Next Generation Optical Networks

Enabler for Future

Wireless and Wireline Applications

White Paper

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List of Acronyms

ADC	A/D Converter
ADM	Add-Drop Multiplexer
A/D	Analog-to-Digital
BS	Base Station
CapEx	Capital Expenditures
CATV	Cable Television
COMP	Collaborative Multi-Point
CW	Continuous Wave
DAC	D/A Converter
DDoS	Distributed Denial of Service
DSP	Digital Signal Processing
D/A	Digital-to-Analog
E/O	Electrical-to-Optical
FCCC	Fast, Cheap, Clean, and Cognitive
FSO	Free-Space Optics
FTTx	Fibre-To-The-x
IC	Integrated Circuit
ICT	Information and Communication Technology
IP	Internet Protocol
IrDA	Infrared Data Association
LED	Light-Emitting Diode
LOS	Line Of Sight
LTE	Long Term Evolution
NGON	Next Generation Optical Networks
OEO	Optical-to-Electrical-to-Optical
OFD	Orthogonal Frequency Division
OFDM	OFD Multiplexing
OFDMA	OFD Multiple Access
OpEx	Operational Expenditures
O/E	Optical-to-Electrical
PIC	Photonic Integrated Circuit
POF	Polymer Optical Fibre
PON	Passive Optical Network
QAM	Quadrature Amplitude Modulation
QKD	Quantum Key Distribution
QoS	Quality of Service
RF	Radio Frequency
ROADM	Reconfigurable Optical ADM
RoF	Radio over Fibre
TV	Television
VLC	Visible Light Communication
WDM	Wavelength Division Multiplexing

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1 Rationale

Information and Communication Technologies (ICT) will continue to be a key driver for the future economy of Europe as evidenced by the national infrastructure of broadband Internet, mobile communications and web services. The ICT infrastructure is now considered in most countries to be part of a Critical National Infrastructure and is the key to future economic growth. The ICT sector is directly responsible for 5 % of Europe's gross domestic product, with an annual market value of €660 Billion [1]. However, ICT contributes considerably more to overall productivity growth (20 % directly from the ICT sector and 30 % from ICT investments). As an enabler, ICT plays a vital role in enhancing other sectors' business growth. According to the Information Technology and Innovation Foundation, a $10 Billion investment in broadband networks, in one year, would create almost 500,000 jobs in the US [2]. Europe is home to the world's largest and most successful telecom industry, with 7 out of the 10 largest telecom operators (Telefonica, Deutsche Telekom, Vodafone, Orange, BT, Telecom Italia, Telenor Group) alongside major world telecom manufacturers (Alcatel-Lucent, ADVA Optical Networking, Ericsson, Nokia Siemens Networks and Intune Networks), leading manufacturers of optical components (e.g. Oclaro, u2t, Leoni, and ULM Photonics) and manufacturers of network test equipment (e.g. JDS Uniphase and Agilent). Maintaining the strong European leadership in communications is essential for its economy, employment and innovation. Europe's communications industry has the strength to remain competitive and to establish leadership in a new wave of broadband networking technologies and business innovations. All this is motivated by the end users' demand for higher bandwidth: Better quality video on smart phones, IP-based television, smart homes with networked appliances, data-hungry business applications and 3D-video conferencing - all of these need data rates which require efficient network infrastructure based on photonic technologies.

Optics plays a key role in making this traffic growth sustainable, not only at the edge of the network based on passive optical network solutions and optical backhauling solutions for radio access networks, but also in its core. Technologies utilised in optical networking are coming ever nearer to the boundaries set by physics and information theory. Only with an extraordinary effort in research will it be possible to sustain the capacity growth in the core network while at the same time reducing power consumption, footprint and cost of the network elements. This cannot only be based on advances on the component and subsystem level, but also by making the network more flexible and reconfigurable to improve resource utilization. All parts of the network (home, wired and wireless access, metro, and backbone) need to support the growing capacity, transparency, dynamic, energy efficiency and security demands [3].

Each person will soon have at least a mobile smart phone with the capability of accessing extremely high data rates. This will require more power generation which will have a severe impact on the environment. Therefore the future network is required to be fast, cheap, clean and cognitive (FCCC). To achieve an FCCC network, the wired and wireless networks need to be fully merged to have a transparent and widely seamless network with as much optical fibre close to the end user as possible to reduce power consumption, increase the data rate and reduce the cost of the transmitted and routed bit. In addition, to achieve such a goal, we need both the network and the end user devices to be cognitive.

2 Research Priorities

2.1 Making optical networks more transparent and secure

By reduction of OEO conversions: Today's optical transport networks are mainly opaque, i.e. they consist of electronic nodes connected by point-to-point wavelength division multiplexed (WDM) links. The on-going introduction of transparency through optical cross-connects based on wavelength selective switches has already removed some limitations on the development of network capacity. In the ideal scenario, an optical data stream enters the network through the input node, possibly travels across several intermediate nodes and reaches its destination node without being converted to electronics along the route. Too many power consuming Optical-to-Electrical-to-Optical (OEO) conversions are performed in today's networks, from transport to access networks, and the potential of photonics technologies to manipulate light itself remains largely unexploited. Increasing optical transparency means removing these conversions as much as possible. It will benefit transport but also the access networks by allowing several bit-rates, several modulation formats, or several radio standards to travel across the same generic fibre infrastructure. In particular, transparency will enable the cost-effective convergence of some networks, such as radio and fixed access. Operational Expenditures (OpEx) savings in all-optical networks over opaque, mostly due to the minimised power needs of photonics, along with the Capital Expenditures (CapEx) savings stemming from the elimination of the costly optoelectronic interfaces, render transparency highly correlated with the deployment of an economically viable network.

