# The evolution to transparent optical networking

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## ABSTRACT

Optical data transmission has undergone a tremendous evolution. Starting with unrepeated point-to-point transmission in the 80s the inventions of wavelength division multiplexing (WDM) and erbium doped fiber amplifiers (EDFAs) have let to an explosion of system capacity as well as of system reach. After the steep downturn of recent years network operators have now regained the strength to upgrade their networks and to implement new services. This paper will review current and upcoming technologies in the long haul (LH) and ultra long haul (ULH) data transmission. It will further discuss the future evolution of transparent optical networks towards dynamically routed meshed optical networks with respect to operator's technical operational and economical requirements. Upgradeability turns out as a key issue as it on the one hand side facilitates low front investments for network providers and on the other hand side enables organic and flexible network growth.

**Key words:** WDM, ASTN, ASON, GMPLS, optical networking, UNI, NNI, layer interworking, physical layer, alternative modulation, equalizer, 160 Gbit/s, OBS, OPS

## 1. INTRODUCTION

Transport networks based on DWDM technology are the backbone of today's communication systems. Their bandwidth is sold to carriers or end customers, mostly in the form of SDH/SONET connections. Carriers in turn retail this bandwidth to end-customers or other carriers/retailers.

Optical communication systems are evolving quickly. First systems being deployed in the 1980s realized pure point-to-point connections with one data channel on one wavelength per fibre. The later emergence of the wavelength division multiplexing technique lead to an explosion of available bandwidth. Since then also the per channel capacity continuously increased from 155 Mb/s up to today's standard 10 Gbit/s. Newest commercially available systems offer a capacity of even 40 Gbit/s. In such high capacity networks not only the change of configurations and rerouting of a connection are time consuming and expensive: As these systems utilize point-to-point links connecting electrical switches or routers (SDH/SONET, IP) high installation costs due to the large number of O/E/O conversion points are also the consequence. Further, the high number of network elements and equipment deployed in the field results in high administration effort and a high possibility of failures.

Recently deployed optical communication systems offer the possibility to selectively add or drop groups of wavelengths in pure optical nodes in between the end points of the transmission link. This describes the next step of evolution of optical networks as such purely optical nodes enable the realization of real meshed, transparent, optical networks. Although re-wiring by hand is not always necessary, intense planning has to precede any switching event, which still makes the process slow and costly. Therefore the connections are basically static with reduced O/E/O conversions for cost optimization.

Newest systems deployed today allow to dynamically add and drop any wavelength of the transmission link at respective optical network nodes They enable the realization of fast on demand bandwidth provisioning. Further, such WDM systems provide optical bypassing of electrical nodes and form a meshed network topology right in the optical layer. Network management will comprise intelligent software, to assign the routes and to setup respective lightpaths, e.g. generalized multiprotocol label switching (GMPLS). To benefit from the advantages of dynamically reconfigurable optical networks, OTNs have to facilitate physically robust and flexible broadband data transmission. All these features are required to realize automated dynamically reconfigurable networks, i.e. automatically switched optical network (ASON) or automatically switched transport network (ASTN), in the future.

This paper discusses first the advantages of optically transparent network. Chapter three pinpoints key technical and operational requirements of future OTNs and reviews required future technologies. Chapter four will finally discuss the role out new functionalities and technologies on existing OTNs as well as their seamless enhancement. This question of upgradeability will become a key issue since it enables new services, minimizes front investments, and protects the legacy. A summary concludes this paper.

## 2. THE ADVANTAGES OF TRANSPARENT, MESHED, OPTICAL NETWORKS

Current optical networks mainly realize optical point-to-point links between electrical nodes, e.g. layer two switches or layer three routers. This means that each electrical node has to be capable of switching the full capacity of in- and out-going traffic. Furthermore the full bandwidth of all channels at a certain electrical node has to be converted from the optical to the electrical domain and back. This results in a huge number of O/E/O conversion and thus in high costs. Usually the average amount of express traffic in the nodes of LH and ULH networks varies between 60% and 70%. In special cases it can be ever higher. Thus, switching or routing capacity in the electrical domain can be significantly reduced if such express channels bypass the electrical switches/routers right in the optical domain. A significant part of the required switching capacity at a node site is moved from the electrical to the optical domain. By this architecture (cf. Fig. 1) network provides can reduce their investments dramatically as it reduces the required switching capacity in the electrical nodes significantly. A large number of line cards for the electrical switches/routers are replaced by relatively simple optical switches.

