Report discussing future scenarios for the funding of network infrastructure in the European research networking community, and of related costs

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SERENATE

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CONTENTS

Executive Summary

The purpose of this deliverable is to present some consolidated views on specific developments that have been investigated in several SERENATE studies. This report is based on the results of six earlier SERENATE work items, and gives their synthesis. It compares the traditional approach where the transport infrastructure used by research and education networks is provided by telecommunications operators, with various possible alternative approaches. The corresponding costs and the cost evolution receive particular attention.

This evolution of the transport infrastructure for research and education networks depends on a wide range of organisational, regulatory, technical and economic parameters. The organisation sets the framework for how the network is managed and affects the overall design. The regulation defines, for example, the rules related to various options for ownership. The technology defines the technical options and specifies characteristics, availability and prices of equipment. Finally, the market for connectivity shapes the availability and the prices for various types of connections.

The European research networks are currently organised in a hierarchy of three levels (four if intercontinental networks are included): the pan-European, the national and the local level. The multi-level structure reflects the underlying organisational structure where each research institution operates its own internal network, which is connected to other research institutions via the national research network, which operated by the National Research and Education Network organisation (the NREN) in the country. In turn, the national networks are interconnected via the pan-European GÉANT network operated by DANTE.

An alternative to the current organisation could, for example, be the establishment of regional networks covering a number of countries as it is done in the Nordic region, or the replacement of the pan-European GÉANT network by bilateral connections between bordering national networks. The latter option would in theory reduce costs as international connections could be established between neighbouring nodes close to the border. However, this model would cause considerable problems in relation to organisation and management. In addition, the real savings might be minimal as fibre links between the capitals often are cheaper than the much shorter links connecting smaller cities on each side of the border.

Regulation is important for the evolution of research and education networks for two reasons:

- Regulation is shaping the market for telecommunications services and thereby the conditions under which research and education networks can lease lines, dark fibres etc.
- Regulation affects the conditions for how research and education networks can construct and operate their own telecommunications infrastructure.

The new EU framework for telecommunications regulation aims to create a competitive market for telecommunications services and it was foreseen to be implemented by mid-2003. The implementation is, however, delayed in several countries. The development of real competition in the telecommunications markets may still be hampered. With respect to this, there is no sharp border between the EU members and the accession countries; rather there is a sliding scale, basically following the ranking from low-income to high-income countries.

Today, European countries can be categorised in four groups of markets:

- liberal markets with transparent pricing
- liberal markets with less transparent pricing structure
- emerging markets without transparent pricing
- traditional monopolist markets.

Today, the prices of a high-capacity connection show huge differences between the four groups of markets. Setting the minimum price to one, the prices vary from 1-1.4 in transparent liberal markets, 1.8-3.3 in less transparent liberal markets, 7.5-7.7 in emerging markets and 18-39 in monopolistic markets.

Three scenarios have been constructed to show how the markets in the four groups could develop:

- an optimistic scenario with annual price reductions of 10% in the liberal markets and convergence towards this level in the other country groups resulting in a uniform market price
- a neutral scenario with annual price reductions of 10% within each country group

- a pessimistic scenario with slight price increases in liberal markets, while emerging and de-facto monopolistic markets remain stable.

The first scenario is considered unlikely without significant new policy initiatives. The probability of the two other scenarios depends among others on how the demand will develop. Up to now the telecommunications markets have seen dramatic decreases in prices for high-capacity lines. It is possible that certain markets will see prices increase. On the other hand, technology improvements and increasing demand will lead to cost reductions in the long run.

The new EU regulatory framework allows in principle NRENs to establish their own networks, but in reality there may still be problems in implementing such solutions. Although such issues in some countries may complicate the construction of NRENs' own network facilities, "do it yourself" will become an option even in the present monopolistic markets.

In this context and comparing the various cost categories, the following four alternatives are studied:

- **Full ownership**, which implies investments in fibres (construction costs) and expenses for operation and maintenance. In addition, full ownership of fibres will also involve full ownership of transmission equipment.

- **Dark fibre**, which implies expenses for leasing or buying a dark fibre. Operation and maintenance will to a certain degree be included in these costs. A dark fibre may include amplification and regeneration underway, but the research network can also choose to be responsible for these operations itself. In this case, expenses for transmission equipment must be added. In any case, transmission equipment at both ends must be added.

- **Direct access**, which implies expenses for leasing or buying a wavelength connection. Transmission equipment at both ends must be added.

- **Leasing of capacity**, which implies expenses for leasing of capacity only, while all other transmission costs are included.

In all of these options, the research and education network organisations will need to invest in their own switching and routing equipment, as they do today.

In the SERENATE studies, a cost model has been developed for the first three alternatives mentioned above. The model is based on cost calculations for the three major building blocks of a network, namely the transmission link, the transmission equipment, and the routing and switching equipment.

In the current report, the cost model has been applied to analyse eight different examples of network links, ranging from a 3,000 km link with a capacity of 4 x 40 Gb/s or 16 x 10 Gb/s, to a 5 km connection with a capacity of 4 x 10 GE.

The general conclusion from these calculations is that the cheapest option is to use a 40 Gb/s wavelength connection for long distances (i.e., over 1,000 km) and to lease a dark fibre with amplification for shorter distances. However, 40 Gb/s equipment and links are still under development and these solutions may not be commercially available within the next couple of years. If a 40 Gb/s wavelength is not available, then a dark fibre with amplification and regeneration should be preferred for long distances. However, this result from the cost model is based on average prices in the European Union for dark fibres and best-practice prices for wavelength connections. In emerging or monopolistic markets, the situation may be very different. Even in liberal markets there may be routes where the terms for acquiring a dark fibre are less attractive.

Construction of one's own fibre is the most expensive solution in all of the examples. It costs about 20 times as much to construct one's own link as it does to lease a dark fibre without amplification. This result is closely related to the assumption that there is no cost sharing with other users. Furthermore, the costs of fibre construction may be drastically reduced if fibres can be laid in co-operation with other users, or if joint use of existing infrastructures provided by railway companies, electricity companies or others is introduced. On routes where dark fibres and wavelengths either are ten times as expensive as best-practice prices or simply not available, a "do it yourself" solution is worth considering. It should be noted that such routes may not be confined to monopolistic markets, but may also be found outside the capital in countries with more developed telecommunications markets.

The option of using one's own fibre is particularly expensive for long distances, and "do it yourself" options are most attractive for short routes and for routes where a high capacity is needed.

When a dark fibre solution with amplification and regeneration is considered, the costs of transmission equipment are higher than the costs of the link. Almost half of the transmission costs are related to amplification equipment, indicating that it pays to leave this task to the carriers even if this implies a substantial increase in the costs of a dark fibre. Only for short distances up to 500 km, where only few amplifiers are needed, it is worth considering taking the responsibility of amplification; however, this depends on the price levels for dark fibres. In areas where the prices of dark fibres are considerably above average, it may pay to let the research and education network be responsible for amplification for longer distances as well.

If a research and education network is responsible for amplification, it must also take the responsibility for regeneration. Regeneration is required for each wavelength implemented, whereas amplification can be used for multiple wavelengths. Regeneration is, however, only needed for distances of more than 600-800 km (some equipment enables transmission without regeneration even at distances above 3,000 km). Regeneration is much more complicated to do, and it may be difficult for an NREN to take this responsibility. However, the task may be outsourced through a service agreement.

The transmission costs are much lower if Gigabit Ethernet is used on a dark fibre. This option is very attractive for shorter distances. This option only requires a "Nothing-In-Line" connection without amplification or regeneration on the route.

Routing costs can in some cases be reduced by use of switches instead of routers in parts of the network. The right mix between routers and switches depends on the size of the network and the ratio between internal and external traffic. If 50% of the traffic is external, it is still cheaper to use routers only than having a combined router/switch solution. However, in small national networks with a substantial share of internal traffic, a more viable solution could be to only deploy routers at some nodes, and switches in all nodes.

The cost model can of course be used to calculate various other examples than the eight that are discussed in the current report. Moreover, in specific countries or regions, the values of the various parameters may be considerably different from the ones in this report, and those values may change over time as well. Therefore, the cost model has been made publicly available on the SERENATE website as a tool for research and education network organisations to make their own calculations of ownership and technology options that may be relevant in their own specific situation.

1. Introduction

SERENATE is the name of a series of strategic studies into the future of research and education networking in Europe. The SERENATE (Study into European Research and Education Networking As Targeted by *e*Europe) project aims to contribute to European policies, social objectives and economic development by providing inputs on initiatives that could help to keep European research networking at the forefront of worldwide development. The objective is to provide important inputs to the development of policies by the European Commission, but also to national governments and funding bodies, the management of universities and research institutions, and the National Research and Education Networks (NRENs).

The current situation is that European NRENs and the wider European research networking community are at the forefront of developments. While much of the history of European research networking over the past two decades was characterised by the need to keep up with developments in North America, Europe currently has a leading position in many aspects of research networking. Gigabit networks are being implemented by a number of NRENs, and in other countries plans for such networks are being elaborated. At the European level, GÉANT, the network interconnecting the national research networks of the various European countries, has been a significant step forward, introducing 10 Gb/s in the core of the network and offering a wide coverage of 2.5 Gb/s capacity. More ambitious longer-term numerical targets may now be appropriate. Similar developments are to be expected at the national and local levels of research networking.

SERENATE contributes to achieving these networking goals by investigating the strategic aspects of the development of such "superfast" networks, looking into the technical, organisational and financial aspects, the market conditions and the regulatory environment. As a result, by the end of the project, the relevant policy makers, funders and managers of research networks in Europe will have at their disposal a set of recommendations and background materials that will enable them to set their policies for the further development of European research networking.

SERENATE is funded by the European Commission as an Accompanying Measure in the Information Society Technologies programme of the Fifth Framework Programme for Research and Technological Development. The project consists of fourteen interrelated work items. In a number of these work items, information has been collected that is relevant for developing a view on the future evolution of the network infrastructure for European research and education.

The evolution of the transport infrastructure for research and education networks depends on a wide range of regulatory, organisational, technical and economic parameters. The regulation defines the rules related to various options for ownership and specifies possible special obligations. The organisation sets the framework for how the networks are managed and affects the overall design. The technology defines the technical options and specifies characteristics, availability and prices of equipment. Finally, the market conditions in the connectivity market shape the availability of, and the prices asked for, various types of connections.

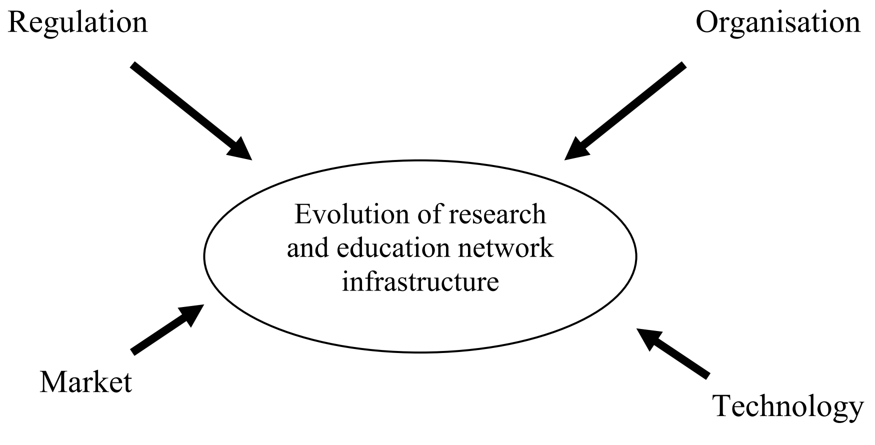

Figure 1. Parameters affecting the evolution in transport infrastructure for research and education networks

Important aspects have been discussed in earlier SERENATE deliverables:

- Deliverable D6 "Report on present status of international connectivity in Europe and to other continents" provides an overview of the current market for international connectivity in Europe.
- Deliverable D7 "Report on the expected development of the regulatory situation in European countries relevant for the SERENATE project" describes the regulatory framework under which the research and education networks in Europe will operate in the future.
- Deliverable D4 "Report on workshop on operators' views on infrastructure and likely evolution" presents the views of traditional and alternative providers of telecommunications and network services on the status of the pan-European telecommunications and network infrastructures and their likely evolution.
- Deliverable D13 "Report on the expected evolution of international connectivity in Europe and to other continents over the next five years" provides an integration of the work that was reported in the three deliverables mentioned above, and presents forecasts of the market development and the price dynamics of the transport and infrastructure market.
- Deliverable D3 "Report on the experience of various communities that have experimented with "alternative" models if infrastructures" presents a number of case studies of "customer-controlled" networks in various places around the world.
- Deliverable D8 "Report on workshop on National Research and Education Network models" reports on a workshop in February 2003, where European NREN managers discussed the progress of the SERENATE studies and in particular SERENATE's findings about the opportunities for research network organisations to obtain some form of "ownership" of the infrastructures that they use.