By optical signal processing: Numerous challenges remain to be solved in order to create fully meshed optically transparent networks or sub-networks (also referred to as 'islands'). For example, longer distances will need to be bridged across a greater variety of fibre types than today. This may require completely new fibre types (e.g. few- or multi-mode fibres) and link designs with appropriate impairment mitigation. The interactions between signals at various bit-rates, travelling across a variety of fibre types will cause propagation impairments that have to be characterised, monitored and contained. The accurate assessment of inevitable distortions stemming from transparent nodes in terms of cross-talk or filtering will need to be included in this picture as well. Chromatic dispersion is the simplest example of an effect that can be easily negated with the use of Digital Signal Processing (DSP), eliminating the need for in-line dispersion-compensating components that introduce side-effects such as non-linearities. In order to contain the above spurious effects, coherent detection and massive DSP will most likely be very helpful and will deserve particular research focus. The all-optical processing techniques for signal regeneration (preferably of the entire wavelength multiplexed signals simultaneously) or for wavelength conversion are also promising techniques. They might not only help to expand transparency further, but also to bring about wavelength agility and, hence, to further save on the number of terminals.

By convergence of network segments: Long-reach optical access networks (up to 100 kilometres) will allow convergence of metropolitan and access networks, with WDM and cheap optical amplification as a common denominator and 'colourless' (i.e. seeded reflective or tuneable) or autonomously tuned low-cost customer modules as a prerequisite. These modules (or wavelengths) can be supported by novel network services such as 'alien wavelengths', i.e. the network has to be open for any client's wavelength that meets a specified set of parameters. Ideally, the respective WDM modules are accommodated, as pluggables, in any type of client equipment. For full interworking in more complex networks, transparent, non-intrusive monitoring and wavelength tracking mechanisms will be required. Different networks for data transmission, telephone and satellite or Cable Television (CATV) are installed in households today. All these network services will converge to an Ethernet based network in future. As an intermediate step, these services could be provided transparently via a single optical fibre infrastructure at separate wavelengths. WDM technology guarantees hereby the independent use of different services simultaneously, making media converters simple and cost effective.

By convergence of fixed and mobile networks: Mobile networks can be connected to the optical network in order to reach a destination in another mobile network using different Internet gateways. These gateways, that can be optical network units, are often considered as bottlenecks because they have to support high bandwidth capacity. The entire network capacity depends on the way that these Internet gateways are managed. Wireless backhaul options comprise classical optical point-to-point connections, using potentially low-cost standard protocols and interfaces as well as novel intelligent and smart Radio over Fibre (RoF) connections in an optical-wireless integrated network, the latter of which can be a potential long term solution. Efficient path formation is very important in any integrated network, as it should at least adhere to the minimum Quality of Service (QoS) requirements of the initiated traffic flows. The radio access points can be used intelligently in path formation and the number of hops needed can be selected so that a fair balance is achieved between the bandwidth required for a flow and its minimum tolerable delay. More hops means that more energy is utilised in a path from the source to the destination and more delay is experienced, especially in cases of congestion. However, if the intermediate devices are selected in such a way that the nearest mesh routers or radio points are discovered, energy utilization and delay can be reduced significantly and higher throughputs can be achieved. Users will benefit from these capabilities by being able to access their required service including on demand applications whenever and wherever needed at minimal cost. On the physical layer, however, RoF solutions might pose a challenge when propagating in an integrated mixed-application environment. The trade-off between the "classical" solutions, which provide radio-optical integration on a digital level, and new approaches need a deeper understanding and research for implementation in next generation optical networks. Another benefit that could be achieved by the convergence of optical and wireless access is the centralization of wireless functionalities. Since several wireless Base Stations (BS) can be backhauled/managed by a single central office, extended wireless features like Collaborative Multi-Point (COMP) operation, self optimization and topology control can be enabled/improved, while handover cost can be reduced. For instance, the logical interface X2 with which the LTE BS are communicating with each other (and is extensively used by collaborative wireless schemes, such as COMP, to interchange measurements between the BS) requires a high amount of bandwidth, while excessive latency due to those exchanges can degrade the performance of the wireless links. In a centralized converged optical wireless architecture, this channel can be located locally at the central office, enhancing thus significantly its efficiency.

By convergence of optical switching networks and datacentres: Datacentres are connected to optical networks to enable home users to access their Internet content and applications. Internet datacentres have recently absorbed many PC type applications including email, productivity and customer relationship management. These applications are generally considered low user interactivity type applications. High interactive multi-media PC applications such as video editing, computer aided design and games consoles have yet to transition into the cloud. The bottleneck is considered to be an optical networking problem and not a cloud server problem as the main technical hurdles are the number of OEO conversions in the network which cause the unwanted latency, jitter and packet loss to the internet services. The key technical hurdles in overcoming the optical networking problems include new distributed optical switching architectures, advanced QoS mechanisms and dynamic managed connections. The research challenges in enabling a converged network and datacentre include how to integrate optical switched network architectures and cloud server technologies and their associated control and data planes into a singular architectural object. It will also be important to study how the telecoms optical network evolves to become the backplane of the datacentre where the optical input/output ports fuse directly with cloud server blades thus minimising latency, jitter and packet loss to the lowest possible level and providing the best possible QoS. In particular, it is very important that the converged architecture is flexible where blades can be dynamically distributed throughout the network in response to local traffic patterns and market demands. The cloud server blades must also be aware of the network parameters and the available wavelengths and as well must have access to dynamic managed connection algorithms to provide content on-demand to home users with guaranteed quality. Users will benefit from transitioning all of their content and multi-media applications to the cloud and having near zero latency, jitter and packet loss within large network geographies. Service providers will benefit from new value added commercial services and new revenue streams. All these aspects need a deeper understanding and research for implementation in next generation optical networks.