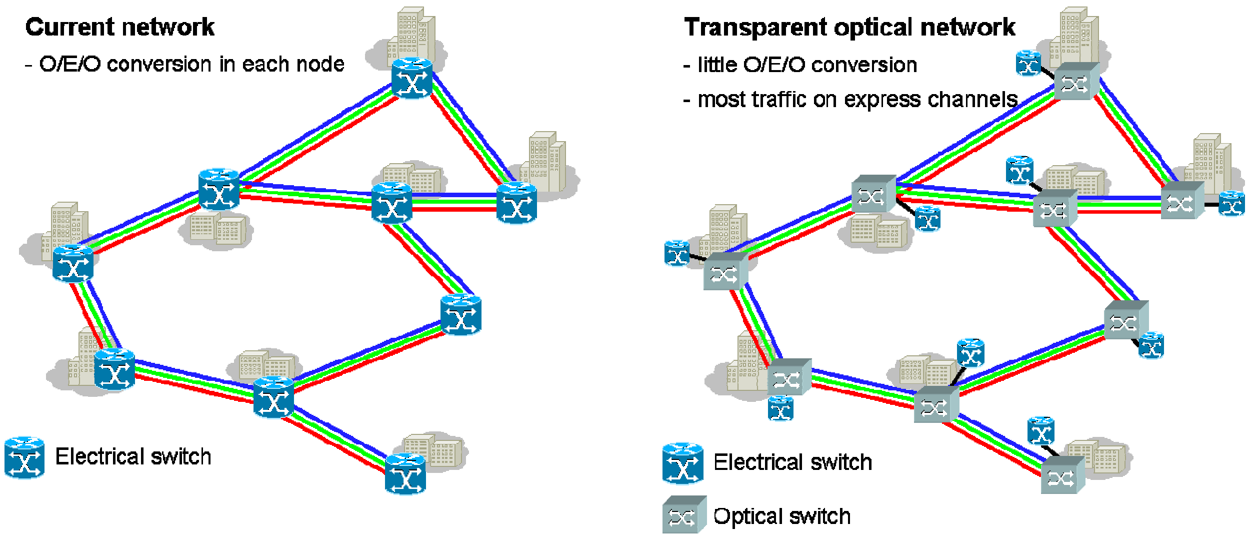



**Fig. 1:** Current expensive network with O/E/O conversion in each node and large L2/L3 switching-capacity demands (left) and CAPEX saving transparent optical network with optical nodes and connected electrical L2/L3 nodes with reduce switching-capacity requirements.

Line cards of the electrical switches and routers comprise not only expensive O/E/O conversion but parts of the switching functionality of the electrical node itself. They are therefore quite costly and contribute significantly to the costs of the growth equipment in case of network-capacity upgrades. In contrast to that, optical nodes are hardly more than a MUX/DEMUX pair with an amplifier and optical switches in between. In optical nodes channel upgrades can be easily realized by adding simple optical switches for the respective wavelength and eventually further MUX/DEMUX pairs – depending on the node architecture. Thus, from an investment point of view transparent optical networks offer significant CAPEX savings compared to current point to point networks with 100% electrical switching in each node.

Another aspect is the reliability and the administration effort required for a certain network. Compared to optically opaque networks with 100% electrical switching transparent optical networks comprise a much smaller number of network elements since they require by far less O/E/O converters. Less components reduce the administration effort as well as the probability of network-element failures. Thus transparent optical networks contribute to OPEX savings.

Furthermore optical networks enable new revenue generating services such as dynamic bandwidth provisioning on demand. In transparent optical networks additional bandwidth is added to the networks by installing the transmitters and the receivers and remotely configuring the intermediate optical nodes correspondingly. This is in contrast to what one finds in current optical networks where initialization of each new wavelength has to be planned, configured and set up by hand. Such procedures are currently time consuming, prone to errors, and thus expensive.

Other revenue generating services are for example secure lambda services. Here optical transparency is an advantage. Whereas in electrical switches each data packet can be potentially examined from a remotely logged in attacker, in optically transparent networks the data packets are not touched or traced on their way through the network. Thus lambda services in transparent optical networks represent a significant increase of data security.

## 3. OPERATIONAL AND TECHNICAL REQUIREMENTS OF OPTICAL NETWORKS

The preceding paragraph pinpointed major advantages of transparent optical networks. However, operators have learned from the past. Their requirements concerning new investments have become stricter since today new investments have to prove their necessity and have to pay off within a shorter period. For each new investment a strong focus is put on the minimization of front investments, i.e. CAPEX, and the effort for network's operation, administration, and maintenance (OAM), i.e. OPEX.

Especially when discussing OPEX and OAM one has to realize that a meshed optical network like promoted here is more than just the sum of its point-to-point links. Operation of such a network can become much more complex, as due to the transparency, different parts of the optical network can interact in an undesired manner. Consequently, new technologies have to enable robust broadband data transmission in the optical network and have to minimize operational effort.

To make use of the whole variety of functionalities and advantages of optical networks, one has to look beyond currently available technology. A couple of technologies which are actually in the research laboratories or leaving the laboratories into the product world enable flexible optical networks or open new possibilities. Novel advanced modulation formats provide lower sensitivity to fiber nonlinearities and dispersion properties and enable thus a more robust and more flexible data transmission in meshed networks. From the operational point of view control planes will enable automated setup of new lightpaths, optical protection and fast service provisioning. Thus, these upcoming technologies as well as more advanced topics such as optical time domain multiplexing, optical networking at highest data rates, and optical burst and packet switching OBS/OPS to support packet based networks right in the optical domain are reviewed next.