In the final phase of the SERENATE project, the SERENATE Steering Committee has developed consolidated views on the various developments that have been investigated in the SERENATE studies. These views are described in three reports. The present deliverable is the first of these reports. It is based on the work items whose results have been described in the six reports mentioned above, and gives their synthesis. It compares the traditional approach where the transport infrastructure used by the NRENs is provided by (traditional or alternative) telecommunications operators, with various possible alternative approaches. The corresponding costs and the cost evolution receive particular attention.

It should be noted that the present report is only an intermediate step in the SERENATE studies. A subsequent report presenting consolidated views will address overall strategic scenarios for the future evolution of pan-European research and education networking[1].

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[1] SERENATE deliverable D18 "Report outlining scenarios for the evolution of the pan-European infrastructure for European research and education networking"

2. Organisational Models, Alternative Models and Ownership Options

2.1. The Multi-Level Structure

The research networks in Europe are organised in a hierarchy of three levels (or even four, if the intercontinental level is also included): trans-European, national and local networks. These three levels reflect the underlying organisational structure. Each research establishment or institution for higher education operates its own internal network, which is connected to other institutions via the national research network, which is operated by the National Research and Education Network organisation in the country. (In some cases there is an intermediate level of regional or metropolitan networks, which usually are not under the control of the NREN.) In turn, the national research networks are interconnected via the European research and education backbone network infrastructure GÉANT, which is managed by DANTE.

The three types of networks have significantly different transmission requirements and network architectures. GÉANT is composed of international links with very high capacities, and the types of services offered are predefined. The essential service to be provided by GÉANT is transport, so the primary concern is capacity. The topology is rather stable, as there is only one point of connection in each country in Europe. However, if and when the amount of traffic grows significantly, the capacity of the backbone network must be expanded easily in order to cope with the increased traffic load. Today, the largest national GÉANT backbone access capacities are based on 10 Gb/s connections. However, it is believed that this capacity level will increase significantly over the next five years, and some connections might reach capacities of 50-100 Gb/s or more.

At the national level and one step "below" GÉANT, there are the national research and education networks. In contrast to GÉANT they have to cope with a variety of services and applications. They provide an infrastructure for direct communication between research institutions and in most cases also deliver to the institutions connectivity to the commercial Internet.

Communication services and applications come in different sizes and with different characteristics, which puts continuously changing demands on the networks. In addition, the topologies of the national and local networks are constantly changing as new entities are connected and already connected entities or access networks demand more bandwidth. Still, most of these networks have a relatively stable topology, but they are continuously expanding their capacity. It is believed that with a five-year timeframe these networks will operate with capacities well above 10 Gb/s.

The access networks connecting the end-user are very diverse with respect to network topologies, protocols etc. Access networks include extensive networks connecting end-users from many different locations within the same research institution, but also networks providing access to a limited number of users concentrated at one location.

Moreover, the networks provide a broad variety of data rates to a substantial number of users. The bursty, asymmetric and more or less unpredictable nature of traffic on these networks presents many challenges, especially if the predicted growth of real-time applications and the ever-growing number of users are taken into account.

In spite of these differences there are also similarities. The three types of networks must all meet the following challenges[2]:

- Flexibility, enabling significant interchanges to offload traffic in various ways.
- Optics must be adapted to distance – in long-haul networks, systems must allow the optical signal to span huge distances without requiring regeneration, whereas cheaper optics may be preferred for shorter distances.
- Links with heavy traffic must be able to carry maximum traffic.

These matters can be handled in different ways. The demand for capacity fluctuates and varies from location to location, and user needs may develop across the three levels presented above. One particular application

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[2] Introduction to optical transmission in a communication network – http://www.iec.org/

may sometimes generate a very substantial part of the total traffic load and may require special facilities in some routes in all of the three network levels.

An uneven distribution of capacity needs implies that a non-discriminatory approach where the same capacity is provided to all locations might be inefficient. Examples[3] of advanced research networks worldwide show that there is a trend to move away from the former monolithic approach.

2.2. Alternative Models

The economic analysis in this report is based on the three-level research network model as presented above. However, this current model might be partly changed in the future, in order to improve and simplify the operations and management of the various networks.

Some alternative solutions are described below, together with the benefits and the disadvantages that they would bring. However, these models should not be seen as replacements of the current model, but more as sources of inspiration for future network design. Some of the suggestions are definitely not suitable for a full-scale implementation, but might be used in some regions or parts of a new network structure.

One of the options would be to create a number of regional networks, each encompassing a (small) number of countries, which when interconnected would serve as a simpler trans-European network, with less connection points than the current one, because some of the national connection points would be moved to the regional networks. This solution would also make a new trans-European research network backbone network smaller and thereby less complex, by transferring some of its workload, operational management and connection points to the new regional networks.

One example of a regional network already exists in the Nordic countries, where NORDUnet has been in place for many years. NORDUnet is the Nordic Internet highway to research and education networks in Denmark, Finland, Iceland, Norway and Sweden. It provides connection between the Nordic backbones and the global set of research networks, by connecting to other research networks (to GÉANT, to Abilene and to other networks via the STAR TAP / StarLight[4]) and it provides connectivity to the general Internet through connections supplied by Sprint and Level 3 Communications. NORDUnet is connected to GÉANT through a single node located in Stockholm. However, NORDUnet is also connected to the outside world via other connections from Stockholm, Copenhagen and Helsinki.

Another alternative approach could be to replace the trans-European backbone network by direct interconnections between national research and education networks in neighbouring countries. Such an interconnection model could either follow the present GÉANT topology with one international node in each country, or it could have a more decentralised approach with the creation of direct links between research institutions on both sides of a border. This approach would eliminate the trans-European level, by interconnecting the various national networks directly and thereby creating a virtual pan-European network. Potentially this approach could lead to cost savings, because the international traffic would in part be channelled through national links and the need for long international links would be limited.

However, such an approach will also create significant management problems with respect to operations and maintenance of the border-crossing links, besides creating potentially complicated routing arrangements. Different national research and education networks may use different types of equipment and network design; they may also have different approaches towards operations and maintenance, and have different strategies for network expansion. These problems will extend beyond the border-crossing links, since no single organisation will have the entire responsibility for international communications. If, for example, communication fails between London and Milan then several national research and education networking organisations must be involved in identifying and correcting the problem.

Border hopping, i.e. combining the border-crossing concept as described above with some form of ownership of the international fibre/wavelength/capacity, will be most attractive for countries where market prices for international connectivity are very high, and in situations where the distance between nodes connected to two

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[3] see SERENATE deliverable D3 "Report on the experience of various user communities that have experimented with "alternative" models of acquisition"

[4] http://www.startap.net/

different national research networks is relatively short. In the latter situation, border hopping would be particularly attractive for stretches (e.g. Berlin-Poznań) where it is possible to establish a direct NIL[5] connection, which could be operated by the NRENs without involvement of a public network operator.

If one would want to use the opportunities offered by border hopping, then it is important to give careful consideration to the location of the trans-European research networking infrastructure's Point(s) of Presence in each country: a location close to the borders of neighbouring countries would make it possible to construct a NIL connection between two or more countries.

Border hopping will not necessarily replace the three-level structure of European research networks completely. However, border hopping might be a suitable solution to establish direct interconnection between research institutions in neighbouring countries with special communication needs, as a complement to the trans-European network. Examples could be between Poland, Germany and the Czech Republic, or between Austria, Slovakia, Hungary and Slovenia.

2.3. Ownership Options

The liberalisation of the European telecommunications market allows organisations that provide network services to users in the research and education communities – for example, NRENs or DANTE – to invest in their own telecommunications facilities. These organisations may therefore consider various models for ownership of the telecommunications facilities that they are using. Forms of ownership may be preferred either for purely economic reasons – for example, if prices charged for leased lines exceed the costs of ownership with a considerable margin – or because direct ownership enables more control over the network.

There are several different forms of ownership, which can be categorised in relation to the three major building blocks of a research network:

- the physical infrastructure providing the links between the connection points; that infrastructure can be based on copper cables, optical fibres or radio links
- transmission equipment transmitting signals via the physical infrastructure
- routing and switching equipment.

Routing and switching equipment is usually owned and operated by the research and education network organisations, while a number of different solutions are used as regards the ownership of the physical infrastructure and the transmission equipment. The following options are believed to be the most interesting for the deployment of the next generation of research and education networks in Europe:

- full ownership (possibly including fibre building): obtaining full ownership of fibre (possibly by laying it oneself) and lighting fibres by deploying one's own transmission and end equipment

- dark fibres: buying dark fibres from telecommunications operators or carriers on a time-limited contract and lighting them by deployment of one's own transmission and end equipment

- managed fibres: buying dark fibres from operators or carriers, but giving operators or carriers the responsibility for amplification and possibly regeneration of signals

- direct access to fibres: buying wavelength connections from operators or carriers; the operators or carriers then provide and maintain the transmission link and transmission equipment, based on optical interfaces

- buying of capacity: buying specific levels of capacities from operators or carriers between two or more points.

Until now, the majority of NRENs in Europe have chosen to lease capacity or to buy data transmission services from telecommunications operators. However, in recent years there has been a clear trend among research and education network organisations to assume more responsibility for, and control over, the network infrastructure, when the market allows it. Today, GÉANT uses wavelength connections on its major routes.

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[5] Nothing-In-Line – see section 5.2.7 of the current report for an explanation of this technical concept.

SWITCH, the NREN in Switzerland, has acquired a pair of optical fibres between Geneva and Zürich and plans to invest further in their own physical infrastructure between Zürich, Basel, Bern, Lausanne and Geneva. This will be done either by direct ownership or through the purchase of a 20-year Indefeasible Right of Use (IRU). The fibres currently in use are part of a cable with more than 100 fibres, which are acquired from the Swiss railways.

The Polish NREN also deploys its own physical infrastructure, as the Polish research community has its own fibre infrastructure within its Metropolitan Area Networks. In 2001, the NREN started the PIONIER project to be independent of external suppliers for long-distance connections as well. The PIONIER project is aimed at building fibre-optic cables and using DWDM infrastructure (10 Gb/s and 40 Gb/s lambdas) connecting all MANs in Poland. The research community has already built more than 2,500 km fibres out of the 5,000 km planned.

In Stockholm, research institutions buy dark fibres for use in local access networks from Stokab, a commercial operator established by the municipality of Stockholm. Dark fibres are also used by the Czech national research network CESNET and the Canadian CA*net 4. The Californian research and education network CalREN offers dark fibres for specific projects.

However, the trend towards more direct control over network facilities by NRENs is not visible everywhere. For example, the Japanese SuperSINET, which was established in January 2002 and offers 10 Gb/s connections, is based on capacity bought from the network operator.

3. Regulatory Aspects

There are two reasons why telecommunications regulation is important for research and education networks:

1. Regulation affects the market for the provision of telecommunications services and thereby the conditions under which the research and education networks can lease lines, dark fibres etc.

2. Regulation affects the conditions for how research and education networks can construct and operate their own networks.

Both the current European Union member states and the accession countries aim to implement the EU framework for telecommunications regulation. All the member states were requested to implement the new communications regulatory package by July 2003. However, it appears that the implementation will be significantly delayed in several countries.

3.1. Market Issues

In regulation and market conditions there is no sharp border between the EU member states and the accession countries; rather there is a sliding scale, basically following the ranking from low-income to high-income countries.

The most important problems for competition that have been encountered in some countries under the existing regulation are:

- apparently unreasonable refusal of licenses, or licenses being granted for a short period, with high fees or on very difficult conditions

- lack of co-operation or even outright opposition from an obstructive incumbent operator, delaying interconnection or provision of other facilities.[6]

These problems can be related to, among others, the governments having a financial interest in the incumbent operator, inadequate separation between the branches of government responsible for regulation and the branches responsible for the financial interests in the telecommunications sector, a long history of bureaucratic traditions, and vulnerability to improper interference from politicians and public officials. Such issues cannot be resolved from one day to the next, and they may even not be resolved entirely by the full implementation of the new telecommunications regulatory package, which has the introduction of real competition as its major objective.

Furthermore, it must be noted that regulation can only facilitate competition. Basically, for real competition to be created new suppliers must enter the market, and that is only attractive for them in areas with a sufficient level of demand. In low-income areas or areas with a low density of population, only limited competition can be expected on the type of services that are demanded by the research and education networks. This implies that excessive levels of charging can be maintained more easily. In turn, this will make it more attractive to (national) research and education networking organisations to establish their own network facilities.

3.2. Regulatory Issues Affecting Ownership Options

A monopoly in the provision of fixed-line telecommunications infrastructure, as existed in a number of accession states until January 2003 and as still exists in Turkey and a large number of countries that are not candidates for EU membership, typically prevents NRENs from deploying their own networks and forces them to lease capacity or rely on data transmission services from the monopoly provider.