By application of Free-Space Optics (FSO): Free-space optical communication is established for inter-satellite communication and is going to be an attractive candidate for high-speed communication between spacecrafts and ground, satellite and ground or vice versa. Application areas for mobile high-speed FSO links are, e.g., short distance point-to-point links in local and metropolitan area networks as well as optical inter-aircraft communication links and communication backbones for future high-altitude platform networks. In addition, application areas for nomadic fixed FSO are, e.g., high density TV-transmission from specific locations, connection for temporary communication capacity during mass-events, temporary communication for emergency after natural disasters as well as secure high-speed links for special operation forces. The implementation of all of these into a future optical network infrastructure requires research activities to be implemented at all levels of the network. Making a relay satellite transparent to the radio signal modulation can be done by applying the techniques of radio over free-space optics, which are similar to those of radio over fibre. For near Earth scenarios, where data rates higher than several Gbit/s are demanded, WDM is the key technology. WDM for up-/downlinks is possible using atmospheric transmission, e.g., in the 1550 nm wavelength region, where components and subsystems of fibre based terrestrial WDM-systems can be deployed. Further research on free-space optics, especially with respect to satellite and terrestrial applications is required to further increase transparency and speed of the network.

By optical layer security: Security as a field of application will anyway need to stay on and exceed the bleeding edge of technology and evolve towards more complex structures and algorithms, yet it must preserve, or even increase, its usability, as the other front of the information technology evolution is user experience. Security is in fact no longer the preserve of an elite group but, due to the diffusion of ICT in everyday lives it is common ground for everyone. Regarding network security (as opposed to the security of servers and user terminals) there might be a need for an increase of the autonomous capabilities of the network nodes to react to outbreaks or attacks, minimising service disruption.

On the economic side, the latest reports on the cybercrime business attest that it is growing and attacks are becoming more profitable. A recent analysis reported that approximately 80 % of infrastructure enterprises faced a large scale Distributed Denial of Service (DDoS) attack in 2010 and a growth of 25 % in “cyber extortions” has been reported as well [4].

The security "incidents" main trend has moved from simple scams or personal fun to become a very profitable crime industry, which could also develop into terrorism and even potential war. In relation to this (and considering the situation of countries like Egypt, where a government action tore down almost the entire Internet connectivity, or China, with their request of traffic control) a growing need for lawful intercept can be expected. This will affect the design and rollout of the networks in order to foresee some 'listening points'. It has to be noted as well that the need for a more strict set of security controls and countermeasures will exponentially grow also on the mobile network, as the mobile devices of the next generation are ideal candidates to become zombie nodes serving some botnet: The high bandwidth and the high percentage of uptime (online up to 24/7), together with their nomadicity (which adds a degree of complication to the botnet) can make them very appealing to the botnet admins. All these facts will require significant investment in continuously more powerful blades from layer 2-3 engines and significant software development to be more and more embedded mainly in routers across the networks.

Secure networking is currently supported by encryption of the secret data in the protocol network layers. The largest security threat is an insecure distribution of the encryption key, which is sometimes performed by arcane methods like physically distributing the key on a piece of paper. Quantum Key Distribution (QKD), enabling a secure key exchange, is one method to make the network security independent of alternative distribution media. Future proof QKD technology provides information-theoretical security, i.e. the laws of quantum physics guarantee that the secret key cannot be retrieved by a large computational effort or by quantum computers. This technology uses unique features of single photons such as the impossibility of duplication and the entanglement with other single photons. Still, the provision of long-haul network security by QKD encounters significant technological challenges, for example an increase of reach to long-haul distances, interoperability with classical communication networks and the increase of key generation rate to the multi-Gbit/s scale.

2.2 Making optical networks more dynamic and cognitive

By optical switching: Optical networks provide unprecedented bandwidth potential far in excess of other known transmission media. Moreover, they are becoming more and more independent from the electronic technologies, decreasing maintenance costs and energy consumption. However, the architecture of an optical network is still complex. In the next generation networks, optical technologies and associated control algorithms will play a key role. Research on optical networks has to address the following issues: What are the functionalities of optical switching, what is the network topology and the associated control plane, how can algorithms be implemented and what are the traffic engineering issues. In order to provide efficient optical-network management, investigation of the technology advances concerning optical switching (how many wavelengths can be used to write or read information, what is the delay caused by the store and forward algorithms in optical networks and dynamic wave allocation considering different network topologies) is necessary. Following the introduction of optical switching nodes that triggered the vision of transparency, reconfigurable optical add/drop and switching equipment enable networks to adapt remotely and on-demand to the traffic changes. It is now envisioned that bandwidth-variable switching components will empower the optical network with a new level of dynamicity and flexibility, where switching no longer occurs on the wavelength level but, e.g., on wavebands of variable size.