Alternative modulation formats are widely researched [1-4]. Although On/Off Keying (OOK) is still by far the most often used format and probably will keep this role for a while, alternative modulation formats can provide some significant advantages, For instance by engineering also the optical phase of OOK signals like in case of Duobinary or carrier suppressed modulation formats one can enhance the signals robustness against chromatic dispersion, polarization mode dispersion and fiber nonlinear effects. Such an enhancement of transmission robustness enables more flexible design of optical networks and reduces engineering constraints. A further advantage of such phase shaped modulation formats is that although their require  modified transmitters, they can utilize standard OOK receivers in most cases. Thus if the use of an alternative modulation format replaces costly dispersion compensation schemes and increases the dispersion tolerance and the tolerance against fiber nonlinear effects it can be commercially attractive.

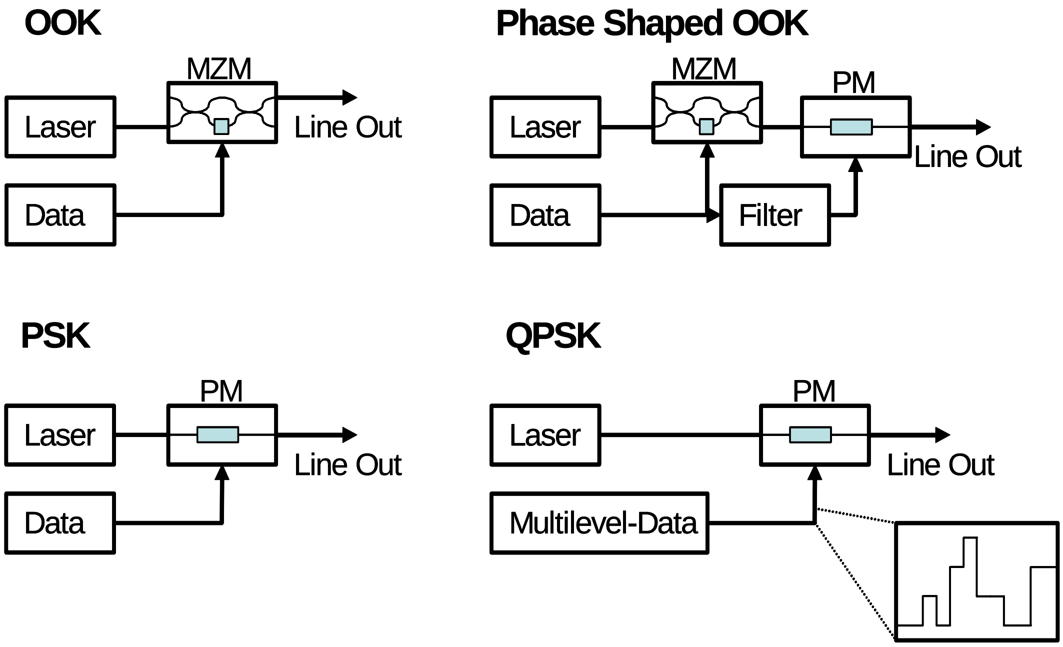



**Fig. 2:** Simplified transmitter setups for different modulation formats. OOK: a Mach Zehnder modulator (MZM) modulates the data onto a cw laser beam. Phase Shaped OOK: a mach zehnder modulator modulates the data onto a cw laser beam and an additional phase modulator (PM), driven by the filtered data signal, supplies the phase shaping. PSK: Laser light is modulated by a phase modulator. QPSK: Laser light is modulated by a four level data signal to generate four distinct optical phases.

Another class of alternative modulation schemes replaces the amplitude modulation of OOK by a merely phase modulated signal or a combination of phase- and amplitude modulation. The information to be transmitted is at least partly inserted into the phase of the optical signal. Such phase shipft keying (PSK) requires modifications of the transmitter and the receiver. They are therefore not compatible to existing OOK-equipment like OOK modulation formats with additional phase engineering. On the other hand binary PSK modulation schemes can increase the receiver sensitivity by up to 3 dB compared to standard OOK and therefore increase the system reach and reduce its sensitivity against fiber nonlinearities. The better sensitivity can also be used to switch to multilevel modulation formats like DQPSK (Differential Quad Phase Shift Keying). DXPSK schemes allow the transmission of more than one bit per transmitted symbol, cutting down the symbol rate on the transmission line. Therefore DXPSK increases significantly the spectral efficiency of the system and reduces all bandwidth dependent effects, e.g. chromatic dispersion and second order PMD. Figure 2 shows schematically the basic transmitter setups for the different modulation formats; real implementations are of course more complex.

Although OOK will be probably the mostly used modulation format within the next years, transmission systems using alternative modulation formats, for example Duobinary modulation are already on the market. Also PSK may become commercially attractive in future when the progress in optical networking pushes towards higher spectral efficiency and increased dispersion tolerances.