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[6] see SERENATE deliverable D7 "Report on the expected development of the regulatory situation in European countries relevant for the SERENATE project"

In a liberalised market, research and education networking organisations have the possibility to choose between leasing capacity from operators and building their own physical infrastructure. If networking organisations deploy their own infrastructure, there are additional questions of access to scarce resources, in particular rights of way (RoW) and radio frequencies. In this situation, research and education networking organisations must have RoW in order to lay cables. When using radio links or radio access facilities, they need rights to mount their radio transmission equipment on masts and they need access to radio frequencies.

In a liberal regime, without special rights of any operators to build and operate communications infrastructures, there should be no overall impediments of a communications regulatory character for national research and education networks to establish self-owned infrastructures. Furthermore, no matter which kind of infrastructure research and education networks choose to implement, there will be technology-neutrality under the new EU regulation, meaning that different kinds of infrastructures will be regulated in the same, neutral manner.

Under the old EU regulation, obligations to obtain licenses and the conditions under which such licenses were granted could constitute limitations on the establishment and operation of networks in various countries. However, with the "light-handed" type of authorisation in the new EU regulatory package, research and education networks and other entities operating communications networks are not required to obtain permission but only to notify national regulatory authorities. This definitely makes it easier for NRENs to choose the network solutions that are best fitted to their needs.

However, RoW may be a real hurdle and this is an important issue for NRENs to be aware of. In addition to the RoW question, there may be other hindrances for research networks that wish to deploy their own infrastructure. As publicly owned or at least publicly supported entities, NRENs may be subject to certain political priorities and decisions, or there may be provisions in the statutes of these organisations that make it difficult for them to own proprietary infrastructure. However, these kinds of limitations on NRENs are specific to a national situation, and they are not determined by telecommunications regulation.

In addition to allowing research and education networks to build their own infrastructures, the telecommunications regulation also affects the viability of different options for ownership through its impact on the structure of the telecommunications market. Unbundling of the local loop may be an important example. The European Union framework does not require general unbundling of the local loop, but only for copper-based networks. Therefore telecommunications operators do not need to offer dark-fibre facilities to their customers. National regulators are allowed to extend the requirement for unbundling to optical network facilities. This has been done in Denmark, for example, and public network operators in that country are therefore requested to provide dark-fibre facilities to other operators, for instance research networks. However, this is not generally the case in Europe, resulting in an additional obstacle for research and education networks in a number of countries.

Besides the telecommunications regulation, the decision on ownership is also affected by a number of other rules and regulations, for example taxation. One example is that some network facilities such as lit fibres may be subject to additional community taxes, as is the case in the United Kingdom. This type of expenses must be taken into consideration when deciding about building one's own physical infrastructure.

4. Trends in the European Market for Communication Facilities

The cost implications of different technological and organisational options depend on how the markets for communication equipment and telecommunications services develop. While prices for equipment are largely global and depend only indirectly on the regulatory situation, prices for telecommunications services differ substantially from country to country.

4.1. Trends in the Equipment Market

Prices of telecommunications equipment have been decreasing for decades and this decrease can be expected to continue for some time, Much of the price decrease can be seen as expansion of capacity for state-of-the-art equipment rather than as a reduction of the total equipment costs for a state-of-the-art network. For example, 2.5 Gb/s transmission equipment is being replaced by 10 Gb/s transmission equipment, which can be expected to be replaced in due course by transmission equipment with a capacity of 40 Gb/s. Usually, the prices for a new generation of high-capacity equipment will after some time decline to a level comparable to the price levels of the old equipment. Prices of the most advanced equipment are reduced faster than prices for equipment that has been marketed for some time. For instance, prices for 40 Gb/s transmission equipment are expected to be reduced by about 20% per year, while prices for equipment with a capacity of 10 Gb/s are expected to fall by 10% per year.

This affects the decisions to be taken by research and educations network organisations in multiple ways:

1. "Do It Yourself" options may be favoured if research and education networks can rely on new (and cheaper) equipment than the telecommunications operators.

2. Decreasing prices reduce the economic lifetime of equipment.

3. The economic lifetime is shortest for the most advanced equipment.

4.2. Trends in the Market for Telecommunications Infrastructure Services

The trend in the pricing of telecommunications services has been a decreasing one over the period 1998-2002, with large reductions in the prices on the most competitive international connections. The average prices for dark fibres in Western Europe have been reduced by around 80% from 1998 to 2002[7]. The reasons for the dramatic reductions are:

- Deregulation and a subsequent competition in key markets
- New network technology enabling huge capacity per fibre strand
- Unprecedented availability of very low cost capital
- Significant over-supply.

While network technology will continue to develop, deregulation in itself will not lead to further price reductions in markets where competition has been established already. However, deregulation can be expected to have a significant impact in countries where real competition still has to be seen, mainly in Eastern Europe.

According to the Band-X report, the worldwide bandwidth pricing index has dropped55.5% in 2001-2002 with the European index dropping 64.8% over the same period. But it is expected that the market will stabilise, because bankruptcies have reduced the number of providers, leaving the survivors with less competition.

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[7] Band-X: Dark Fibre Pricing Analysis Europe 1998-2002

In addition, more companies see the benefits of service provision over network acquisition. Transactions for dark fibre are still being made but largely to meet specific demands and, therefore, smaller in scale geographically and very location-specific[8]. In parallel, however, the divergence of connectivity prices has increased greatly in this period.

Also charges for leased lines have fallen, although these price reductions are less dramatic than for dark fibres. The average prices in the European Union for high-capacity leased lines have been reduced by 25-45% in 1998-2002, mostly so for long distances. The average price in the European Union for a national 140/155 Mb/s line of 200 km is now 400,000 euro per year, while international connections are more expensive[9]. These international prices are very significantly higher than prices for the equivalent capacity within the GÉANT network. Price differences between the cheapest and the most expensive locations are very significant. One of the SERENATE deliverables[10] reports differences in prices up to a factor 39 if the accession countries are included.

Table 1. Prices for national connections: 140/155 Mb/s, 200 km (euro per month)[11]

Country	1998	2002
Austria	48,691	33,000
Belgium	126,095	24,529
Denmark	38,794	34,794
Germany	59,244	10,085
France	56,939	46,650
Italy	98,788	66,324
Luxembourg	-	8,671
Sweden	15,151	15,151
UK	117,968	100,363

The key parameter here seems to be the level of competition. In markets with limited competition, the responses from each operator are crucial for pricing and availability of services. Of the European countries currently connected to GÉANT, around half can be considered to have competitive internationalised markets for telecommunications. In the remaining countries, prices remain high and, in some countries, the availability of advanced building blocks is very restricted.

The strong correlation between the number of suppliers and the price levels is analysed in SERENATE deliverable D6. From analysis of the GÉANT tender data, it is apparent that at least four international suppliers are necessary to create a reasonably competitive market. Operators expect that competition in Eastern Europe will increase during the next five years. But in spite of the extension of the EU regulatory framework to the accession countries, most operators do not envisage a further build-out of their fibre-optic networks in the short to medium term. The number of suppliers will therefore remain limited at least in some of the countries connected to the GÉANT network.

One problem is that GÉANT demands services for which there is a very limited market both in terms of suppliers and in terms of the number of customers. While research networks may want 80 Gb/s as the building blocks for the future infrastructure, operators see no serious demand for 40 Gb/s connectivity, and none of them have it as part of their portfolio.

One solution to this problem is to lease dark fibres directly from operators, but this may not be an option everywhere. Unbundling of fibre facilities is not part of the EU regulation and is only required in a few countries. International telecommunications operators are divided on the issue of dark fibres. Some refuse to sell or lease dark-fibre facilities, as this will harm their core business, while others offer dark fibres as part of

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[8] Total Telecom, 25 June 2002.

[9] Commission staff working paper: Technical Annexes of the Eight Report on the Implementation of the Telecommunications Regulatory Package. SEC(2002) 1329, Brussels, 3 December 2002

[10] SERENATE deliverable D6 "Report on the present status of international connectivity in Europe and to other continents"

[11] Source: Teligen: Report on Telecom Price Developments from 1998 to 2002. Produced for: European Commission Directorate General for Information Society.

their product portfolio[12]. Most operators offer wavelength solutions and recommend this to their customers, as this gives the benefits of a dark fibre without the associated capital investment.

4.3. Market Scenarios for Telecommunications Infrastructure Services

It is not possible to predict with any accuracy the way that the market for international telecommunications in Europe will develop in the next five years. In earlier SERENATE reports, the European countries have been categorised in four groups of markets:

- liberal markets with transparent pricing: Belgium, France, Germany, Italy, the Netherlands, Switzerland, the United Kingdom and the Nordic region
- liberal markets with less transparent pricing structure: Austria, the Czech Republic, Hungary, Ireland, Luxembourg, Slovakia and Spain
- emerging markets without transparent pricing: Croatia, Poland and Slovenia
- traditional monopolist markets: Bulgaria, Cyprus, Estonia, Greece, Latvia, Lithuania, Malta, Portugal and Romania.

Three scenarios have been constructed to show how the markets in the four groups could develop:

1. an optimistic scenario with annual price reductions of 10% in the liberal markets and convergence towards the same level in the other groups of countries, resulting in a uniform market price
2. a neutral scenario with annual price reductions of 10% within each group of countries
3. a pessimistic scenario with slight increases in prices on liberal markets, while emerging and de-facto monopolistic markets remain stable.

Market developments in the four groups corresponding to the three scenarios are discussed below.

Scenario 1: An optimistic scenario

In this scenario there is growing competition, particularly in the accession states and in the less liberalised parts of the European market. The very large difference of prices between inexpensive and expensive locations essentially disappears. Direct access to infrastructure or to very high speed data links becomes ubiquitously available internationally at prices that relate directly to the cost of provision of service. In the GÉANT environment this will make the issue of cost sharing between national research and education networks significantly easier.

This scenario is unlikely without significant political initiatives to foster and develop a competitive and transparent market in telecommunications.

There are a number of factors to be taken into account. Firstly, some of the companies that invested heavily in trans-European networks following liberalisation – for example, KPN Qwest, Global Crossing and Teleglobe – have left the market, failed or sought protection under the Chapter-11 status. The market entry of these new players was the catalyst for very significant investment and large reductions in price. The remaining players who offer trans-European connectivity are either not yet profitable "in the strict sense of the word", e.g. COLT, Level 3 Communications and Telia International Carrier, or are "old incumbents" such as Deutsche Telekom, British Telecom and France Télécom, where the international networking business is integral to their domestic business. The domestic business is typically suffering from very large levels of debt related to the auctions for Third Generation mobile licenses. As a result, there is currently very limited free capital available for investment. In the absence of significantly rising demand, it will be impossible to make the case for large-scale investment in a difficult economic environment.

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[12] see SERENATE deliverable D4 "Report on workshop on operators' views on infrastructure and likely evolution"

For some of the countries with a less liberalised market it is possible that competition will increase. This will give rise to reductions in prices from their current high levels, although much will depend on the extent to which alternative network operators emerge. As prices are much higher than the underlying costs, there is scope for profitable business in this marketplace. It is likely that other infrastructure providers, e.g. electricity and gas companies, have also invested in fibre-optic capacity without exploiting the investment as telecommunications operators. A successful development of the telecommunications market will depend on owners of fibre-optic capacity recognising that there is a business case to be made exploiting such capacity, rather than on the incumbent providers.

Scenario 2: A neutral scenario

In this scenario there is more limited development of the market with little, if any, changes in the regulatory intervention to encourage a competitive international marketplace. As a consequence, the price differences between inexpensive and expensive countries will remain. In parts of Europe, the availability of direct access to infrastructure or to very high capacity connectivity services will be seriously limited. As market liberalisation gradually develops, it is likely that there will be some modest reduction in prices of connectivity, together with an increase in the availability of direct access to high-capacity wavelength connectivity. As a result, the commercial and technical distortions apparent in GÉANT today will continue for the foreseeable future. The overall picture is one of stability, in terms of the infrastructure providing pan-European connectivity.

Today, the liberalised market covers the major financial and economic centres in Europe. It is likely that demand between these locations will be maintained and further developed. Prices will decline at a moderate rate. However, one exception will be that prices and costs will become more closely aligned than is the case today. The cost of DWDM capacity is heavily distance-dependent, with break points for spans over 200 km and over 600 km. The underlying investment required to implement a span of 2,000 km is approximately three times the investment that is required for a span of 600 km. This is not reflected in pricing today. As the market rationalises, it is likely that shorter-distance routes will see bigger reductions in price than longer-distance routes, which are more competitive today relative to costs.