By dynamically managed connections: The increasing competition in the area of leased-lines and virtual private network services strongly encourages operators to offer quicker provisioning of connections or even customer-controlled switched connections at the transport network level. The dynamicity of the optical network is thus related to the possibility for the network to automatically and dynamically control and manage connections, either for protection or restoration purposes in case of equipment failure, for traffic engineering purposes or at the customer's demand. In a longer term view, a truly agile network will require self-learning and auto-discovery of the available resources, making it really zero-touch. It will thus pave the way towards truly dynamic optical circuit switching or even optical flow switching (switching very large bursts of packets). The introduction of optical cross-connects is one of the first requirements for transport network dynamicity. But dynamicity also requires a control software (or plane) of the network. In each node, it should drive the configuration of the optical cross-connects (which wavelength from an input fibre goes to which output fibre) but also force electronic regeneration of a given wavelength that cannot be sent transparently all the way to its destination. This software has to be impairment-aware, i.e. aware of the feasibility of all optical paths before establishing connections: This is, by itself, a real challenge. Impairment-aware routing, supported by an impairment-enabled control plane, takes advantage of the optical signal performance to allocate efficiently and therefore cost-effectively the available resources. In the routing process of optical channels, the control plane will also have to take into account energy consumption, thus allowing energy-aware optical networking. To be accurate, it needs to be fed with photonic components parameters, possibly from active monitoring, and should rely on dedicated fast routing algorithms.

By better utilization of network resources: The network needs to be able to reconfigure itself automatically to follow load requirements and to avoid over-provisioning. New routing algorithms, network planning tools and adaptive transponder technologies are topics that need research attention to enable maximum use of the available network bandwidth for any instantaneous signal quality. The motivations for dynamicity can also be partly addressed by remote wavelength management thanks to cross-connects. However, the list mentioned is not final and other approaches deserve to be investigated. The most promising of them consist of automatically varying the bit-rate per wavelength, continuously or step-wise, at constant channel bandwidth or of varying the channel bandwidth at constant bit-rate. Dynamicity can also be obtained by adding or dropping sub-bands in/from a multicarrier signal, e.g. an Orthogonal Frequency Division Multiplexing (OFDM) signal. The use of emerging transmission technologies, like OFDM, enhances the utilization of network resources by allowing increased spectral efficiency as well as finer, sub-wavelength, granularity when sharing transmission links among multiple connections. On a longer time scale, optical burst or packet switching is considered for end-to-end all-optical switching in the entire network. All these approaches deserve deep investigation and research to assess their potential.

By scalable optical routers: Network dynamicity and flexibility can be measured by the support of multi-granular services. Key technologies are thus optical routers which will transparently and adaptively support port rates of up to 1 Tbit/s and will dynamically switch optical timeslot, packets, bursts, wavelengths and wavebands together in one optical switching fabric. It is particularly important to provide flexible and scalable solutions both in switching dimensionality as well as in bit rate and throughput. A main research focus should be the design of modular, flexible and scalable optical routers that can be deployed in the metro-core network in order to guarantee end-to-end transparency and service delivery and support much higher rates and throughput than electronic routers alone. Further advanced functions should include: Contention management in order to achieve a virtually lossless end-to-end packet loss performance, unicast and multicast functions (using replication at the optical layer). Timing and synchronisation for real-time applications (flows) are very important and the capability to achieve this optically at very high rates should become part of research. A fundamental rethinking of what constitutes an optical router and its architecture is now possible due to a number of enabling technologies.

By scalable distributed optical switches: Network simplification can be achieved by integrating various network objects into a single unified but distributed system. New innovations in dynamic optics and optical packet switching technology enable optical switches to be geographically distributed in metro networking applications. A main research focus should be the design of modular, flexible and ultra-scalable distributed optical switches which can be deployed in metro/access networks, guarantee end-to-end QoS and support much higher data rates and throughput. A critical area of research will be how to scale from individual distributed switching objects into multi-stage distributed switching object architectures encompassing very large national geographical areas. The major architectural research challenges will include dynamic and unpredictable end-to-end services, distributed scheduling algorithms, photonic interconnects and dynamic optical sub-systems. Next generation networks are increasingly providing more dynamic services and next generation dynamic optical components and integrated sub-systems will also be a key enabling research challenge in dynamic service provisioning. All these aspects need a deeper understanding and research for implementation in next generation optical networks.

By autonomous network operation: More emphasis should be put on system level research and innovation with integration and optimisation of advanced multi-cell, multi-user and multi-networks cooperative techniques that collaborate and operate cognitively. The cognitive radio and cognitive networking together with network resources virtualisation and information-centric networking are salient features and requirements of next generation smart mobile and wireless systems. These, together with already extensive worldwide connectivity, purpose designed QoS mechanisms, efficient mobility management, robust security schemes and efficient support of other domains mean that mobile and wireless networks can be considered as the important basic building blocks of the Future Internet. Cognitive optical networks are promising to be the major step towards an efficient autonomic management of the increasing complexity in optical networks. In order to deliver cognition, optical networks have to be initially aware, adaptive and then learn from those adaptations and use them to make future decisions, while taking into account end-to-end goals. All these challenges require further research.