Another widely researched topic is the use of equalizers to overcome the fiber induced distortions of the transmission links [5-10]. Those equalizers can be either in the optical or the electrical domain. Optical equalizers can be realized as feed forward equalizers (FFE) or as Fiber Bragg Gratings (FBG) and are able to adaptively compensate for dispersion. Polarization diverted FFE are also able to compensate PMD distortions[1,2]. These components are very promising but have not left the laboratories into the market yet. Electrical equalizers are used to compensate the optical distortions in the electrical domain, i.e. after the photodiode in the receiver. Unfortunately, the direct detection by a photodiode squares the optical electromagnetic field. This squaring results in a loss the phase information of the optical signal of linearity of the equalizer. Therefore, simple electrical equalizers such as FFE or decision feedback equalizers (DFE), see fig. 3, provide only limited performance. Whereas FFEs are only capable of compensating linear distortions DFEs can also compensate a fairly amount of nonlinear distortions. Thus electrical FFEs and DFEs suited to cost-effectively compensate for medium distortions in optical metro and region networks. However they are not suited for LH and ULH applications unless some coherent optical detection scheme is used which gives the full information about the amplitude and phase of the optical field. The currently most advanced and powerful equalizing scheme is the Maximum Likelihood Sequence Estimator (MLSE). Its operation at data rates of 10.7 Gbit/s has been demonstrated recently[3] and devices have become commercially available now. A sensitivity gain of up to 10 dB is possible when the MLSE equalizer is used in combination with a coherent receiver.

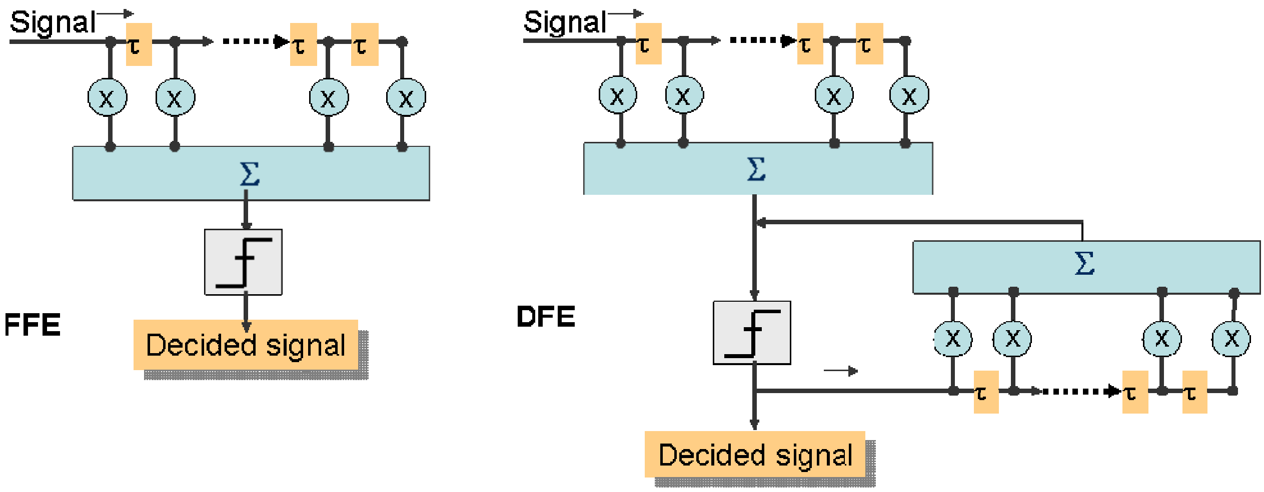



**Fig. 3:** Filter structures of electrical FFE (left) and DFE (right) filters.

The equalizer's adaptation coefficients can be set electrically. Therefore the equalizers can adapt themselves to changes in the characteristics of the incoming signal. Signals can therefore be switched through the network and their path can be changed without manually changing dispersion compensation. The equalizers adapt themselves to the resulting differing signal qualities. Adaptive equalizers significantly increase the system robustness against signal distortion and strongly facilitate future dynamically switched transparent optical networks.

An important topic in modern optical networks is the management of the whole network and the control of the network elements. To ensure a general view on the network, a so called control plane is implemented. Such a control plane can automatically detect the network topology and has full knowledge about properties and configurations of the network elements. Together with network elements which are able to switch data streams between different ports without any operator interaction, a control plane enables broadband capacity on demand and automated interlayer functionality. It also enables fast protection and restoration capabilities. By setting up and tearing down light path connections automatically ASONs can react quickly on new and changed bandwidth demands as well as in case of network failures when protection and re-routing is needed [11-14]. Such automatic operation of the network helps reducing OPEX [15].

Figure 4 shows the basic architecture of an ASON. The network is structured in three layers: a management plane, a control plane and the transport plane. The management plane usually centralizes key network management functions and common tasks such as network monitoring. The control plane on the other hand is formed by net-element controllers of individual network nodes, which provide all the necessary switching functionalities. The control plane also provides so-called network-network interfaces (NNI) to facilitate the exchange of relevant data between neighboring domains and user-network interfaces (UNI) to enable automated bandwidth provisioning on demand without further actions of the management plane. Finally, the transfer of the payload data is accomplished by the transport plane.