For the de-facto monopoly markets and emerging markets, some incremental investment will occur, which will improve the competitiveness of international routes to and from these countries. This could lead to quite significant reductions in prices, in the order of multiples of 10% per year. However, there is no driving force or political initiative likely to make this happen. There are some signs that owners of fibres outside the telecommunications sector are prepared to make them available to third-party operators. This will give rise to some investment for certain routes.

Scenario 3: A pessimistic scenario

In this scenario further market failures occur among the alternative operators. As a consequence, the market will revert to its former structure, where dominant national operators are the major providers of international services. They may well extend their networks with a limited footprint to meet the basic requirements for international connectivity, but the majority of connectivity is provided via interconnection agreements similar to the old "half-circuit" arrangements for the provision of international connectivity prior to deregulation.

In this scenario there will be very considerable divergence of price, with a reasonably competitive market between those countries where there is maximum investment today – namely France, Germany, the Netherlands, the United Kingdom and Belgium –, and much more limited competition in other regions. This scenario will lead to greater divergence of price to the extent where it will be difficult to organise effective cost sharing in the GÉANT environment and where access to infrastructure will vary significantly between countries. It is likely that for the research and education community this will lead to limited pan-European interconnection with relatively low capacity. It could lead to a complete fragmentation of the provision of research networking.

The alternative operators have invested significantly in building trans-European networks. However, as a consequence of the fact that the national bankruptcy legislation in Europe does not have an equivalent to the US Chapter 11, whenever one of these operators failed, its infrastructure was disposed of in a piecemeal way and the coherent network was destroyed. None of the current alternative operators are profitable yet, and it is likely that they will see the pan-European market demand as being significantly overstated. Even growth factors of 2 to 2.5 per year in Internet traffic are unable to fill the installed capacity internationally across

Europe within a period of five years. A further complication is that Internet traffic is not especially profitable. The major current source of revenue, i.e. switched voice services for mobile operators, is a very competitive market with large-scale purchasers and it does not generate significant profitability either. Further company failures will result in unconnected infrastructure across major parts of Europe. As a consequence of these failures, there will be no incentive whatsoever for investment in the markets emerging from the traditional monopolist environment. The absence of any emerging competition will entrench current prices. The reduction of competition in the more liberal parts of the market will lead to general price increases.

Implications

The three scenarios have very different implications for how service cost and prices will develop in different parts of Europe. This can be illustrated by the table below, where the forecasted price ranges according to each of the four different categories of countries are depicted.

Table 2. Forecasting of telecommunications service prices by group of countries in the three scenarios

	Initial cost range	Annual change in prices	Cost range after 5 years
Scenario 1			
Liberal markets I	1-1.4	-10%	0.6-0.8
Liberal markets II	1.8-3.3	-20%	0.6-1.1
Emerging markets	7.5-7.8	-40%	1.2-1.3
De-facto monopolistic markets	18-39	-50%	0.6-1.2
Scenario 2			
Liberal markets I	1-1.4	-10%	0.6-0.8
Liberal markets II	1.8-3.3	-10%	1.1-1.9
Emerging markets	7.5-7.8	-10%	4.4-4.6
De-facto monopolistic markets	18-39	-10%	10.6-23
Scenario 3			
Liberal markets I	1-1.4	10%	1.6-2.2
Liberal markets II	1.8-3.3	5%	2.3-4.2
Emerging markets	7.5-7.8	0%	7.5-7.8
De-facto monopolistic markets	18-39	0%	18-39

[The basic value "1" is the price for the cheapest connection available in any GÉANT country in 2003.]

5. Economic Analysis of Technology and Ownership Options

The choice of technology and ownership options for network development will depend on the costs related to the various options. Those costs depend on the prices for leasing capacity and the prices for the various types of equipment needed. As was indicated in the previous chapter, neither the market for leased lines nor the market for the type of equipment needed for the establishment of a Gigabit network is particularly transparent. The leased-line prices offered in one region may be quite different in other regions. In addition, prices change very rapidly, making it difficult to come up with firm conclusions as to which options are most attractive even within a short time span.

Therefore, the economic modelling in this report focuses on an analysis of basic technical and economic relations that drive the cost implications for each option. Such an analysis must build on a simplified network model depicting the different options. In our model, the network has three major building blocks:

1. the transmission link
2. the transmission equipment
3. the routing and switching equipment.

The main purpose of the economic analysis is to produce cost information, which can be used to compare costs implied by the different options for each part of the network, and to identify the most attractive solution from an economic point of view. Hence the model can be seen as a decision tree that can be used to find the optimum solution for designing future networks.

5.1. Transmission Link

The transmission link is the physical medium through which data are transmitted between two locations. That medium can be copper cables, optical fibres or wireless. The current report concentrates on analysing solutions based on optical fibres, as these are considered to be the most relevant for high-capacity networks. However, copper cables and wireless solutions are still used in parts of the current research networks in Europe, and will remain a relevant option in parts of national and local networks with limited bandwidth requirements.

Two types of optical fibres are currently used. Multimode fibres are able to carry numerous modes or light rays simultaneously, but due to a high level of dispersion these fibres are only used for short distances. Single-mode fibres have a much smaller core than multimode fibres and transmit only one mode of light at a time, but they can transmit the signal over longer distances. Therefore, single-mode fibres are preferred for longer distances. In Europe, most long-distance networks are using first-generation single-mode fibres (G.652). However, new fibre routes are usually equipped with G.655 fibres designed for multi-channel DWDM systems and are therefore more suitable for transmission rates of 10 Gb/s and higher.

The potential fibre capacity in Europe is very large. The capacity depends on the type of fibre as well as the type of transmission equipment. State-of-the-art equipment supports 10 or 40 Gb/s in one lambda (wavelength channel). In a single fibre, 128 lambdas at 10 Gb/s or 32-128 lambdas at 40 Gb/s can be transmitted. Today, "normal" fibre cables on the market contain up to 192 or 288 fibres per cable and some cables contain up to 720 fibres. A cable with 720 fibres, where each fibre contains 128 wavelengths at 10 Gb/s would in theory be able to carry a capacity of 921 Terabits per second. This indicates that if two locations are connected by a fibre cable, it is usually not the fibre but the transmission equipment that limits the capacity.

However, fibres that are more than ten years old, and those are common particularly in Western Europe and the northern regions of the continent, can be used for transmission rates up to 2.5 Gb/s but will require very expensive compensation equipment to support higher bit rates[13].

Today, there is ample fibre capacity on the major routes and it is not economically attractive to lay down additional fibres. If ample fibre capacity is available, it is worth considering using low-capacity transmission equipment (which is cheaper) on more fibres instead of using more advanced equipment that enables a high capacity on each fibre.

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[13] see SERENATE deliverable D9 "Report on the availability and characteristics of equipment for next-generation networks", section 5.1.

The key decision to be taken for transmission links is the degree of outsourcing, i.e., should all operations be left to an operator or should they be performed by the research network organisation itself? The ownership options introduced in section 2.3 imply different cost profiles:

- **Full ownership** implies investments in fibres (construction costs) and expenses for operation and maintenance. In addition, full ownership of fibres will also involve full ownership of transmission equipment (see below).

- **Dark fibre** implies expenses for leasing or buying a dark fibre. Operation and maintenance will to a certain degree be included in these costs. A dark fibre may include amplification and regeneration underway, but the research network can also choose to be responsible for these operations itself. In this case, expenses for transmission equipment must be added. In any case, transmission equipment at both ends must be added (see below).

- **Direct access** implies expenses for leasing or buying a wavelength connection. Transmission equipment at both ends must be added (see below).

- **Leasing of capacity** implies expenses for leasing of capacity only, while all other transmission costs are included.

In all of these options, the research and education network organisations will need to invest in their own switching and routing equipment, as they do today.

The option of leasing capacity is considered to be less relevant in the future and is therefore not included in the cost calculations below. Therefore, our cost model includes the following options:

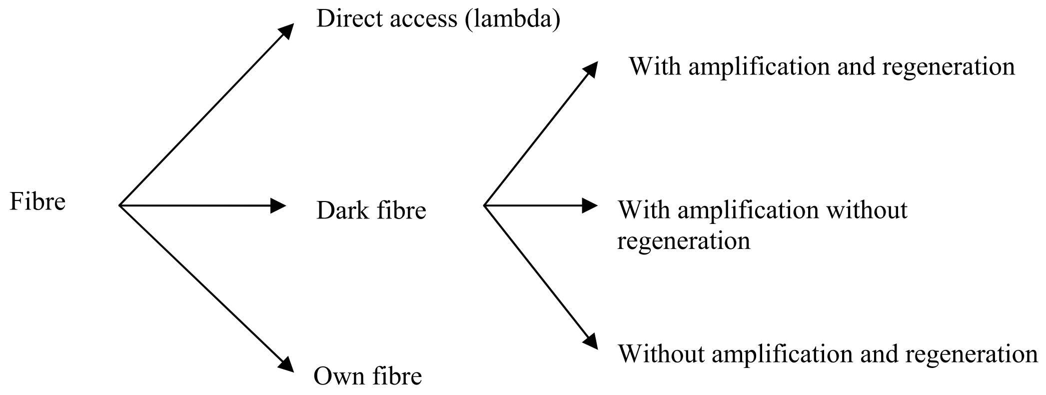

Figure 2. Transmission link model

5.2. Transmission Equipment

Transmission equipment is defined as the equipment needed to enable transmission through the link. There are two kinds of equipment: end-equipment for sending and receiving signals at each end of the link, and equipment for amplification and regeneration of signals underway.

We will consider three different network configurations:

1. Carrier-class networks. This is the type of network used by network operators demanding very high capacities over long distances. It implies the use of very advanced and also very expensive transmission equipment.

2. Metro networks. These are used for shorter distances, for instance within one metropolitan area. Capacity and costs are somewhat lower than in carrier-class networks.

3. CWDM networks. This type of network can be used as local networks. Capacity and costs are lower than in Metro networks.

For simplification, only three kinds of equipment are considered:
- interface cards
- transponders
- multiplexers

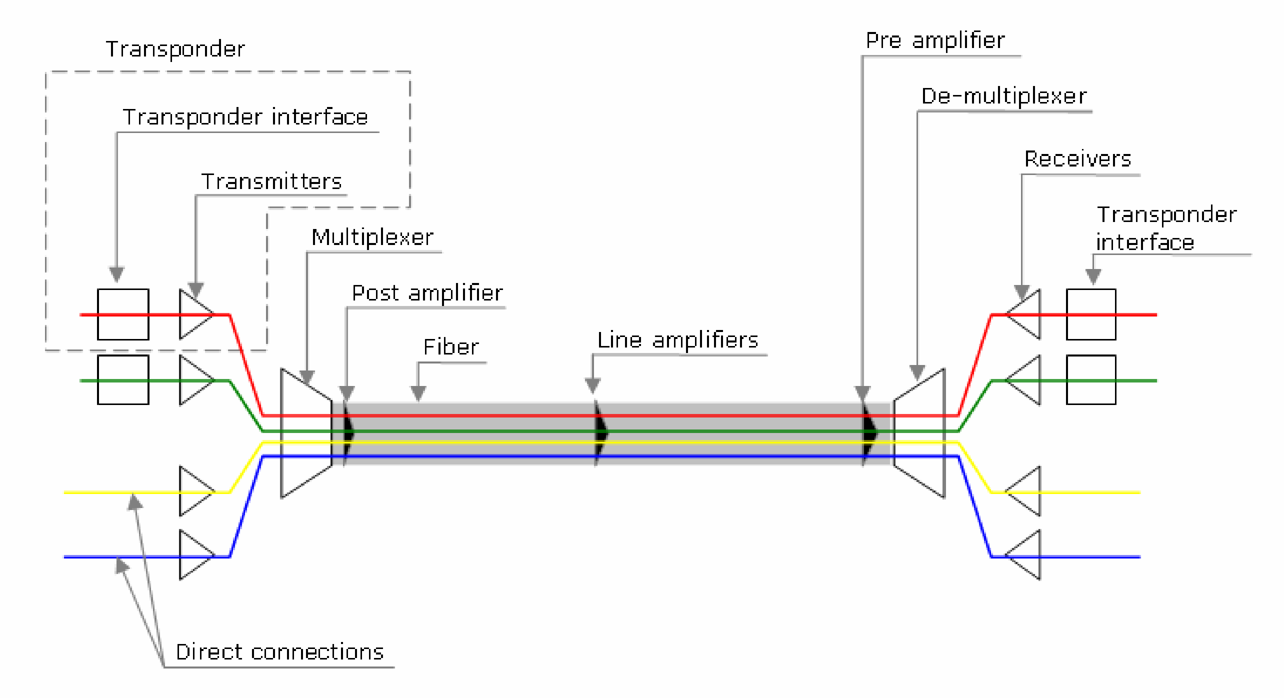

Figure 3. Overall network architecture[14]

In addition to this, amplifiers and regenerators may be added on the line for transmission over long distances. The model assumes that transponders are integrated with the multiplexer into a single piece of equipment, while interface cards can be added one by one, according to capacity needs.