By cross-layer optimization: Apart from the layer specific cognition deployment, cognitive cross-layer optimization is an important element of a holistic approach for delivering end-to-end performance. To do so, states of a cognitive cycle (e.g. observe, act) of one layer can interact with the states of another layer (e.g. orient, decide, etc.) in order to create a cross layer cognitive cycle and to consider complete aspects of the network stack. Finally, when an optical network is aware, adaptive and learns it becomes cognitive. The physical layer, for example, can consist of cognitive hardware/software modules that are able to self-adapt, self-configure and self-optimise their structure and behaviour. Modulation format, bit-rate, number of wavelengths used, launch power, amplification gain, compensation and many others can be adapted, re-purposed and optimised according to the needs of infrastructure and service provider as well as user and application requirements. A self-optimised physical layer can also observe local and network-wide physical impairments to optimise the performance of individual devices and nodes to guarantee end-to-end quality of transmission levels. For all these reasons, hardware programmable elements need to be developed so that the state-of-the-art optical modules can be controlled and adapted to enable cognitive optical systems and networks. Moreover, cognitive, cross-layer optimized concepts can also be applied to the access part of the network. The need to support a larger user base within the same metro/access converged network is expected to lead to a significant diversity of user locations and transmission link qualities. For this reason, a different modulation format can be dynamically assigned to each user, maximizing thus the aggregate network capacity.

2.3 Making optical networks faster

By broadband wireless access: The number of mobile users and mobile traffic are increasing at staggering rates. CISCO predicts that in 2015 every person in the world will have a mobile and 2/3 of the world's mobile traffic will be video. Continuous growth is attributed to the appeal of smart phones as well as the increasing penetration of basic mobile services in developing and emerging markets. The increasing demand for data rate delivery to mobile devices requires mobile networks to improve spectral efficiency and to extend their services to new bands of the frequency spectrum. The newest wireless cellular technologies, such as Long Term Evolution (LTE), promise a significant increase in spectral efficiency, but nevertheless more wireless capacity is needed. This requirement is met by two major trends which are currently maturing from an idea to reality: Wireless network densification and spectrum aggregation which both boost the available capacity per user and location. While microwave inter-site connectivity might be a temporal solution for the first roll-out of LTE networks, the LTE sites require Gbit/s-connectivity, which means fibre to the BS and preferably between them. Regarding wireless signal carrier spectrum limitation in terms of cost, congestion, and bandwidth, the requirements for switching to higher frequency carriers such as license free mm-wave range frequency, sub-THz (covering 0.1 to 0.3 THz) and even the THz range (from 0.3 to 10 THz) are essential. These frequency bands suffer from high signal attenuation, which turns into an advantage to reduce the cell size and increase carrier frequency re-use. These femto base stations in buildings are expected to be deployed in very high numbers, again requiring high capacity backhauling to the core network. As system implementation at these high frequency carriers requires expensive electronic components, cost-effective integration is needed, either through the key technologies of hybrid integration (components on different substrates are integrated at the package level) or monolithic integration (several functional blocks on a single chip). Component integration is expected to have an impact as it affects several important factors of the system, such as reducing footprint, inter-element coupling losses, packaging cost, and usually power dissipation. The motivation for cost-effective integration of components and systems for all-photonic Radio Frequency (RF) and mm-wave signal processing application in photonic research projects and markets is expected to achieve the required cost reduction.

By broadband fibre based access: Access networks capable of interconnecting higher number of users with a symmetrical or asymmetrical bandwidth are required. The challenge is to achieve the requested capacity and QoS performance in the access network by exploiting the vast bandwidth, low loss and dispersion of new types of fibres currently being developed to set up a massive pool of WDM channels at aggregate rates which can be selected from a range up to 10 Gbit/s for the residential users and between 40 Gbit/s and 100 Gbit/s for the business users. The challenge will be in exploiting the full 400 nm of bandwidth across up to 1,000 WDM channels for creating a hierarchically-flat access network. In addition, there is a technical challenge concerned with the possibility of ultra-long-reach access performance i.e. “unregenerated” transportation of the WDM channel pool over long distances, bridging the barrier between Access and Core. The future long reach access networks will result in consolidated metro-access networks. This will reduce the number of central offices which current subscribers are connected to. Utilizing coherent technology enables automatic tuning to any wavelength and eliminating WDM inventory issues. Today’s lab prototypes are based on tuneable lasers that enable up to 100 km of reach and 1000 subscribers to be served with 1Gbps per user. The development of truly cost-effective integrated components and subsystems for the high-speed optical access network is required, supporting the requirements – such as low latency – for high capacity mobile backhauling. Another approach for achieving the aforementioned requirements makes use of the Orthogonal Frequency Division Multiple Access (OFDMA) Passive Optical Network (PON) concept. The latter is based on the utilization of several low-bitrate orthogonal sub-carriers of the link carrying different Quadrature Amplitude Modulation (QAM) symbols simultaneously, with different users assigned to different OFDM sub-carriers. Recent studies have shown that OFDM/OFDMA technology can provide high capacity, long-reach and cost-effective operation for PONs. Most importantly OFDMA-PON offers finer bandwidth granularity than WDM-PON and overcomes the complexity burden of high-speed optics and ultra-fast burst mode operation that are associated with scaling current Time Division Multiple Access (TDMA) PONs to rates of 40 Gbit/s or 100 Gbit/s.