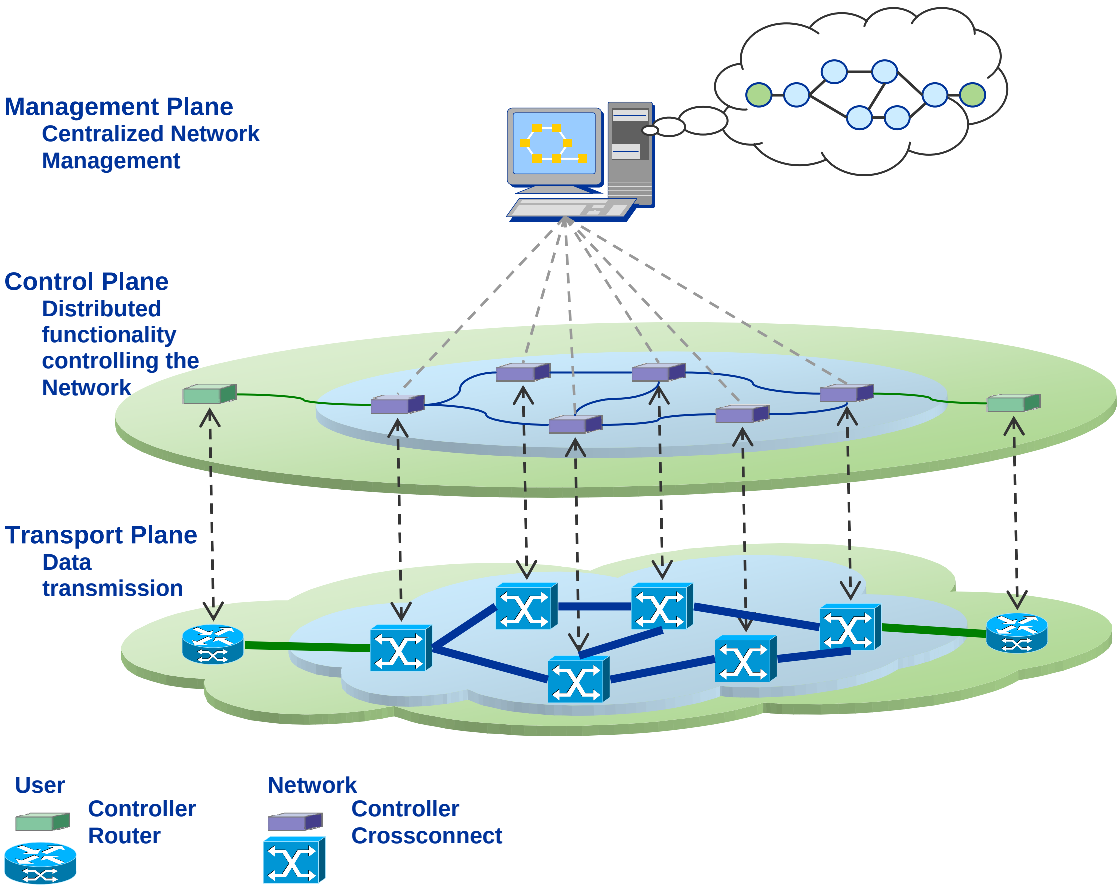



**Fig. 4:** Control Plane Architecture: a management plane has generic knowledge about the network and governs the control plane which consists of the network elements that finally route optical data paths through the transport plane.

From today's point of view the interpolation of the previous evolutions of optical data transmission shows two major trends: towards higher bit rates per wavelength and towards more flexible switched optical networks up to possibly optical burst switched/ optical packet switched networks (OBS/OPS).

Today, data rates of 10 Gbit/s per wavelength are state of the art and are widely sold. Systems with 40 Gbit/s are at the horizon and first systems are on the market. It may be questioned if the next step in the data rate will be another quadrupling up to 160 Gbit/s or if intermediate steps like 80 Gbit/s or the next step in Ethernet evolution (100 G Ethernet) will be realized first.

However, it has been shown that 160 Gbit/s technology could be the next step [16-19]. For example, a fully functional 160 Gbit/s network including add-drop multiplexers have been demonstrated in a field trial in England [17]. Also transmission over up to 550 km of deployed SSMF in the field has been shown[7]. All network functionalities, i.e. transmission, clock recovery, and switching showed good performance. The result proves that OTDM add/drop functions in the existing fiber networks are feasible. All necessary key components are available and experimentally tested. As 160 Gbit/s technology seems to be feasible to be converted into commercial systems, the intermediate steps like 80 Gbit/s or 100 Gbit/s Ethernet are also covered by that technology.

On the architectural side, flexible transparent optical networks may evolve towards burst or even packet switched networks, implementing the network control and the light path setting directly within the optical layer [20,21]. Optical data packets or bursts are routed through the network depending on the information modulated onto a present header. A couple of concepts concerning this topic are actually under research but until now no specific concept seems to be the winner. All concepts have their pros and cons. This topic requires still a lot of research and useful realizations still seem to be a couple of years away.