5.2.1. Interface cards / Gigabit Ethernet

The type of interface card to be used depends on the required capacity and the format of data. The use of Gigabit Ethernet is of particular interest, since this format is widely used and easy to connect with local networks. One interface card per lambda connection is needed at both ends.

The Gigabit Ethernet transmission technology is based on the Ethernet frame format; the protocol is used in local-area networks (LANs) and can currently be used for a link up to 1 Gb/s. The Gigabit Ethernet protocol is defined in the IEEE 802.3 standard; Gigabit Ethernet is currently used as the backbone in many company networks. Gigabit Ethernet is primarily carried on optical fibres, but can also be carried on copper cables on very short distances. Existing Ethernet LANs with 10 and 100 Mb/s cards can feed directly into a Gigabit Ethernet backbone, which makes Gigabit Ethernet very useful in many areas. Gigabit Ethernet serves transmission distances of up to 200-300 km without amplifiers and regenerators.

Gigabit Ethernet is becoming available for 10 Gb/s connections as well. 10 Gb/s Ethernet is also part of the IEEE 802.3 family and, therefore, useful as an extension of Ethernet networks used by local-area networks today. 10-Gigabit Ethernet can be described as a "disruptive" technology, which offers a more efficient and

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[14] Introduction to DWDM for metropolitan networks, http://www.cisco.com/

less expensive approach to data transmission via backbone connections between networks by a technology that is end-to-end consistent. Gigabit Ethernet ports cost only 5-10% of those used for SDH or ATM.

10-Gigabit Ethernet is expected to be used to interconnect local-area networks, wide-area networks (WANs), and metropolitan area networks (MANs). 10-Gigabit Ethernet uses full-duplex transmission over a considerable distance range. On multimode fibres, 10-Gigabit Ethernet will support distances up to 300 meters and on single-mode fibres, it will support distances up to 40 km or more. As 10 and 100 Mb/s Ethernet cards can feed into Gigabit Ethernet and 1 Gigabit Ethernet can feed into 10-Gigabit Ethernet networks, the Ethernet transmission technology is very flexible and scalable.

At the moment, Gigabit Ethernet is only relevant in Metro and CWDM networks, and not for carrier-class networks.

5.2.2. Transponder (transponder interface and transmitter)

The transponder converts signals coming from different types of physical media using different protocols and traffic types. Most WDM systems support SONET/SDH short-reach optical interfaces where any SONET/SDH compliant service client device can attach. In addition, other interfaces are supported, e.g. Fast Ethernet and Gigabit Ethernet. Future designs will include so-called passive interfaces, which accept light streams following the ITU standards directly from an attached switch or router with an optical interface.

The main purpose of the O-E-O (Optical-Electrical-Optical) signal conversion is restoration, reshaping and retiming of the optical signal. This cannot be done in full with the optical devices available on the market today[15]. By converting incoming signals into precise ITU-standard wavelengths to be multiplexed, transponders are currently a key component of WDM systems, where the transmitter converts electronic signals into wavelengths.

5.2.3. Multiplexers

The multiplexers currently enable transmission of up to 128 lambdas in the same fibre. The more lambdas in the same fibre, the more expensive the multiplexer will be. If only one channel is used, it is not necessary to install a multiplexer. Two types of multiplexing are considered in the model:

- Dense Wavelength Division Multiplexing (DWDM)
- Coarse Wavelength Division Multiplexing (CDWM)

5.2.4. Dense Wavelength Division Multiplexing

DWDM can multiplex 128 (and theoretically more) separate wavelengths or channels of data into a light-stream transmitted on a single optical fibre. A DWDM multiplexer converts the bit stream to an optical signal using a laser. A colour (a wavelength or a frequency) is assigned to each channel or lambda and they are all transmitted through the same fibre. The wavelength used for DWDM is chosen within a certain range of frequencies (around 1550 nm), also called a window. The tight spacing between wavelengths (DWDM uses a 1.6 nm spacing between wavelengths) can very easily be disturbed by changes in temperature. This will mix signals from different channels and a loss of data may occur. In order to avoid this problem, it is necessary to equip DWDM devices with expensive cooling systems controlling the temperatures and ensuring that the correct wavelengths are maintained.

Each channel is de-multiplexed at the end of the transmission back into its original format, and each channel can apply different data formats and use different transmission rates. Thus IP, SONET/SDH, ATM and Gigabit Ethernet can be transmitted within the same fibre.

From both a technical and an economic perspective, the ability to provide potentially unlimited transmission capacity is one of the biggest advantages of the DWDM technology. The current fibre network can be optimised as demand changes, and more capacity can be added.

The technical advantages of the DWDM technology can be summarised as follows:

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[15] see SERENATE deliverable D9 "Report on the availability and characteristics of equipment for next-generation networks"

- Transparency: DWDM is a physical-layer architecture and it can transparently support different data formats: ATM, GE, SONET/SDH and IP.

- Scalability: DWDM can leverage the abundance of dark fibre and relatively quickly meet demand for increased capacity.

- Dynamic provisioning: DWDM can provide fast, simple and dynamic network connections[16].

5.2.5. Coarse Wavelength Division Multiplexing

CWDM also employs multiple light wavelengths to transmit signals over a single optical fibre. The CWDM technology is based on the same WDM concept as DWDM technology; the two technologies differ primarily in the spacing of the wavelengths, the number of channels, and the ability to amplify signals in the optical spacing between the wavelengths.

CWDM currently operates with standardised sixteen-channel spectral grids and 20 nm spacing, between 1300 nm and 1620 nm compared to 1.6 nm spacing with DWDM. The wide-channel spacing enables use of components that are much cheaper than those used in the DWDM system architecture. Among others, the savings relate to the above-mentioned impact of the temperature on wavelengths. The output wavelength of a laser can vary by several nanometres, depending on the operating temperature. The wider spacing between the wavelengths used by CWDM technology reduces signal mixing and allows for the use of simpler technology and equipment, for example un-cooled lasers.

CWDM technology is a crucial component of Ethernet LAN and MAN networks, because it maximises the use of the installed fibre infrastructure without use of expensive DWDM equipment. This low-cost, high-performance multiplexing of multiple optical signals is attractive to apply within metropolitan and access networks. The limitation of CWDM to maximum sixteen channels implies that DWDM is preferred in a situation where demand for very high bit rates can be expected, and where it is costly to deploy additional fibres.

5.2.6. Add/Drop multiplexers

Optical Add and Drop Multiplexers (OADM) are used if there is a need to remove or insert one or more wavelengths in a fibre at some point between the sending and receiving points on a fibre connection. The OADM can remove some of the wavelengths while others are transmitted directly to the other end of the fibre link, without any conversion to electrical signals. Advanced OADM equipment is able to add and drop wavelengths dynamically for any or all wavelengths carried by a fibre pair without affecting the remaining part of the traffic. This advanced equipment is scalable and able to support up to 284 wavelengths. It can be upgraded to optical switches in order to support multiple fibre routes[17].

The function of the OADM is illustrated in the figure below.

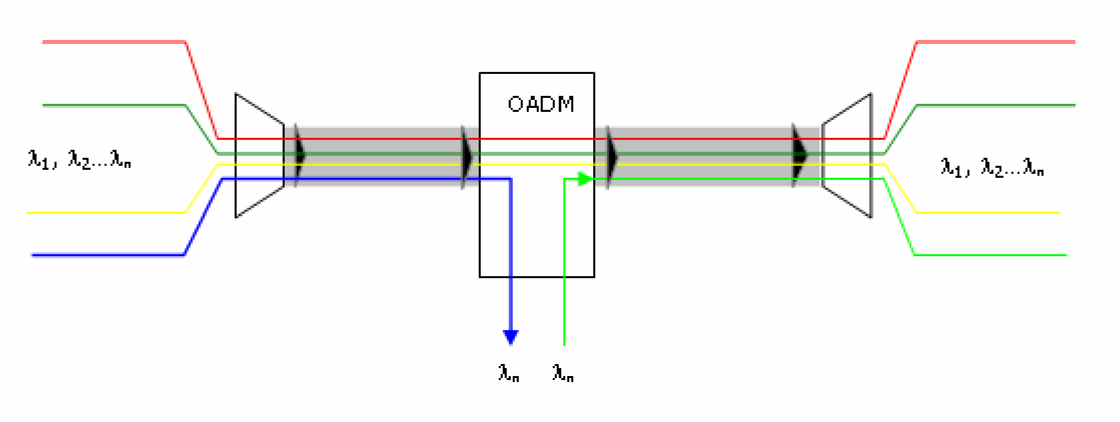

Figure 4. The function of an Optical Add and Drop Multiplexer

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[16] Introduction to DWDM for metropolitan networks, http://www.cisco.com/

[17] see SERENATE deliverable D9 "Report on the availability and characteristics of equipment for next-generation networks", section 5.2.

5.2.7. Amplifiers and regenerators

Optical amplification and regeneration is used in optical networks to increase the possible maximum distance of the optical link. An amplifier simply amplifies the signal (both the optical signal and background noise), while a regenerator restores, reshapes and retimes the optical signal. Contrary to amplification, regeneration requires separate conversion to electrical signals and amplification for each wavelength. In practice, signals can travel up to around 75 km between amplifiers depending on type of equipment, and regeneration is done every 700-1000 km. The higher the data rates are, the shorter the possible span without amplification and regeneration. However, state-of-the-art equipment is capable of transmissions over more than 1500 km without regeneration.

The span between the sending and receiving points can be expanded further without placing equipment in the line if optical amplifiers are placed in both ends of a dark fibre and connected directly to the termination equipment. One example of the use of this technology can be found in CESNET, which is using a Nothing-In-Line (NIL) connection with a G.652 fibre for 1 Gb/s on a distance of 189 km based on standard Cisco equipment and a Keopsys 24 dBm Erbium-Doped Fibre Amplifier (EDFA) as a booster (post amplifier) on the transmitter side. In addition to this, CESNET has tested narrow-band DWDM equipment and here the reach was extended up to 230 km by adding another optical amplifier (pre-amplifier) at the receiver end and to 280 km by further adding a Raman amplifier on the receiver side.

5.2.8. Transmission equipment model

In the cost model it is assumed that the carrier-class network is based on DWDM technology and uses either 10 or 40 Gb/s wavelengths. The Metro network is based on CWDM and deploys 10 or 40 Gb/s wavelengths or 1 or 10 GE connections. In addition to this, also amplifiers and regenerators are included when necessary and otherwise a NIL connection is deployed, all depending on the transmission span.

The carrier-class network can either be based on 40 Gb/s with up to 40 wavelengths or based on 80 wavelengths each carrying 10 Gb/s, whereas the Metro network can transmit maximum 32 wavelengths of either 10 or 40 Gb/s.

The CDWM network will use equipment allowing four or eight wavelength connections with either 10 Gb/s connections or 1 and 10 GE connections. The four or eight 10 Gb/s wavelengths are only considered as a NIL connection, or with some amplifiers but no regenerators.

The key decisions for the transmission equipment include:

- the network configuration: carrier-class, Metro or CWDM network
- wavelengths or Gigabit Ethernet solutions
- the capacity: 10 or 40 Gb/s wavelengths or 1 or 10 Gigabit Ethernet connections
- NIL connection or connection with amplifiers and possibly regenerators.

The relevance of these options depends on the choices made on the transmission link. If the transmission capacity is bought from a network operator, they are responsible for the transmission and the research network does not have to study the various options. However, if research networks want to deploy their own equipment in different degrees and levels, the decision tree / economic model in the following figure can be used as a starting point.