By broadband terrestrial backbones: The exponentially growing data consumption in fixed and mobile access puts more and more stress on the core of the network. In fact, based on various traffic measurements and predictions, traffic volume in the core network is expected to grow roughly by a factor of 10 within the next 5 years and by a factor of 100 within the next 10 years. Peak throughput at core network nodes is expected to reach several 100 Tbit/s by 2020. Technologies utilised in optical networking are more and more approaching boundaries set by physics and information theory and therefore require extraordinary effort in research before being applicable. In general, several options (e.g. increase of baud-rate, constellation size, additional wavelength-bands, flexible grids, or by utilizing spatial or mode multiplexing) exist to cope with future capacity demands of the optical core network. Electronic functionalities (e.g. A/D converters, regenerators) should be implemented on a photonic basis (e.g. photonic A/D, all-optical regeneration), which offers the potential to reduce cost, increase the data rate and reduce energy. All options require significant advances in technology and must most likely to be combined for the core network to be able to cope with traffic demand from the edge of the network. Research effort is required on the component level (efficient, linear and broadband E/O and O/E converters, new fibre types, new optical amplifiers, optical regenerators), on electronics (analog-to-digital and digital-to-analog converters, linear amplifiers, power-efficient signal processors) and on processing (signal processing algorithms, advanced coding techniques) for transmission rates towards 1 Tbit/s per channel.

By broadband submarine links: The field of submarine transmission links is especially challenging because of the distances that must be covered (from 6,300 km and up to 12,000 km in the Atlantic and the Pacific Ocean, respectively). This is certainly the field of optical networking where the physics of fibre propagation needs the deepest understanding. Even though transatlantic cables concentrate the biggest flows of data, they lag behind by a few years in terms of total bit-rate. Most of today's submarine systems still run at 10 Gbit/s rate and the deployment of systems based on the next-generation standard bit-rate, namely 40 Gbit/s, has just begun, lagging behind terrestrial systems by a few years, while 100 Gbit/s is still full of research challenges, especially for transpacific distances. For very long reach, a thorough re-design of the system, including updated repeater and fibre designs, would be advisable. However, some operators would prefer a smooth upgrade of their existing links by gradually replacing the 10 Gbit/s transponders by 40 Gbit/s or 100 Gbit/s transponders. The challenges associated with smooth system upgrades are even greater than for green-field deployment. Original fibre arrangements, alternative modulation formats, alternative detection schemes, new amplifiers, and advanced forward-error correction, algorithms against fibre impairments in coherent receivers are all potential enablers to meet the 100 Gbit/s requirements and require further research. As a follow on, the target must be to enable truly cost efficient 40 Gbit/s and 100 Gbit/s transport technology for both upgrades and new builds.

By faster routing and handover: Fast traffic routing and handover are the main anxiety in future super/ultra broadband networks. High-speed data transportation and high end-user mobility require fast signal processing techniques. Optical-to-electrical and electrical-to-optical signal conversions cause delay and are the main bottleneck in today's networks. The solution in future networks is the implementation of a high-speed fully-photonic signal processing system for dynamic channel allocation to maintain the transmission channel connection continuity in very high-speed mobility circumstance with the highest possible throughput.

2.4 Making optical networks greener

By network simplification: The optimised optical access network has an especially high impact on the energy efficiency of the overall network. The requirements to be fulfilled are extended maximum reach of more than 100 kilometres, a high per-client bit rate in the range of 1-10 Gbit/s, and the use of simple and passive optical technologies as far as possible. Photonics is the only transmission technology able to fulfil these requirements. Fibre to the curb, building, or home (FTTx) networks are now on the way to being implemented. The replacement of digital subscriber line solutions by optical techniques reduces energy consumption in access and in-house networks. Planning tools for such FTTx networks, especially covering the next generation optical access system approaches (e.g., based on WDM, sub-carrier multiplexing, or OFDM), are needed to choose an optimised solution under different conditions. The optimised optical access network can eliminate sites completely or at least reduce their complexity by removing active electronic equipment. It allows aggregation layers to be eliminated and consolidated. Layer 2 and layer 3 switching and routing functionalities are concentrated in fewer sites. This, however, may be contradicted by a strong trend towards 'locality-of-traffic' (e.g. driven by peer-to-peer ultra high definition video services) which would lead to an increased requirement of local switching or routing in order to prevent backbones from being flooded with broadband video streams, and which could also finally make the participating clients becoming servers in the network. Hence, optimization between site consolidation and increased site number for efficient support of 'locality-of-traffic' is required. This optimization must consider simplification of the network and in particular a reduction of the total resulting power consumption.

By optical switching: Power consumption strongly depends on the network architecture itself. To achieve a significant improvement, energy efficiency must be included from the beginning as a major criterion in the design and assessment of new network architectures. In today's optical core networks, most of the power is consumed by the electronic switching and routing equipment. IP look-up and forwarding engines are the biggest power consumer in the network. More power efficiency can be achieved by using optical technologies such as reconfigurable optical add-drop multiplexers or optical cross-connects, which allow for optical bypassing and therefore for longer transparent transmission reach. Multi-layer optimisation of optical networks to achieve the best mix of photonic and electronic devices with respect to low hardware and operations costs and especially low power consumption is an important field of future research. Moreover, the development of new protocols, allowing for a reduction of the address lookup processing, is required. Aside from simplifying the network structure, future research is required to reduce the power consumption of the active devices (E/O and O/E converters). Design of modules and line-cards has to be improved to reduce power-hungry chip-to-chip and board-to-board interconnection. Intense research is required for a tighter integration of optics and electronics for moving optical interconnects onto the boards or even onto the chips. The introduction of low-power and sleep modes has to be considered at chip, component and system level and the trade-off between performance and energy consumption of the network has to be investigated in more detail. The potentially unstable behaviour in higher network layers caused by the deactivation and activation mechanisms needs to be understood. The implication of these mechanisms for network design, defining the right trigger criteria for initialisation or termination and algorithms for energy saving modes are all items for research. Finally, the energy-driven optical network is not only the result of a careful architecture selection and adoption of advanced energy-saving technologies. It is an intelligent system that utilizes its intrinsic characteristics, like the power consumption and the energy source of a device, to bring an additional level of optimization in the planning and operation phase with novel methods such as energy-aware routing and resource allocation as well as energy-efficient traffic engineering.

