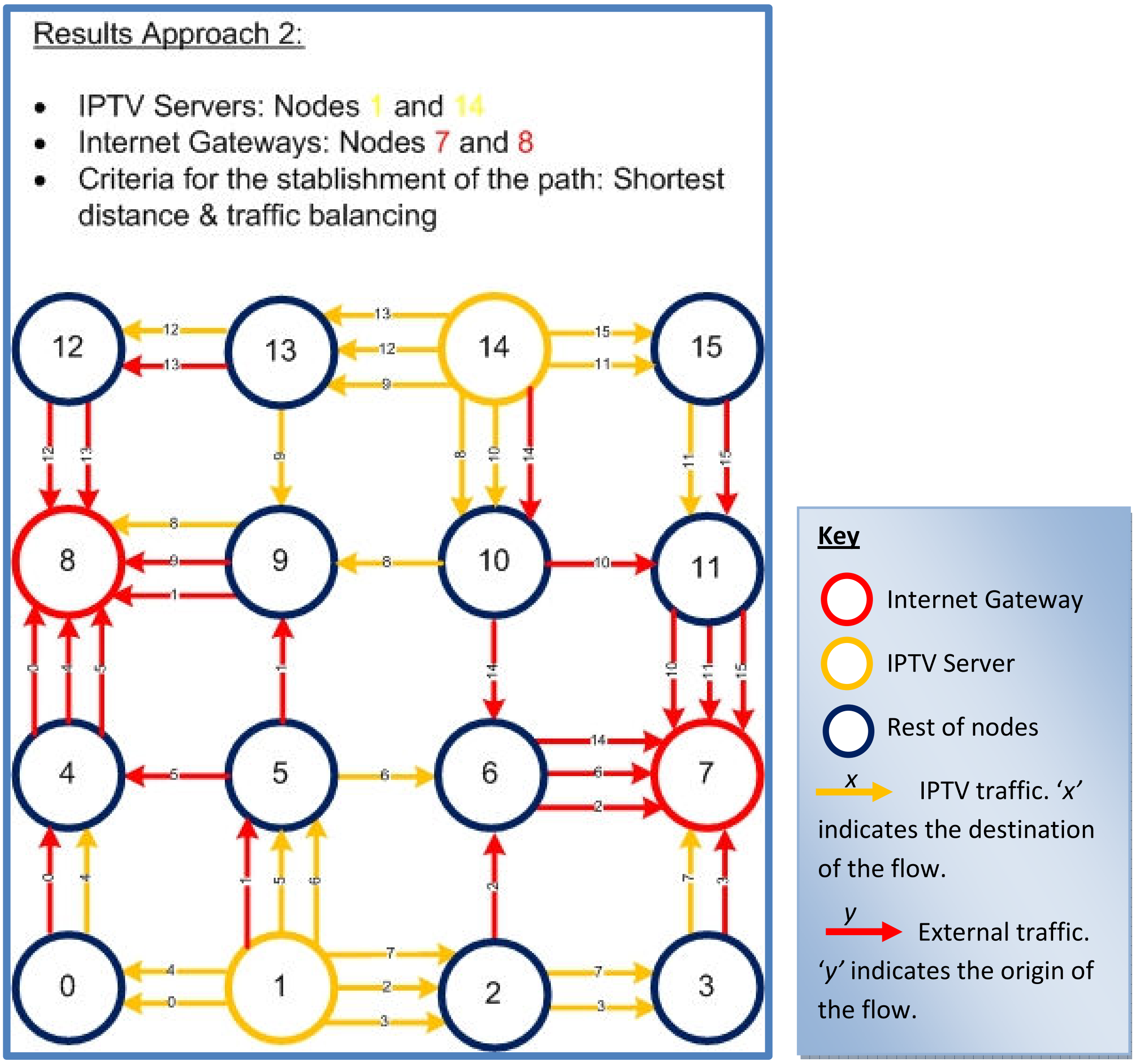


Figure 46: Detailed paths for IPTV and external traffic. Approach 2.

Appendix E: Regional traffic distribution

This appendix shows the percentage of traffic that would go from each node to each node **(Table 20)** if we use a criteria that the % of packets with a concrete destination x is directly proportional to the amount of NT that this node X is covering. Hence, statistically nodes that cover more NTs will receive more traffic from the rest of nodes that nodes that cover less.