## 4. UPGRADEABILITY OF NETWORKS

The previous section has shown that currently many issues and different concepts are under discussion. Various technologies and concepts for transparent optical networks offer many possibilities. At the same time the user behavior and the whole IT environment changes quickly. Under such conditions long-term decisions concerning the best technology and the right network architecture are hard to make. Consequently, upgradeability and flexibility are key system features which provide network architects with the necessary degree of freedom to design and deploy future-proof optical networks today. Thus, upgradeability and design flexibility are key enablers for operators to pick up investments in LH and ULH optical networks. In particular there are two main components of the network which determine its performance. These are the first the network nodes and second the transmitters.

### 4.1. Channel and bandwidth upgrades

Considering first the transmitters and receivers the goal is to enable transmission of different types of modulation formats or data rates over the same system. This easily written requirements leads to some serious consequences for the system design. The mixing of different data rates or modulation formats on the same link or the upgrade for instance from a 10 Gbit/s channel to a 40 Gbit/s channel at a given wavelength can become a serious problem. Two points make is difficult to run 40 Gbit/s channels over an installed 10 Gbit/s system. One problem is that 10 Gbit/s NRZ channels offer optimum performance on a dispersion map implementing dispersion under-compensated scheme (DUCS) whereas 40 Gbit/s channels perform best at a dispersion over-compensated scheme (DUCS)[9]. Consequently, to run 40 Gbit/s channels over a deployed system optimized for 10 Gbit/s channels one has to take measures to adapt the dispersion maps.

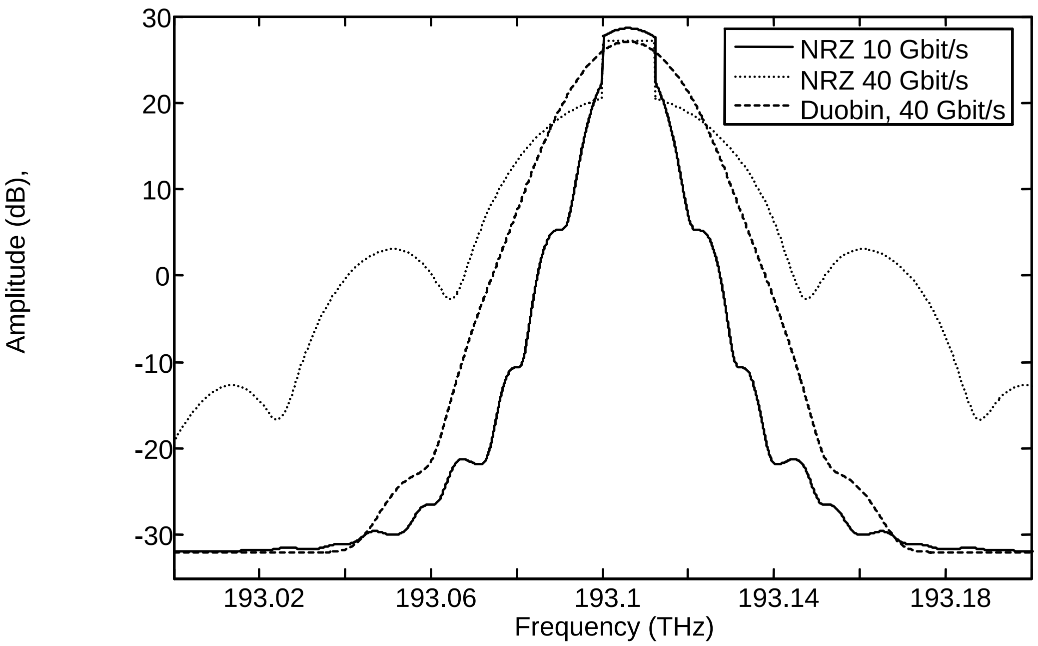



**Fig 5:** Spectra for different modulation formats: 10 Gbit/s NRz, 40 Gbit/s NRZ and 40 Gbit/s Duobinary modulation.

The second major problem is the about four times bigger bandwidth of the 40 Gbit/s channel – same modulation format assumed. This means that optical filters i.e. MUX/DEMUX or interleavers implemented in the system will cut parts of the optical signal spectrum leading to a high penalty for the 40 Gbit/s channels. This limitation however can be overcome by engineering the phase of the optical signal of OOK signals by utilizing advanced modulation formats. Figure 5 shows the spectral occupancy of a 10 Gbit/s NRZ format, compared to a 40 Gbit/s NRZ and a 40 Gbit/s Duobinary format. The 40 Gbit/s NRZ format occupies a much bigger part of the spectrum than the 10 Gbit/s NRZ format (4 times) and can therefore not pass the 10 Gbit/s optimized filters within the system A 40 Gbit/s Duobinary signal still has a bigger spectral occupancy than the 10 Gbit/s NRZ signal but it will pass the optical filters with a much smaller penalty than the 40 Gbit/s NRZ signal.