By introducing efficient bridging technologies: In order to promote green communications and efficient bridging traffic from the wireless domain to the optical domain, the specifications of the protocol stack used in the wireless domain need a cross layer definition. Another important aspect of this is to identify the required parameters which are to be passed between the wireless-optical domains. The identification of suitable parameters is essential for efficient operation and a smooth transition between the two domains and moreover to maintain the QoS and energy efficiency. QoS-aware media independent handover implementation in the optical control plane with a required end-to-end optical network performance is important. The next generation optical wireless networks will define and implement the control plane technology-independent modules to be able to provide support for end-to-end multi-domain QoS. Moreover, seamless mobility for real-time and high-bandwidth demanding applications will also be supported through the bridging between the application layer signalling for session setup and the technology-dependent control plane protocols that enable the dynamic resource allocation in the various network segments (i.e. the fibre network and the heterogeneous wireless networks).

By smart routing: The infrastructure based energy aware routing on the fibre side should be rapid and based on the user acquired QoS. The variations in the end-to-end path due to the wireless side and optical side should also be taken into consideration. Suitable routing approaches should be developed for the optical (wired) domain, which can maintain the QoS parameters as required by the wireless domain. Since different radio gateways and implementations will have different tolerances to optical impairments, the development of routing and wavelength assignment algorithms that will provision an end-to-end optical connection with the required optical integrity is necessary. Offering differentiated optical services to the wireless gateways will make more efficient use of optical resources and potentially reduce the transmission engineering requirements and energy consumption of the optical network. In addition, the ability to provide protected or restored paths, whilst adhering to the optical constraints (impairment constraint routing), is also very important and requires further research.

2.5 Bringing optical networks closer to the customer

By utilisation of optical fibres in the homes: Optical networks in the home and in private, public and office buildings are a prerequisite for broadband end-to-end services for the end users to offer higher data rates that cannot be achieved with non-optical solutions. YouTube and other services give people the chance not only to consume information but to distribute their own information, videos or data. New global trends, like the aging society or ambient assisted living, are an additional driver for high-speed optical in-house networks. The installation of optical fibre inside the house itself, in order to have a high bit-rate, low delay, high quality and future-proof wired medium is an essential step towards this direction. These optical networks must be installable as easily as copper based networks. Therefore, pre-connectorised glass and Polymer Optical Fibres (POF) become more and more important to push their acceptance. In private households, POF, which can be installed by craftsmen or by the owners themselves, will play an increasing role. POF infrastructure can provide a point-to-point architecture suitable for already constructed houses, and will reach multi-Gbit/s capacity over several tens of meters. In addition, optical backbone networks in the building make it possible to use access points with low power consumption and low electro-magnetic field strengths. These backbones will be suited to green-field installations where the optical cables will be installed in ducts running in the walls during construction. The architecture will have the possibility of evolving from a point-to-point to a fully transparent multipoint-to-multipoint network able to respond to any future bandwidth requirements. These backbone home networks will probably rely on single-mode fibre to guarantee the long-term suitability of the network and benefit from the economy of scale and experience gained from current FTTH deployments. Optical fibre-based home networks will thus require much research effort so as to design cost-effective and power-efficient architectures and technologies for home networking, taking into account economical factors, end-user requirements, and installation constraints.

By utilisation of optical wireless communication: In this context, optical wireless links for short and mid-range indoor and outdoor applications are another topic of research. Optical wireless links can be used in point-to-point mobile-2-mobile, fixed-2-mobile, fixed-2-infrastructure, or infrastructure-2-mobile scenarios and provide an enormous benefit in consumer, medical, industrial, and transportation areas. Current state-of-the-art LEDs will be used for the purpose of illumination but their secondary duty will be to ‘piggyback’ onto those lighting systems and to act as a Visible Light Communication (VLC) source. This will be particularly relevant in indoor smart lighting systems, where the light is always on to provide broadcasting channels or even bi-directional channels to transfer future mass data and multi-media content effectively. Nevertheless, it is anticipated that data rate will have to be traded-off with room coverage. Alternatively, the LEDs’ primary purpose will be to transmit information while the secondary purpose of illumination would be to alert the user to where the data is being transmitted from or to generate guiding and emotional effects for users. Using general lighting sources as access points and optical wireless gateways to mobile devices and terminals is a future step to reduce the power consumption of home and in-building networks.

Transmission rates of the most recent prototypes for VLC are in the range of 100 Mbit/s. However, the highest transmission speeds so far achieved in laboratory experiments for point-to-point short range applications are 500+ Mbit/s (single VLC channel) and 800+ Mbit/s (WDM). Traditionally, infrared-based optical wireless communications research and products have indeed been concentrated on short-range point-to-point links based on Line Of Sight (LOS). Today, Infrared Data Association (IrDA) interfaces can be found in a variety of portable devices, like mobile phones, laptop computers and personal digital assistants. In its most recent version (fast IrDA), the standard offers rates up to 16 Mbit/s (over approximately 1 m range), but point-to-point interfaces for much higher data rates are in development (up to 1 Gbit/s with Giga-IR). In practical applications, it is often desired to combine the high-speed capability of LOS systems with user mobility and coverage supported in diffuse links: This is the key issue of indoor applications of optical wireless technologies. Research topics are, for example, interplay with existing communication infrastructures (such as power-line communications), lower-rate applications such as indoor navigation, lighting control, and physically secure high-speed short range mass data and multi-media content transfer and synchronization for different kinds of smart objects and terminals.