		Destination															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Origin	0		6,60%	6,93%	6,21%	6,60%	5,67%	7,61%	7,61%	6,98%	6,20%	7,61%	7,61%	6,99%	3,64%	7,13%	6,58%
	1	6,14%		6,97%	6,24%	6,63%	5,70%	7,65%	7,65%	7,01%	6,23%	7,65%	7,65%	7,02%	3,66%	7,17%	6,61%
	2	6,16%	6,66%		6,26%	6,66%	5,72%	7,68%	7,68%	7,04%	6,25%	7,68%	7,68%	7,04%	3,67%	7,19%	6,64%
	3	6,12%	6,61%	6,94%		6,61%	5,68%	7,62%	7,62%	6,99%	6,20%	7,62%	7,62%	6,99%	3,65%	7,14%	6,59%
	4	6,14%	6,63%	6,97%	6,24%		5,70%	7,65%	7,65%	7,01%	6,23%	7,65%	7,65%	7,02%	3,66%	7,17%	6,61%
	5	6,09%	6,57%	6,90%	6,18%	6,57%		7,58%	7,58%	6,95%	6,17%	7,58%	7,58%	6,96%	3,63%	7,10%	6,55%
	6	6,21%	6,70%	7,04%	6,31%	6,70%	5,76%		7,73%	7,08%	6,29%	7,73%	7,73%	7,09%	3,70%	7,24%	6,68%
	7	6,21%	6,70%	7,04%	6,31%	6,70%	5,76%	7,73%		7,08%	6,29%	7,73%	7,73%	7,09%	3,70%	7,24%	6,68%
	8	6,17%	6,66%	6,99%	6,26%	6,66%	5,72%	7,68%	7,68%		6,25%	7,68%	7,68%	7,05%	3,67%	7,20%	6,64%
	9	6,12%	6,61%	6,94%	6,22%	6,61%	5,68%	7,62%	7,62%	6,98%		7,62%	7,62%	6,99%	3,65%	7,14%	6,59%
	10	6,21%	6,70%	7,04%	6,31%	6,70%	5,76%	7,73%	7,73%	7,08%	6,29%		7,73%	7,09%	3,70%	7,24%	6,68%
	11	6,21%	6,70%	7,04%	6,31%	6,70%	5,76%	7,73%	7,73%	7,08%	6,29%	7,73%		7,09%	3,70%	7,24%	6,68%
	12	6,17%	6,66%	6,99%	6,27%	6,66%	5,72%	7,68%	7,68%	7,04%	6,25%	7,68%	7,68%		3,67%	7,20%	6,64%
	13	5,97%	6,44%	6,77%	6,06%	6,44%	5,54%	7,43%	7,43%	6,81%	6,05%	7,43%	7,43%	6,82%		6,96%	6,42%
	14	6,18%	6,67%	7,00%	6,27%	6,67%	5,73%	7,69%	7,69%	7,05%	6,26%	7,69%	7,69%	7,06%	3,68%		6,65%
	15	6,14%	6,63%	6,97%	6,24%	6,63%	5,70%	7,65%	7,65%	7,01%	6,23%	7,65%	7,65%	7,02%	3,66%	7,17%	

Table 20: Destination of the regional traffic. Distribution

Appendix F: Traffic per link. Scenarios B and C

		IPTV Traffic per Link. Scenario B													
Table 21a		Fluxes:													
Origin	Destination	1→0	1→2	1→3	1→4	1→5	1→6	1→7	14→8	14→9	14→10	14→11	14→12	14→13	14→15
0	1	27.818			30.038										
1	2		31.548	28.262											
2	3			28.262											
4	5														
5	6						34.652	34.652							
6	7							34.652							
8	9								31.756						
9	10								31.756						
10	11														
12	13												31.790		
13	14									28.200			31.790	16.576	
14	15											34.652			29.948
0	4				30.038										
1	5					25.820	34.652	34.652							
2	6														
3	7														
4	8														
5	9														
6	10														
7	11														
8	12														
9	13									28.200					
10	14								31.756		34.652				
11	15	27.818			30.038										

Links

Table 21b			External Traffic per Link. . Scenario B													
			Fluxes:													
Links	Origin	Destination	0→8	1→8	2→7	3→7	4→8	5→8	6→7	9→8	10→7	11→7	12→8	13→8	14→7	15→7
	0	1														
	1	2														
	2	3														
	4	5						20.656								
	5	6														
	6	7			25.238				27.722						25.971	
	8	9		24.032						22.560						
	9	10														
	10	11									27.722					
	12	13												13.261		
	13	14														
	14	15														
	0	4	22.254													
	1	5		24.032												
	2	6			25.238											
	3	7				22.610										
	4	8	22.254				24.030	20.656								
	5	9		24.032												
	6	10													25.971	
	7	11									27.722	27.722				23.958
	8	12											25.432	13.261		
	9	13														
	10	14													25.971	
	11	15														23.958