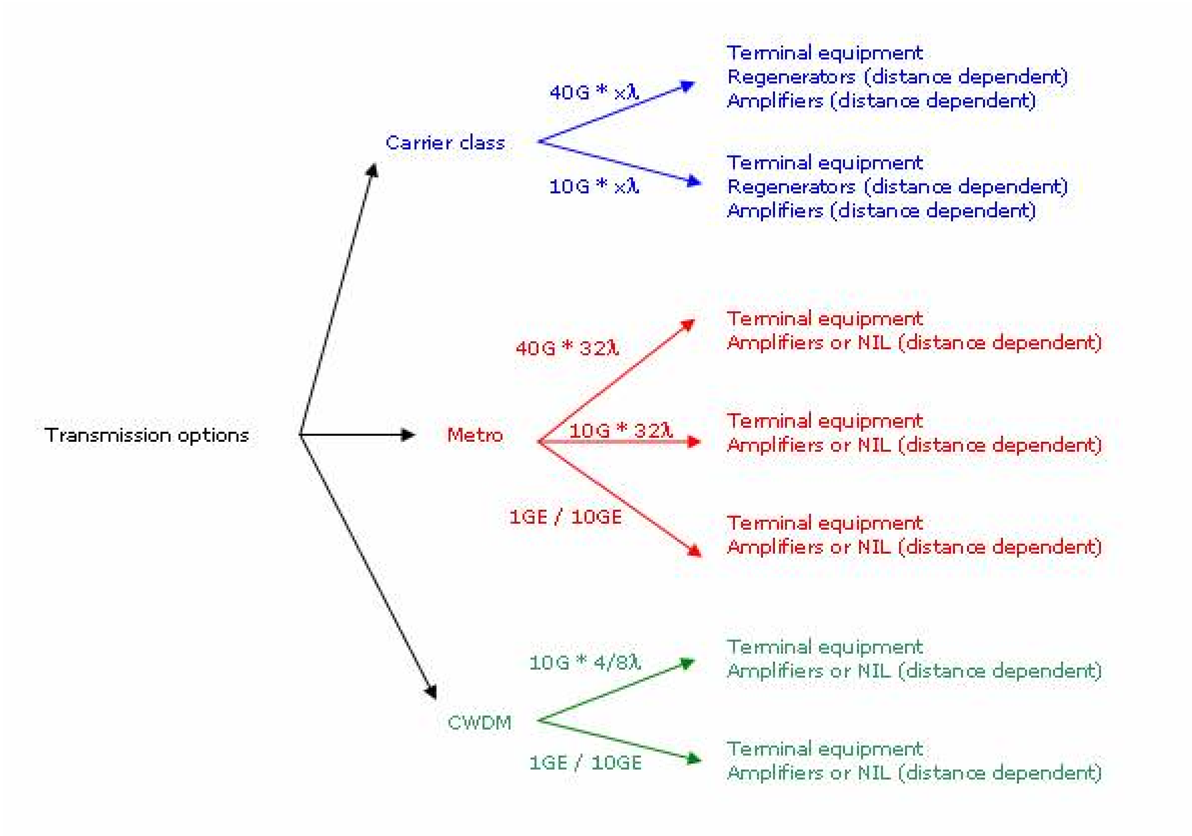

Figure 5. Transmission equipment model

The terminal equipment costs are based on frame equipment and interface cards, where the average cost of interface cards for a particular network scenario is used for each interface card. Where NIL transmission scenarios are used, amplifiers are included in the transmission equipment, depending on the distance of the particular transmission span. Amplifiers and regenerators are priced according to number of wavelengths and wavelength capacities, and can therefore vary considerably in different scenarios.

5.3. Routing and Switching Equipment

Routing and switching equipment is used to direct the traffic to its destination. Such equipment is located in the nodes of the network and includes routers, switches and interface cards. A major issue in the design of a research and education network is to decide where to use routers and where to use switches. Routers have wider functionality, but are more expensive than switching equipment.

5.3.1. Routers

The main function of a router is to determine the next network point to forward a packet to, on its way to its final destination. The router is connected to at least two networks. A router is normally located at any gateway or connection point where one or more networks meet.

Routers use headers and forwarding tables to determine the best path for forwarding the packets, and they use protocols such as ICMP to communicate with each other and configure the best route between any two hosts[18]. A router creates and maintains a table of the available routes and their conditions and it combines this information with distance and cost algorithms to determine the best route for a given packet. Typically, a packet may travel through a number of network points before arriving at its final destination. The core router function is done at the IP layer (layer 3 in the OSI model).

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[18] http://www.webopedia.com/TERM/R/router.html

5.3.2. Switches

A switch is a network component that channels incoming data from multiple input ports to that output port that will bring the data to its destination, depending on the address information contained in the message[19]. In a local-area network with a limited number of destinations, the switch looks at each packet or data unit and determines from a physical address (the "MAC address") where to direct the information. By contrast, in wide-area networks the destination address requires a look-up in a routing table by a router. However, most new switches also perform some routing functions (layer 3) and are referred to as IP switches or layer-3 switches.

Routers and switches include both a box or a frame and a number of interface cards (one for each channel). More cards can be installed if more channels are needed. The different components in the routing and switching building block are shown in the figure below.

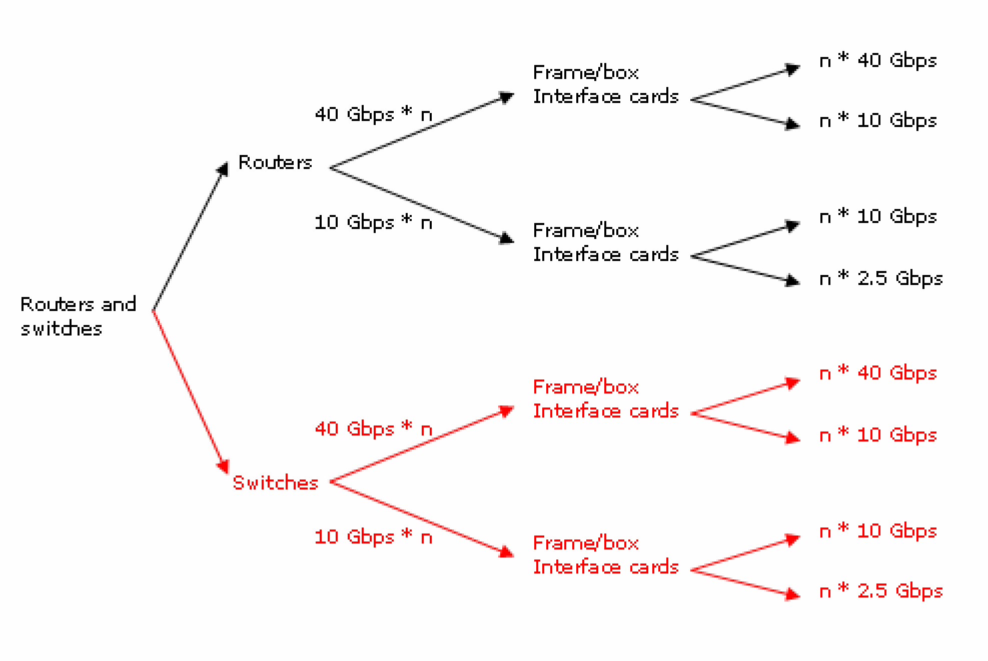

Figure 6. Routing and switching equipment model

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[19] http://ieee1588.nist.gov/

6. Examples of Cost Implications of Network Options

The cost implications of the various network options depend on the types of connections and equipment involved. Costs for both equipment and network connections vary over time and according to location. As was indicated in chapter 4, high-capacity connections following major routes are far cheaper per Mb/s than connections with lower capacity following routes outside the major communication highways. Moreover, the market for the types of services and equipment demanded by research and education networks are not very transparent. Special reductions are offered to major customers and cost figures are kept secret.

In order to study the economy of high-capacity research and education networks, in this chapter the costs for alternative ownership models are calculated for eight different types of links, which represent typical examples of national and international connections in European research and education networking:

1) 3000 km link with a capacity of 4 x 40 Gb/s or 16 x 10 Gb/s

2) 1000 km link with a capacity of 4 x 40 Gb/s or 16 x 10 Gb/s

3) 500 km link with a capacity of 4 x 40 Gb/s or 16 x 10 Gb/s

4) 225 km link with a capacity of 4 x 10 Gb/s (CWDM and Metro equipment)

5) 150 km link (NIL connection) with a capacity of 4 x 10 GE

6) 50 km link with a capacity of 4 x 10 Gb/s (CWDM and Metro equipment)

7) 15 km link (NIL connection) with a capacity of 4 x 10 GE

8) 5 km link (NIL connection) with a capacity of 4 x 10 GE

The calculated costs include the link and the transmission equipment. The costs of routing and switching are analysed in a separate section.

The calculations presented in the examples below are based on cost figures prepared in consultation with equipment manufacturers and network operators. Some NRENs may, however, experience costs that are quite different from those used in our examples, in particular with regard to prices for network services such as dark fibres.

The costs for construction of a new fibre link are highly dependent on the physical environment. For example, they are higher in metropolitan areas than in rural areas. The costs can be reduced considerably by relying on existing infrastructures such as ducts, railway lines and others. Co-operation with other infrastructure providers is therefore a way for obtaining cheaper fibre access. In the calculations, an investment cost of 50,000 euro per kilometre is used. This includes all costs related to investment in a fibre connection. As the additional cost of laying one extra fibre is almost zero, there are substantial economies of scale; co-operation with other operators is thus another way to reduce costs. Finally, it may be possible to buy an existing fibre at a price lower than the full construction costs.

In our calculations, fibres are assumed to have a lifetime of five years. Although it may be possible to use the fibre for a much longer period of time, it is too risky to base calculations on income for more than five years ahead. This assumption is, however, essential for the cost calculations for building your own fibre. If the fibre lifetime is extended to fifteen years instead of five, the total annual link costs will be reduced by approximately 50% (see Table 11 below).

The price for the annual lease of a dark fibre is set at the European Union average of 500 euro per kilometre. If amplification is included, the price is assumed to be 50% higher (750 euro per kilometre), and it is assumed to be double (1,000 euro) if regeneration is included. All these market prices are tentative and based on an average, but they can be used as guidelines to compare with the costs for research and education network organisations to build their own fibre links. The prices for a wavelength connection reflect the prices offered on major routes today, and are lower than what can be obtained in other locations.

Operation and maintenance of end-equipment is assumed to be 20% of the investment costs, whereas the operation and maintenance of all types of fibres depend on the distance and is assumed to cost 1,000 euro per year per kilometre. Maintenance and operation of dark fibres are set at 1/10 of the costs for a complete fibre. The reason is that the maintenance of a dark fibre is assumed to be shared between several users.

Capital costs are set at 10% per year. This is higher than the banking rate, but lower than the average cost of capital in the telecommunications sector, which has been estimated to be 12-13%.

6.1. Example 1: 3000 km Point-to-Point Connection

The first example is a hypothetical point-to-point trans-European link. The distance between point A and B is 3000 km and they are connected by an optical fibre of type G.652. The link includes 40 spans, with an average distance of 75 km.

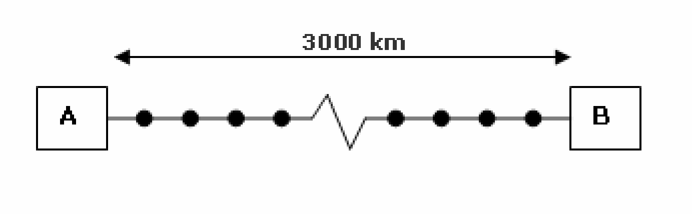

Figure 7. Point-to-point trans-European transmission link

The example is based on a point-to-point DWDM transmission between two high-speed IP routers and the overall transmission system should be able to support up to 32 wavelengths, where each wavelength is capable of carrying one 40 Gb/s channel or multiple 10 Gb/s channels. However, only four 40 Gb/s or sixteen 10 Gb/s wavelengths will be activated from the beginning and are therefore included in the calculation.

Equipment needed for the 4 x 40 Gb/s transmission

- two complete 40 Gb/s DWDM terminals
- eight 40 Gb/s interface cards
- 36 amplifiers
- three regenerators
- twenty-four 40 Gb/s regenerator interface cards

Equipment needed for the 16 x 10 Gb/s transmission

- two complete 10 Gb/s DWDM terminals
- thirty-two 10 Gb/s interface cards
- 36 amplifiers
- three regenerators
- ninety-six 10 Gb/s regenerator interface cards

The costs are depicted in Table 3 below.

6.2. Example 2: 1000 km Point-to-Point Connection

As in the previous example, this example refers to a hypothetical point-to-point trans-European or national link (Figure 8). The distance between point A and B is 1000 km and they are linked by an optical fibre of type G.652. The link includes thirteen spans, with and average span of 77 km.

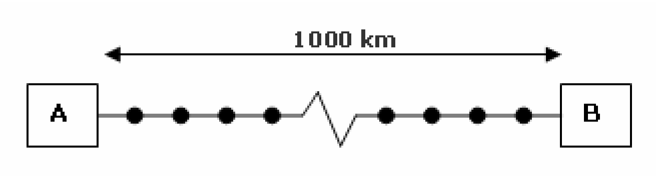

Figure 8. Point-to-point trans-European/national transmission link

The example is based on a point-to-point DWDM transmission between two high-speed IP routers and the overall transmission system is able to support up to 32 wavelengths, where each wavelength can carry a single 40 Gb/s channel or four 10 Gb/s channels. However, only four 40 Gb/s wavelengths or sixteen 10 Gb/s wavelengths will be activated immediately and only the costs of these are therefore included in the calculations.