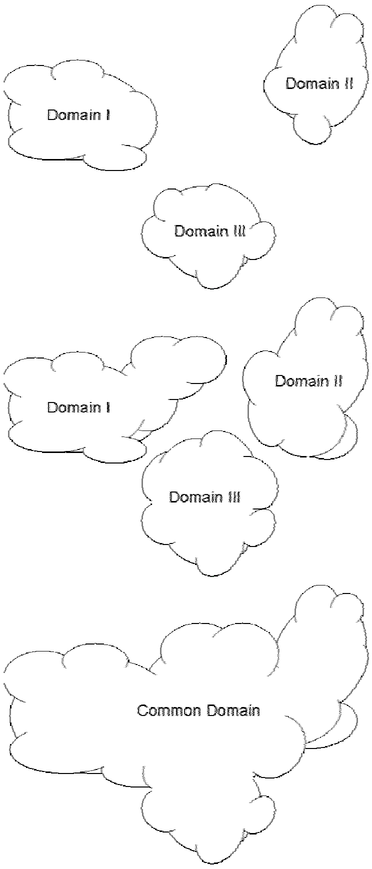
By addressing these key issues, i.e. filter bandwidth and dispersion map adaptation, one can enable transmission of 40 Gbit/s channels over existing network infrastructure optimized for 10 Gbit/s data rates at high performance. This as mentioned above enables operators to install cost-effective 10 Gbit/s channels first and to upgrade these later if the higher bandwidth is required. Operators can therefore minimize their front investments and follow a pay-as-you-grow strategy. This example highlights how intelligent system design and choosing advanced modulation formats can obtain upgradeability and thus protection of legacy investments.

4.2. Network upgrade

The second big issue regarding upgradeability considers the network architecture itself. Today, network operators plan new networks to be deployed based on current demands and on traffic forecasts. A certain topology is assumed for all planning issues. The network is setup correspondingly. This however limits significantly the ability to respond to new demands and circumstances in the future. An organic growth of the network is not foreseen and not possible. The topology is fixed from day one. However, advanced network designs will have to provide exactly such flexibility in the future. Major advantages of such flexible upgradeable network elements are:

- Eased network planning as topological changes can be easily done some when in the future.
- Flexibility to respond to new topological demands by upgrading respective network nodes and adapting the network correspondingly.
- Protection of upgradeable legacy equipment and related investments.
- Lower front investments as minimum requirements can be installed first and installed equipment can be upgraded later.
- Facilitates a pay as you growth strategy.

By providing respective net element architectures system vendors put network providers in a position, where they can start to deploy next generation optical networks without picking up investments for the next decade. Also network operators can start to deploy new networks in regions with high demands. Such areas where new networks are installed first may be spatially separated. With the demand increasing also in other locations these domains may grow. Such an organic growth of network's topology can be supported by respective upgradeable networks. With further increasing demand network domains may continuously grow until they start to overlap. From this point in time network operators can start to merge the formerly individual domains into one big transparent, optical network. By merging several smaller domains to one bigger transparent, optical network operators can take advantages from the meshed topology of the newly formed network. Such advantages may either be a reduced effort for OAM or a gain of additional efficient routes for protection and restoration. Also capacity adaptation may be possible and reduce CAPEX and OPEX.




First step:
High capacity upgradeable networks are deployed in core areas with high demands. Domains are initially independent.

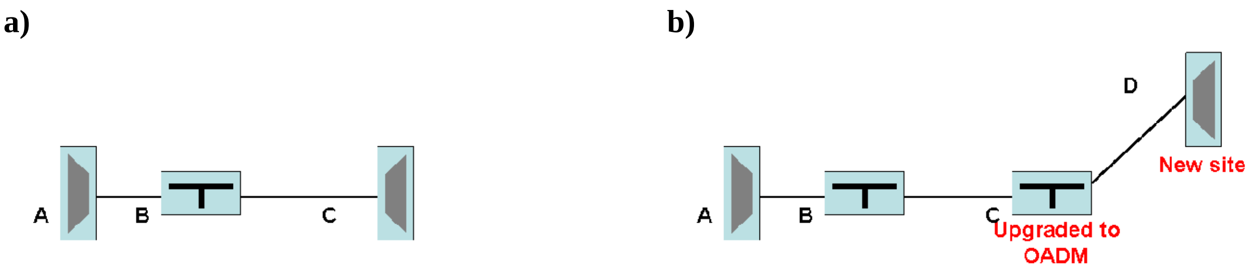
Second step:
Optical domains grow according to the bandwidth demands in less populated areas.

Third step:
Optical domains start to overlap. They can be merged to one bigger domain to minimize OAM effort and to take advantage for the meshed topology, i.e. protection bandwidth optimization etc.