3 Technology Roadmap

The vision described in the preceding sections is dependent for its realization upon developments in a number of areas of component technology, which we may briefly summarize as follows: For area 2.1, *Making optical networks more transparent and secure*:

- Optical cross-connects or wavelength selective switches with a large number of input/output ports (e.g. ~20)
- Optical performance monitors
- Data-rate independent transponders
- Format-flexible transceivers
- Gridless wavelength-selective switches
- Low-cost transceivers that are 'colourless' (i.e. without pre-assigned wavelength)

For area 2.2, Makin*g optical networks more dynamic and cognitive:*

- Fast tunable lasers
- Fast tunable receivers
- Coherent optical transceivers
- Colourless, directionless and contentionless ROADMs
- Burst-mode receivers
- Transient-free optical amplifiers
- Programmable transponders
- Optical switches
- Ultrafast, high-extinction-ratio optical gates

For area 2.3, *Making optical networks faster*:

- Ultra-large bandwidth optical amplifiers
- High-bandwidth optoelectronic interfaces
- Transponders based on advanced modulation formats and coherent reception
- Vectorial modulators with excellent linearity
- Linear coherent receivers
- Photonic integrated circuits
- High performance ADC/DAC and digital signal processing

- Ultra-narrow linewidth CW lasers
- Multi-mode fibres
- Multi-mode amplifiers
- Mode Division multiplexer/demultiplexer
- Multi-core amplifiers

For section 2.4, *Making optical networks greener*:

- Integrated devices
- Cooler-less optoelectronic components
- Low-power ADC/DSP for coherent receivers
- Integration of opto-electronic interfaces with high speed digital signal processing
- Hardware that is robust with respect to multiple on-off cycles
- Low-energy switches
- Advanced thermal cooling

For section 2.5, *Bringing optical networks closer to the customer:*

- Optical home gateways with low power consumption
- Bending-insensitive fibres
- Polymer optical fibre
- Integrated LED drivers that enable visible light communication

Photonic Integrated Circuit (PIC) technologies based on III-V semiconductors, silicon and other materials are vital for the realization of the component set required here. Furthermore, many of the concepts described above depend upon very close interworking of photonic elements and high speed electronics. The emerging field of silicon photonics, in which photonic and electronic IC elements are integrated monolithically, offers exciting prospects, as does hybrid integration of III-V semiconductor PICs with complementary IC technologies. We recommend that PIC technology in silicon, III-V semiconductors and related materials continue to receive high priority and that the coupling between electronic and photonic technologies is given particularly close attention.

4 Summary and Recommendations

The consensus within Photonics21, Net!Works and in the world telecommunications industry is that the demand for bandwidth will continue to grow at an exponential rate, fuelling the growth of new services, new ways of doing business and novel 'infotainment' applications.

Optics plays a key role in making this traffic growth sustainable, not only at the edge of the network based on passive optical network solutions and optical backhauling solutions for radio access networks, but also in the core of the network. Technologies utilised in optical networking are more and more approaching boundaries set by physics and information theory. Only with extraordinary research effort will it be possible to sustain capacity growth in the core network and in the fixed and mobile access areas of the network while at the same time reducing power consumption, footprint and cost of the network elements. This cannot only be reached by advances on component and subsystem level, but also by making the networks more flexible, reconfigurable, adaptive and autonomous to improve resource utilization.

To prevent Europe from falling behind in the development of the next generation of optical network technology as an enabler for future wireless and wireline services, the consortia Photonics21 and Net!Works recommend the following research topics:

To make optical networks more transparent and secure:

- By removing unnecessary optical-to-electrical-to-optical conversions in aggregation nodes, routers and switches while managing the resulting increase in heterogeneity in fibre types and network architectures. Allowing several bit-rates, modulation formats, and radio standards to travel across the same generic infrastructure, enabling future-proof and cost-effective convergence of mobile and fixed, metro and access networks.
- By optical layer security to enable secure exchange of data in the network on the lowest possible layer.

To make optical networks more dynamic and cognitive:

- By introducing true flexibility in photonic networks through fast-established circuits or optical packets, coping with varying traffic demands, benefiting from flexibility and elasticity in format, channel spacing or bit-rate, while reducing latency, and managing quality of service at the photonic layer, to achieve autonomous operation of photonic network elements, including self diagnosis, restoration and optimisation with efficient use of monitoring and adaptation capabilities.

To make optical networks faster:

- By elaborating a disruptive mix of technologies to keep up with capacity growth of 1 Gbit/s per user in wireless access, of up to 10 Gbit/s per user in wired access and of up to 1 Tbit/s per channel in the core, involving coherent detection with intelligent digital signal processing, exploiting all modulation spaces and multiplexing schemes, so as to increase spectral efficiency, while expanding the bandwidth of optical amplifiers and improving their noise properties.

To make optical networks greener:

- By expanding the role of photonics from core down to home access, promoting optical bypass whenever possible, turning all photonic equipment to idle mode when possible, performing power-efficient all-optical switching and processing as appropriate, simplifying or removing unnecessary protocols, performing energy-aware optical routing to reduce cost per transmitted and routed bit.

To bring optical networks closer to the customer:

- By ensuring high-bandwidth, mobile, fast, green, secure, and reliable customer services by optical wired and wireless home and in-building networks.

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