Equipment needed for the 4 x 40 Gb/s transmission
- two complete DWDM terminals
- eight 40 Gb/s interface cards
- eleven amplifiers
- one regenerator
- eight 40 Gb/s regenerator interface cards

Equipment needed for the 16 x 10 Gb/s transmission
- two complete DWDM terminals
- thirty-two 10 Gb/s interface cards
- eleven amplifiers
- one regenerator
- thirty-two 10 Gb/s regenerator interface cards

The costs are depicted in Table 4 below.

6.3. Example 3: 500 km Point-to-Point Connection

Also this example refers to a hypothetical point-to-point trans-European or national link (Figure 9). The distance between point A and B is 500 km and an optical fibre type G.652 is used. The link includes seven spans, with and average span of 75 km.

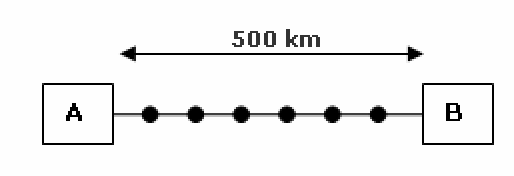

Figure 9. Point-to-point trans-European/national transmission link

The example is based on a point-to-point DWDM transmission between two high-speed IP routers and the overall transmission system can support up to thirty-two wavelengths, where each wavelength can carry a single 40 Gb/s channel or up to four 10 Gb/s channels. But only four 40 Gb/s wavelengths or sixteen 10 Gb/s wavelengths will be activated immediately and are therefore included in the calculations.

Equipment needed for the 4 x 40 Gb/s transmission
- two complete DWDM terminals
- six amplifiers
- eight 40 Gb/s interface cards

Equipment needed for the 16 x 10 Gb/s transmission

- two complete DWDM terminals
- six amplifiers
- thirty-two 40 Gb/s interface cards

The costs are depicted in Table 5 below.

6.4. Example 4: 225 km Point-to-Point Connection

This example refers to a hypothetical point-to-point national link (Figure 10). The distance between point A and B is 225 km and involves an optical fibre type G.652. The link includes three spans with an average span of 75 km.

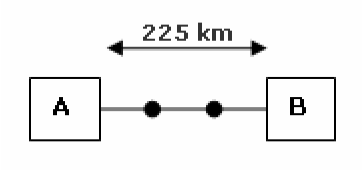

Figure 10. Point-to-point national transmission link

The example is based on a point-to-point CWDM or Metro transmission between two high-speed switches and the overall transmission system is able to support up to eight wavelengths, where each wavelength can carry a single 10 Gb/s channel or multiple 2.5 Gb/s channels. However, only four 10 Gb/s wavelengths will be activated from the beginning and are therefore included in the calculation.

Equipment needed for the 4 x 10 Gb/s CWDM transmission

- two complete CWDM terminals
- two amplifiers
- eight 10 Gb/s interface cards

Equipment needed for the 4 x 10 Gb/s DWDM Metro transmission

- two complete Metro DWDM terminals
- two amplifiers
- two 10 Gb/s interface cards

The costs are depicted in Table 6 below.

6.5. Example 5: 150 km NIL Point-to-Point Connection

This example is based on a hypothetical Nothing-In-Line point-to-point connection, which consists of optical fibre of 150 km. The scenario is based on a point-to-point GE transmission between two routers or switches.

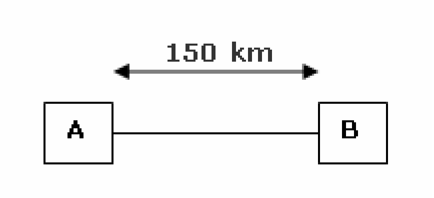

Figure 11. NIL point-to-point connection

The transmission system is able to support up to eight wavelengths, where each wavelength is capable of carrying a single 10 GE channel or multiple 2.5 GE channels. However, only four 10 GE wavelengths will be activated from the beginning and are therefore included in the calculations.

The equipment needed for is (excluding switches):

- eight 10 GE interface cards
- eight Gbic interface modules
- two amplifiers (one in each end)

The costs are depicted in Table 7 below.

6.6. Example 6: 50 km Point-to-Point Connection

This example refers to a hypothetical Nothing-In-Line point-to-point national link (Figure 12). The distance between point A and B is 50 km and consists of an optical fibre type G.652.

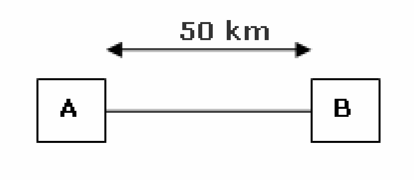

Figure 12. Point-to-point national transmission link

The example is based on a point-to-point CWDM or Metro transmission between two high-speed switches and the overall transmission system is able to support up to eight wavelengths, where each wavelength can carry a single 10 Gb/s channel or multiple 2.5 Gb/s channels. However, only four 10 Gb/s wavelengths will be activated from the beginning and are therefore included in the calculation.

Equipment needed for the 4 x 10 Gb/s CWDM transmission

- two complete CWDM terminals
- eight 10 Gb/s interface cards

Equipment needed for the 4 x 10 Gb/s DWDM Metro transmission

- two complete Metro DWDM terminals
- eight 10 Gb/s interface cards

The costs are depicted in Table 8 below.

6.7. Example 7: 15 km NIL Point-to-Point Connection

This example is based on a hypothetical Nothing-In-Line point-to-point connection, which consists of optical fibre. The scenario is based on a point-to-point GE transmission between two routers or switches.

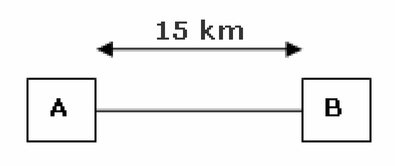

Figure 13. NIL point-to-point connection

The transmission system is able to support up to eight wavelengths, where each wavelength is capable of carrying a single 10 GE channel or multiple 2.5 GE channels. However, only four 10 GE wavelengths will be activated from the beginning and are therefore included in the calculations.

The equipment needed is (excluding switches):

- eight 10 GE interface cards
- eight Gbic interface modules

The costs are depicted in Table 9 below.

6.8. Example 8: 5 km NIL Point-to-Point Connection

This example is based on a hypothetical Nothing-In-Line point-to-point connection, which consists of optical fibre. The scenario is based on a point-to-point GE transmission between two routers or switches.

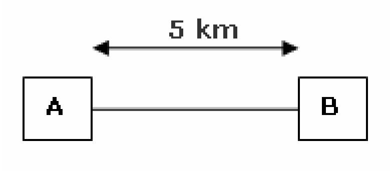

Figure 14. NIL point-to-point connection

The transmission system is able to support up to eight wavelengths, where each wavelength is capable of carrying a single 10 GE channel or multiple 2.5 GE channels. However, only four 10 GE wavelengths will be activated from the beginning and are therefore included in the calculations.

The equipment needed is (excluding switches):
- eight 10 GE interface cards
- eight Gbic interface modules

The costs are depicted in Table 10 below.

Table 3. Network costs for a 160 Gb/s connection and 3,000 km transmission

Ownership	**Network part**	**Total investment** [1,000€]		**Operation and maintenance per year** [1,000€]		**Total annual costs** [1,000€/year]		**Annual Costs per Capacity** [€ per Mb/s per year]		**Annual incremental Costs per Capacity** [€ per Mb/s per year]	
		40 Gb/s	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*
Own fibre	Link	150,000	150,000	3,000	3,000	42,600	42,600	266	266	0	0
	Transmission	10,300	19,600	2,100	3,900	4,500	8,600	28	54	9	37
	Total	**160,300**	**169,600**	**5,100**	**6,900**	**47,100**	**51,200**	**294**	**320**	**9**	**37**
Dark fibre	Link	0	0	300	300	1,800	1,800	11	11	0	0
	Transmission	10,300	19,600	2,100	3,900	4,500	8,600	28	54	9	37
	Total	**10,300**	**19,600**	**2,400**	**4,200**	**6,300**	**10,400**	**39**	**65**	**9**	**37**
Dark fibre with amplification	Link	0	0	450	450	2,700	2,700	17	17	0	0
	Transmission	4,200	14,500	840	3,000	1,850	6,400	12	40	9	37
	Total	**4,200**	**14,500**	**1,290**	**3,450**	**4,550**	**9,100**	**29**	**57**	**9**	**37**
Dark fibre with amplification and re-generation	Link	0	0	600	600	3,600	3,600	22	22	0	0
	Transmission	1,200	2,600	240	520	530	1,140	3.3	7.1	2	6
	Total	**1,200**	**2,600**	**840**	**1120**	**4,130**	**4,740**	**25,3**	**29,1**	**2**	**6**
Direct Access (Lambda)	Link	0	0	0	0	2,800	11,200	18	70	18	70
	Transmission	0	0	0	0	0	0	0	0	0	0
	Total	**0**	**0**	**0**	**0**	**2,800**	**11,200**	**18**	**70**	**18**	**70**

Table 4. Network costs for a 160 Gb/s connection and 1,000 km transmission

Ownership	**Network part**	**Total investment** [1,000€]		**Operation and maintenance per year** [1,000€]		**Total annual costs** [1,000€/year]		**Annual Costs per Capacity** [€ per Mb/s per year]		**Annual incremental Costs per Capacity** [€ per Mb/s per year]	
		40 Gb/s	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*
Own fibre	Link	50,000	50,000	10,000	10,000	14,200	14,200	89	89	0	0
	Transmission	4,100	6,600	800	1,300	1,800	3,000	11	18	4.5	12.5
	Total	**54,100**	**56,600**	**10,800**	**11,300**	**16,000**	**17,200**	**100**	**107**	**4.5**	**12.5**
Dark fibre	Link	0	0	100	100	600	600	3.7	3.7	0	0
	Transmission	4,100	6,600	800	1,300	1,800	3,000	11	18	4.5	12.5
	Total	**4,100**	**6,600**	**900**	**1,400**	**2,400**	**3,600**	**14.7**	**21.7**	**4.5**	**12.5**
Dark fibre with amplification	Link	0	0	150	150	900	900	5.6	5.6	0	0
	Transmission	2,200	5,000	400	1,000	1,000	2,200	6	13.7	4,5	12,5
	Total	**2,200**	**5,000**	**555**	**1,150**	**1,900**	**3,100**	**11.6**	**19.3**	**4.5**	**12.5**
Dark fibre with amplification and re-generation	Link	0	0	200	200	1,200	1,200	7.4	7,4	0	0
	Transmission	1,200	2,600	240	520	530	1,140	3.3	7	2.2	6.2
	Total	**1,200**	**2,600**	**440**	**720**	**1,730**	**2,340**	**10.7**	**14.4**	**2.2**	**6.2**
Lambda	Link	0	0	0	0	1,400	5.600	9	35	9	35
	Transmission	0	0	0	0	0	0	0	0	0	0
	Total	**0**	**0**	**0**	**0**	**1,400**	**5.600**	**9**	**35**	**9**	**35**

Table 5. Network costs for a 160 Gb/s connection and 500 km transmission

Ownership	**Network part**	**Total investment** [1,000€]		**Operation and maintenance per year** [1,000€]		**Total annual costs** [1,000€/year]		**Annual Costs per Capacity** [€ per Mb/s per year]		**Annual incremental Costs per Capacity** [€ per Mb/s per year]	
		40 Gb/s	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*	*40 Gb/s*	*10 Gb/s*
Own fibre	Link	25,000	25,000	500	500	7,000	7,000	44	44	0	0
	Transmission	2,200	3,500	440	700	980	1,540	6.1	9.6	2.2	4
	Total	**27,200**	**28,500**	**940**	**1,200**	**7,980**	**8,540**	**50.1**	**53.6**	**2.2**	**4**
Dark fibre	Link	0	0	50	50	300	300	1.9	1.9	0	0
	Transmission	2,200	3,500	440	700	980	1,540	6.1	9.6	2.2	6
	Total	**2,200**	**3,500**	**490**	**750**	**1,280**	**1,840**	**8**	**11.5**	**2.2**	**6**
Dark fibre with amplification	Link	0	0	75	75	450	450	2.8	2.8	0	0
	Transmission	1,200	2,600	240	518	530	1,140	3.3	7.1	2.2	6
	Total	**1,200**	**2,600**	**315**	**593**	**880**	**1,590**	**6.1**	**9.9**	**2.2**	**6**
Lambda	Link	0	0	0	0	1.400	5.600	9	35	9	35
	Transmission	0	0	0	0	0	0	0	0	0	0
	Total	**0**	**0**	**0**	**0**	**1.400**	**5.600**	**9**	**35**	**9**	**35**