**Fig. 6:** The three stages of the evolution of optical networks with upgradeable network nodes.

To enable such organic network growth the net elements have to provide respective functionalities and a corresponding design. The key elements affected by such a concept of network upgradeability are the network nodes and termination points. These have to be designed in a manner that their topological properties, i.e. the nodal degree, can be increased. In particular, optical termination terminals (OTT) have to be upgradeable to optical add/drop multiplexers (OADM). Further OADMs, which represent nodes of degree three, have to be upgradeable to real optical cross-connects (OXC) with a nodal degree of four or higher. By providing this any network node or terminal can be upgraded to that nodal degree, which is required.

An example of an upgrade scenario is displayed in Fig. 7. It shows how network growth or topological upgrades can take place. The general ability to upgrade the nodal degree of a terminal enables organic network growth according to the bandwidth demands, topological or functional requirements of the operators, e.g. protection paths etc.



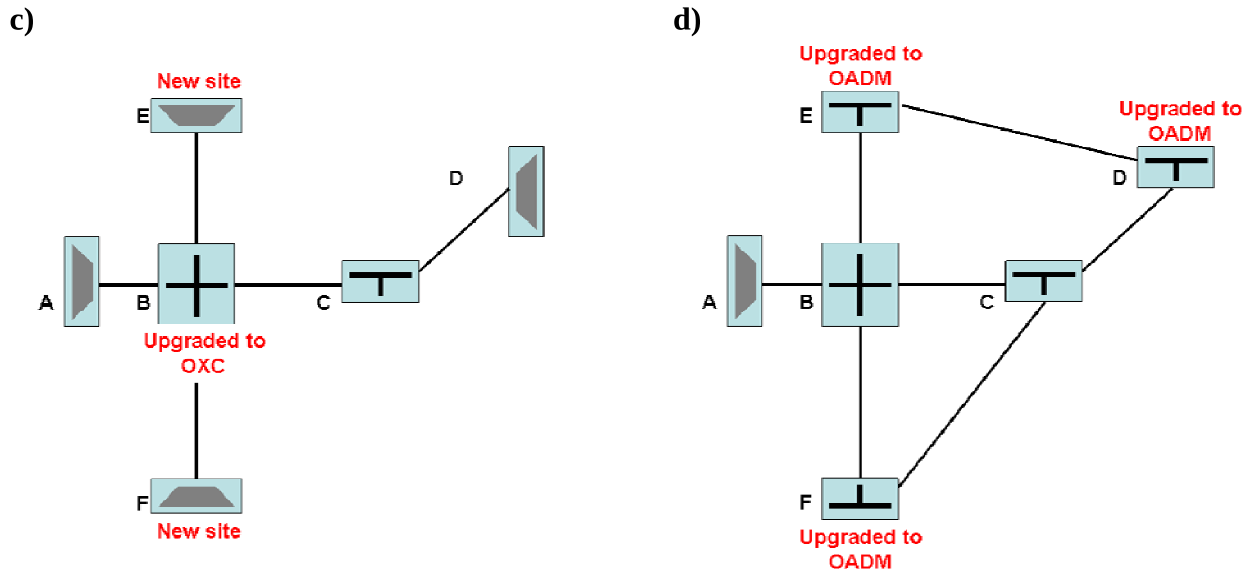



**Fig. 7:** Upgrade scenario for future optical networks. A first link with an intermediate node is deployed (a). A new site is connected and the former OTT becomes and OADM (b). Further sites are added and the OADM is upgraded to an OXC (c). The linear topology turns into a star. Finally network nodes are upgrade so that the topology becomes a ring or a meshed network (d)

An initial link from A to C with an intermediate OADM at B is set up. In the next phase the additional site D is connected to the network. The former OTT at C transforms into and OADM and increases its nodal degree. Further sites E and F are added and the OADM at B become a real OXC. The topology is now a star. In the final step the star transforms into a real meshed network enabling functionalities such as path disjoint protection and restoration.
This example pinpoints the ease of system planning, as operators can expand their network according to their needs. Long-term developments needn't to be accounted for as seriously as before since the network can be easily adapted to future requirements if necessary. Further due to the organic growth operators maintain one homogeneous network. They do not have to add further separated networks or have to rebuild them completely in case of new topological requirements. The example clarifies also that this concept minimizes front investments and protects the legacy as already deployed equipment can be upgraded to support the new network structure. Such an upgradeability may therefore become a key feature of future networks as the nodal degrees of terminals can be increased what enables organic network growth networks.

## 5. SUMMARY

This paper has provided an overview over the evolution of optical networking. We discussed the current situation of point-to-point DWDM networks and highlighted the advantages of transparent optical networks. We discussed key operational and technical requirements of optical networks. According to that we reviewed up-coming technologies facilitating the further distribution of optical networks such as alternative modulation formats, control planes or even more advanced topics like 160 Gbit/s optical networking and OBS/OPS.

To facilitate a smooth migration towards high capacity optical networks we identified upgradeability as a key issue to save the legacy investments and to enable organic network growth at the same time. The ability to move from 10 Gbit/s channels to 40 Gbit/s channels without further changes in the network is one big requirement to enable easy implementation. Further node upgrades, from OTT to OADM and from OADM to OXC, provide network operators with a new kind of flexibility and loosens long-term traffic-planning requirements while enabling organic network growth.

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