Links	Origin	Destination	Reg. avg. Traffic x 3	Semi Total	+40%	Total	Total with BW reservation
	0	1	8.933	66.789	26.716	93.505	**187.010**
	1	2	8.933	68.743	27.497	96.241	**192.482**
	2	3	8.933	37.195	14.878	52.074	**104.147**
	4	5	8.933	29.589	11.836	41.425	**82.850**
	5	6	8.933	78.237	31.295	109.532	**219.065**
	6	7	8.933	122.517	49.007	171.523	**343.047**
	8	9	8.933	87.281	34.913	122.194	**244.388**
	9	10	8.933	40.689	16.276	56.965	**113.930**
	10	11	8.933	36.655	14.662	51.317	**102.634**
	12	13	8.933	53.984	21.594	75.578	**151.156**
	13	14	8.933	85.499	34.200	119.699	**239.398**
	14	15	8.933	73.533	29.413	102.947	**205.894**
	0	4	8.933	61.226	24.490	85.716	**171.432**
	1	5	8.933	128.089	51.236	179.325	**358.650**
	2	6	8.933	34.172	13.669	47.841	**95.681**
	3	7	8.933	31.543	12.617	44.160	**88.320**
	4	8	8.933	75.874	30.350	106.224	**212.448**
	5	9	8.933	32.965	13.186	46.152	**92.303**
	6	10	8.933	34.905	13.962	48.866	**97.733**
	7	11	8.933	88.335	35.334	123.669	**247.338**
	8	12	8.933	47.626	19.050	66.677	**133.353**
	9	13	8.933	37.133	14.853	51.987	**103.974**
	10	14	8.933	101.313	40.525	141.838	**283.675**
	11	15	8.933	67.544	27.018	94.561	**189.123**

Table 21c: Scenario B. Traffic per Link

Table 22a		IPTV Traffic per Link. Scenario C													
		Fluxes:													
Origin	Destination	1→0	1→2	1→3	1→4	1→5	1→6	1→7	14→8	14→9	14→10	14→11	14→12	14→13	14→15
0	1	69.545			75.095										
1	2		78.870	70.655											
2	3			70.655											
4	5														
5	6						86.630	86.630							
6	7							86.630							
8	9								79.390						
9	10								79.390						
10	11														
12	13												79.475		
13	14									70.500			79.475	41.440	
14	15											86.630			74.870
0	4				75.095										
1	5					64.550	86.630	86.630							
2	6														
3	7														
4	8														
5	9														
6	10														
7	11														
8	12														
9	13									70.500					
10	14								79.390		86.630				
11	15											86.630			

Links

Table 22b			External Traffic per Link. . Scenario C													
			Fluxes:													
Links	Origin	Destination	0→8	1→8	2→7	3→7	4→8	5→8	6→7	9→8	10→7	11→7	12→8	13→8	14→7	15→7
	0	**1**														
	1	**2**														
	2	**3**														
	4	**5**						51.640								
	5	**6**														
	6	**7**			63.096				69.304						64.928	
	8	**9**		60.080						56.400						
	9	**10**														
	10	**11**									69.304					
	12	**13**												33.152		
	13	**14**														
	14	**15**														
	0	**4**	55.636													
	1	**5**		60.080												
	2	**6**			63.096											
	3	**7**				56.524										
	4	**8**	55.636				60.076	51.640								
	5	**9**		60.080												
	6	**10**													64.928	
	7	**11**									69.304	69.304				59.896
	8	**12**											63.580	33.152		
	9	**13**														
	10	**14**													64.928	
	11	**15**														59.896

Links	Origin	Destination	Reg. avg. Traffic x 3	Semi Total	+40%	Total	Total with BW reservation
	0	**1**	22.334	166.974	66.789	233.763	**467.526**
	1	**2**	22.334	171.859	68.743	240.602	**481.204**
	2	**3**	22.334	92.989	37.195	130.184	**260.368**
	4	**5**	22.334	73.974	29.589	103.563	**207.126**
	5	**6**	22.334	195.594	78.237	273.831	**547.662**
	6	**7**	22.334	306.292	122.517	428.808	**857.616**
	8	**9**	22.334	218.204	87.281	305.485	**610.970**
	9	**10**	22.334	101.724	40.689	142.413	**284.826**
	10	**11**	22.334	91.638	36.655	128.293	**256.585**
	12	**13**	22.334	134.961	53.984	188.945	**377.890**
	13	**14**	22.334	213.749	85.499	299.248	**598.496**
	14	**15**	22.334	183.834	73.533	257.367	**514.734**
	0	**4**	22.334	153.065	61.226	214.290	**428.581**
	1	**5**	22.334	320.224	128.089	448.313	**896.626**
	2	**6**	22.334	85.430	34.172	119.601	**239.203**
	3	**7**	22.334	78.858	31.543	110.401	**220.801**
	4	**8**	22.334	189.686	75.874	265.560	**531.120**
	5	**9**	22.334	82.414	32.965	115.379	**230.758**
	6	**10**	22.334	87.262	34.905	122.166	**244.332**
	7	**11**	22.334	220.838	88.335	309.173	**618.345**
	8	**12**	22.334	119.066	47.626	166.692	**333.384**
	9	**13**	22.334	92.834	37.133	129.967	**259.934**
	10	**14**	22.334	253.282	101.313	354.594	**709.188**
	11	**15**	22.334	168.860	67.544	236.403	**472.807**

Table 22c: Scenario C. Traffic per Link