Table 6. Network costs for a 4 x 10 Gb/s connection and 225 km transmission

Ownership	**Network part**	**Total investment** [1,000€]		**Operation and maintenance per year** [1,000€]		**Total annual costs** [1,000€/year]		**Annual Costs per Capacity** [€ per Mb/s per year]		**Annual incremental Costs per Capacity** [€ per Mb/s per year]	
		Metro	*CWDM*	*Metro*	*CWDM*	*Metro*	*CWDM*	*Metro*	*CWDM*	*Metro*	*CWDM*
Own fibre	Link	11,250	11,250	225	225	3,200	3,200	80	80	0	0
	Transmission	450	130	90	25	198	56	5	1.4	4.2	0.9
	Total	**11,800**	**11,480**	**315**	**250**	**3,398**	**3,256**	**85**	**81.4**	**4.2**	**0.9**
Dark fibre	Link	0	0	22.5	22.5	135	135	3.4	3.4	0	0
	Transmission	450	130	90	25	198	56	5	1.4	4.2	0.9
	Total	**450**	**130**	**112.5**	**47.5**	**333**	**191**	**8.4**	**4.4**	**4.2**	**0.9**
Dark fibre with amplification	Link	0	0	33.8	33.8	203	203	5.1	5.1	0	0
	Transmission	410	88	82	18	180	38	4.5	0.9	4.2	0.9
	Total	**410**	**88**	**115.8**	**51.8**	**383**	**241**	**9.6**	**6**	**4.2**	**0.9**
Lambda	Link	0	0	0	0	1,400	1,400	35	35	35	35
	Transmission	0	0	0	0	0	0	0	0	0	0
	Total	**0**	**0**	**0**	**0**	**1,400**	**1,400**	**35**	**35**	**35**	**35**

Table 7. Network costs for 4 x 10 GE NIL connection and 150 km transmission

Ownership	**Network part**	**Total investment** [1,000€]	**Operation and maintenance per year** [1,000€]	**Total annual costs** [1,000€/year]	**Annual Costs per Capacity** [€ per Mb/s per year]	**Annual incremental Costs per Capacity** [€ per Mb/s per year]
Own fibre	Link	7,500	150	2,100	53	0
	Transmission	52	10	23	0.6	0.3
	Total	**7,552**	**160**	**2,123**	**53.6**	**0.3**
Dark fibre	Link	0	15	90	2.2	0
	Transmission	52	10	23	0.6	0.3
	Total	**52**	**25**	**113**	**2.8**	**0.3**
Lambda	Link	0	0	1.400	35	35
	Transmission	0	0	0	0	0
	Total	**0**	**0**	**1.400**	**35**	**35**

Table 8. Network costs for a 4 x 10 Gb/s connection and 50 km transmission

Ownership	**Network part**	**Total investment** [1,000€]		**Operation and maintenance per year** [1,000€]		**Total annual costs** [1,000€/year]		**Annual Costs per Capacity** [€ per Mb/s per year]		**Annual incremental Costs per Capacity** [€ per Mb/s per year]	
		Metro	*CWDM*	*Metro*	*CWDM*	*Metro*	*CWDM*	*Metro*	*CWDM*	*Metro*	*CWDM*
Own fibre	Link	2,500	2,500	50	50	709	709	17	17	0	0
	Transmission	410	88	82	18	180	38	4.5	0.9	4.2	0.9
	Total	**2,910**	**2,588**	**132**	**68**	**889**	**737**	**21.5**	**17.9**	**4.2**	**0.9**
Dark fibre	Link	0	0	5	5	30	30	0.75	0.75	0	0
	Transmission	410	88	82	18	180	38	4.5	0.9	4.2	0.9
	Total	**410**	**88**	**87**	**23**	**210**	**68**	**5.25**	**1.65**	**4.2**	**0.9**

Table 9. Network costs for 4 x 10 GE NIL connection and 15 km transmission

Ownership	**Network part**	**Total investment** [1,000€]	**Operation and maintenance per year** [1,000€]	**Total annual costs** [1,000€/year]	**Annual Costs per Capacity** [€ per Mb/s per year]	**Annual incremental Costs per Capacity** [€ per Mb/s per year]
Own fibre	Link	750	15	213	5.3	0
	Transmission	32	6.4	14	0.3	0.3
	Total	**782**	**21.4**	**227**	**5.6**	**0.3**
Dark fibre	Link	0	1.5	9	0.2	0.2
	Transmission	32	6.4	14	0.3	0.3
	Total	**32**	**7.9**	**23**	**0.5**	**0.5**

Table 10. Network costs for 4 x 10 GE NIL connection and 5 km transmission

Ownership	**Network part**	**Total investment** [1,000€]	**Operation and maintenance per year** [1,000€]	**Total annual costs** [1,000€/year]	**Annual Costs per Capacity** [€/ per Mb/s per year]	**Annual incremental Costs per Capacity** [€ per Mb/s per year]
Own fibre	Link	250	5	71	1.8	0
	Transmission	32	6.4	14	0.3	0.3
	Total	**282**	**11.4**	**85**	**2.1**	**0.3**
Dark fibre	Link	0	0.5	3	0.1	0.1
	Transmission	32	6.4	14	0.3	0.3
	Total	**32**	**6.9**	**17**	**0.4**	**0.4**

It follows that construction of one's own fibre is by far the most expensive solution in all of the examples. This could be expected, because by assumption this option excludes the possibility of cost sharing with other users. As a cable with optical fibres can provide almost an unlimited capacity, there are substantial economies of scale associated with sharing infrastructure elements. The economies of scale are reflected in the annual incremental costs. These are zero if one uses one's own fibre or leases a dark fibre. However, these economies of scale can only be obtained on distances where a common infrastructure is in place and where there is sufficient demand to cover the costs. If this is not the case, then the costs of the other options will be much higher than those used in the calculations – therefore the "build yourself" calculation is a very useful yardstick.

In order to test the robustness of this conclusion, the impact of the assumed lifetime of fibres on the annual link costs has been calculated. It follows from Table 11 that the link costs are reduced by about 50% if the lifetime of fibres is extended to fifteen years. Building one's own fibre is therefore still the most expensive option.

Table 11. Impact of lifetime on fibre costs on annual link costs

Distance (km)	**5 years' lifetime** [1,000€]	**10 years' lifetime** [1,000€]	**15 years' lifetime** [1,000€]
3,000 (example 1)	42,600	27,400	22,700
1,000 (example 2)	14,200	9,100	7,600
500 (example 3)	7,000	4,500	3,800
225 (example 4)	3,200	2,100	1,700
150 (example 5)	2,100	1,400	1,100
50 (example 6)	709	457	379
15 (example 7)	213	137	114
5 (example 8)	71	46	38

There are no economies of scale in the use of wavelength connections. It is assumed that the costs of a wavelength with 10 Gb/s and with 40 Gb/s are the same. But no economies of scale can be achieved if more wavelengths are needed. However, both these assumptions can be questioned, as prices may be negotiable.

The costs of having one's own fibre can be reduced if the fibre can be laid together with other fibres or if it is possible to buy an existing fibre.

The option of using one's own fibre is particularly expensive for long distances as the costs are proportional to distance. In the model the same holds for dark fibres, but it is likely that in that case substantial reductions can be achieved for longer distances. Today, the prices of a wavelength connection depend more on the actual route than on the total distance. This may also be the case for dark fibres, but it has not been possible to obtain data that can support this hypothesis.

The calculations indicate that "do it yourself" options are more attractive for short routes and for routes where a high capacity is needed.

Transmission costs are about three times the costs of the link if a dark-fibre solution without amplification and regeneration is used, the only exception being the 40 GE NIL connection (example 5). Almost half of the transmission costs are related to amplification, indicating that it pays to leave this task to the carrier even if this implies a substantial increase in the costs of a dark fibre. In examples 1-3 with distances between 500 and 3,000 km, all based on carrier-class equipment, it is cheaper to leave amplification to the carrier if this leads to a 50% increase in the dark fibre costs. Only in example 4, where the distance is so short that only two amplifiers are needed, such an increase in dark fibre costs cannot be justified. Again this depends entirely on the price levels for dark fibres. In areas where the prices of dark fibres are considerably above average, it may pay to let the research and education network be responsible for amplification.

If a research and education network is responsible for amplification, it must also take the responsibility for regeneration. Regeneration is, however, only needed for distances of more than 600-800 km (some equipment enables transmission without regeneration even at distances above 3,000 km). Also the costs of regeneration depend on the distance. In example 1, where the total distance is 3,000 km, transmission costs are reduced to one third if the research and education network assumes the responsibility for regeneration. In example 2 where the total distance is 1,000 km, the savings are much smaller.

Regeneration is complicated, and it may be difficult for an NREN to take this responsibility. However, the task may be outsourced through a service agreement. Economies of scale for regeneration are much more limited than for amplification, as the costs increase with the number of channels. For amplification there are no incremental costs if capacity is increased.

In examples 1-3, costs are calculated for use of both 10 and 40 Gb/s wavelengths. The costs of using 40 Gb/s are lower than for 10 Gb/s. The reason is that although 40 Gb/s equipment is more expensive, the same capacity can be obtained by use of far fewer interface cards.

Example 4 compares the cost of Metro DWDM and CWDM equipment. The CWDM solution is here the cheapest one, as CWDM equipment is cheaper than Metro equipment. However, the capacity of CWDM equipment is lower and the incremental costs may be higher if the capacity needs to be expanded beyond the maximum level offered by the CWDM equipment.

The transmission costs are much lower in examples 5, 7 and 8 than in any of the other examples. In addition to a shorter distance and lower capacity, the reason is that transmission equipment is much cheaper for an Ethernet connection.

6.9. The Economies of a Combined Router and Switch Solution

Layer-3 or IP switches are able to perform many of the functions of routers in the network. Therefore it is sometimes possible to substitute routers with switches and vice versa. The question is how to identify the most cost-effective mix between routers and switches. This depends on the overall topology of the network, traffic characteristics and the relative costs of routers and switches. This section analyses the economic parameters behind this problem, using as an example a node in a larger network. For example, this could be a POP in the GÉANT network, with a combined switch and router solution.

The idea is to analyse a specific network node where both a router and a switch are deployed and compare the cost of this solution with that of a situation where only routers are deployed, which is the conventional solution. It is assumed that the overall transmission system is capable of supporting up to ten wavelengths of either 10 Gb/s or 40 Gb/s.

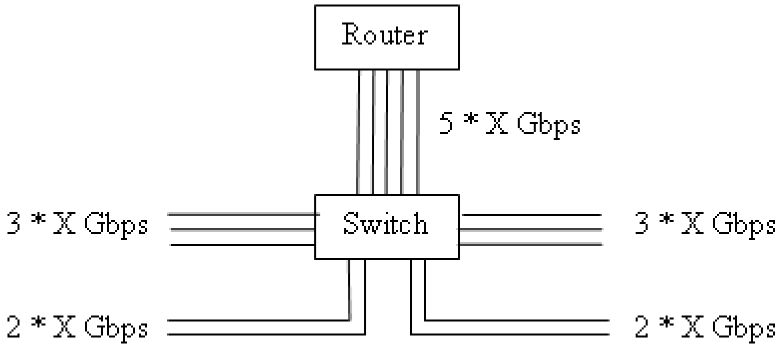

Figure 15. Combined router and switch solution

The example is based on wavelength transmission between different nodes. Each node receives wavelengths from four different locations (Figure 15). A node can either have a router or both a router and a switch, where each switch is connected to the router. In the mixed solution, it is assumed that 50% of the traffic needs to go through the router, while the rest can be handled by the switch alone. The equipment needed for both solutions is listed below. The associated costs for each option follow from Table 12.

10 x X Gb/s pure router solution

- one X Gb/s router
- ten X Gb/s router interface cards

10 x X Gb/s router and switch solution

- one X Gb/s switch
- one X Gb/s router
- fifteen X Gb/s switch interface cards
- five X Gb/s router interface cards

Table 12. Cost associated with different router and switch solutions

Solutions	Routing costs [€]	Switching costs [€]	Total cost [€]
5 * 10 Gb/s router	1,345,000	---	1,345,000
10 * 10 Gb/s router	2,520,000	---	2,520,000
10 * 40 Gb/s router	3,270,000	---	3,270,000
5 * 10 Gb/s router and switch	875,000	685,000	1,560,000
10 * 10 Gb/s router and switch	1,345,000	1,885,000	3,230,000
10 * 40 Gb/s router and switch	1,770,000	2,385,000	4,155,000

As can be seen in Table 12, a combined switch and router solution is more expensive than the pure router solution. However, if the percentage of traffic that needs to be processed by the router is lower than 50%, then a combination solution might be interesting to look into.

In small national networks with a substantial share of internal traffic, one solution could be to deploy only routers at some nodes and switches in all nodes. It would make a combined router and switch solution more economically viable, if routers only are deployed in every second node, as much of the traffic is internal. This solution is not believed to be deployable in a pan-European network like GÉANT, since there much of the traffic is external and therefore needs to be routed by routers. However, a switch-based solution could be deployed on a pan-European scale, if there is a heavy load of dedicated traffic between certain specific locations. In this situation, a switch-based solution would be possible and less expensive than a solution based on routers only.